DOKUZ EYLUL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

FUZZY ANALYTIC HIERARCHY BASED APPROACH FOR SUPPLIER SELECTION IN A WASHING MACHINE COMPANY

by

Suzan Aslı ÖNAL

October, 2006

İZMİR

FUZZY ANALYTIC HIERARCHY BASED APPROACH FOR SUPPLIER SELECTION IN A WASHING MACHINE COMPANY

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by
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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"FUZZY ANALYTIC HIERARCHY BASED APPROACH FOR SUPPLIER SELECTION IN A WASHING MACHINE COMPANY"** completed by **SUZAN ASLI ÖNAL** under supervision of **ASSIST.PROF.DR. ÖZCAN KILINÇCI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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FUZZY ANALYTIC HIERARCHY BASED APPROACH FOR SUPPLIER SELECTION IN A WASHING MACHINE COMPANY

ABSTRACT

Competitive international business environment has forced many firms to focus on supply chain management to cope with highly increasing competition. Hence, supplier selection process has gained importance recently, since the cost of raw materials and component parts constitutes the main cost of a product and most of the firms have to spend considerable amount of their revenues on purchasing. Supplier selection is one of the most important decision making problems which includes both qualitative and quantitative factors which may conflict with each other. The objective of a supplier selection problem is to identify suppliers with the highest potential for meeting a firm's needs consistently and at an acceptable cost.

In this study, supplier selection problem of a washing machine company in Manisa is investigated and a fuzzy analytic hierarchy process based methodology is used to select the best supplier firm providing the most customer satisfaction for the criteria determined. The study is carried out in three phases: In the first phase, the main attributes and sub-attributes for supplier selection are defined to design the hierarchy structure. The main attributes, which are supplier, product performance and service performance, are determined based on literature survey and the experience of the expert. In the second phase, the weights of the main attributes, sub-attributes and alternatives are calculated. Linguistic variables and triangular fuzzy numbers are used for the preferences of one criterion over another in making pair-wise comparisons. In the last phase, the priority weights for main attributes, sub-attributes and alternatives are combined to determine the priority weights of the three alternative suppliers. The supplier with the highest priority weight is selected as the best supplier. Macros in Excel are used to calculate the priority weights of the alternatives based on the questionnaire forms used to facilitate comparisons of main attributes, sub-attributes and alternatives.

Keywords: Multi-criteria Decision-making, Supplier Selection, Analytic Hierarchy Process, Fuzzy Analytic Hierarchy Process

BİR ÇAMAŞIR MAKİNASI İŞLETMESİNDE BULANIK ANALİTİK HİYERARŞİ PROSESİNE DAYALI TEDARİKÇİ SEÇİMİ ÇALIŞMASI

ÖZ

Firmalar uluslararası rekabetçi piyasalarda artan rekabet koşullarına ayak uydurabilmek için tedarik zinciri yönetimine yönelmişlerdir. Hammadde ve yarı mamul maliyeti ürün maliyetinin büyük bir bölümünü oluşturduğu için birçok firma elde ettiği kazancın büyük bir bölümünü malzeme maliyetine yatırmak zorunda kalmaktadır, dolayısıyla tedarikçi seçimi son zamanlarda büyük önem kazanmıştır. Tedarikçi seçimi birbiriyle çelişen, sayısal ve sayısal olmayan birden fazla kriteri bünyesinde barındıran en önemli karar verme problemlerinden birisidir. Tedarikçi seçimi probleminin amacı işletmenin istekleri doğrultusunda kabul edilebilir maliyete sahip en uygun tedarikçilerin belirlenmesidir.

Bu çalışmada, Manisa'da faaliyet gösteren bir çamaşır makinası işletmesinin tedarikçi seçimi problemi ele alınmış ve bulanık analitik hiyerarşi prosesine dayalı bir yaklaşım kullanılarak belirlenen kriterler doğrultusunda en iyi tedarikçi seçilmiştir. Çalışma üç fazda gerçekleştirilmiştir: Birinci fazda, tedarikçi seçimi problemi için ana kriterler ve alt kriterler belirlenmiş ve hiyerarşik yapı oluşturulmuştur. Tedarikçi, ürün performansı ve servis performansı ana kriterleri, literatür taraması ve uzman kişinin tecrübelerine dayanarak belirlenmiştir. İkinci fazda, ana kriter, alt kriter ve alternatif tedarikçilerin ağırlıkları belirlenmiştir. İkili karşılaştırmalarda, bir kriterin diğer kritere olan üstünlüğünün belirlenmesinde dilsel değişkenler ve üçgensel bulanık sayılar kullanılmıştır. Son fazda, ana kriter, alt kriter ve alternatiflerin öncelik değerleri birleştirilip üç alternatif tedarikçinin öncelik değerleri belirlenmiştir. En yüksek ağırlığa sahip olan tedarikçi en iyi tedarikçi olarak seçilmiştir. Excel'de yazılan makrolarla, ana kriter, alt kriter ve alternatiflerin ikili karşılaştırmalarında kullanılan anket formları baz alınarak alternatiflerin öncelik değerleri belirlenmiştir.

Anahtar sözcükler: Çok Kriterli Karar Verme, Tedarikçi Seçimi, Analitik Hiyerarşi Prosesi, Bulanık Analitik Hiyerarşi Prosesi

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CHAPTER ONE
INTRODUCTION

1.1 Supplier Selection

Increases and varieties of customer demands, advances of recent technologies in communication and information systems, competition in global environment, decreases in governmental regulations and increases in environmental consciousness have forced companies for focusing on supply chain management (Tracey & Tan, 2001). The "supply chain management" term has been used for almost 20 years and is defined as the integration of activities to procure materials, transforms them into intermediate goods and final products, and delivers to customers (Heizer & Render, 2001). The supply chain consists of all links from suppliers to customers of a product. Goffin et al. (1997) have stated that supplier management is one of the key issues of supply chain management because the cost of raw materials and component parts constitutes the main cost of a product and most of the firms have to spend considerable amount of their sales revenues on purchasing. Hence, supplier selection is one of the most important decision making problems, since selecting the right suppliers significantly reduces the purchasing costs and improves corporate competitiveness (Ghodsypour & O'Brien, 2001).

On the other hand, supplier selection decision-making problem involves trade-offs among multiple criteria that involve both quantitative and qualitative factors, which may also be conflicting (Ghodsypour & O'Brien, 1998). In other words, buyer-supplier relationships based on only the price factor has not been appropriate in supply chain management recently. Considerations have been given also to the other important strategic and operational factors such as quality, delivery, flexibility, and etc. Supplier selection decisions must include strategic and operational factors as well as tangible and intangible factors in the analysis (Sarkis & Talluri, 2002). Hence, supplier selection problem can be modeled and solved by means of utilizing multi-criteria decision analysis.

In this thesis, a fuzzy analytic hierarchy process based approach is used to solve the supplier selection problem in a washing machine company. The study is carried out in three steps: In the first step, the main attributes and sub-attributes for supplier selection are defined to design the fuzzy analytical hierarchy process (FAHP) tree structure. The main attributes, which are supplier, product performance and service performance, are determined based on literature survey and the experience of the expert in the Production Planning Department. In the second step, the weights of the main attributes, sub-attributes and alternatives are calculated. Linguistic variables and triangular fuzzy numbers are used for the preferences of one criterion over another. In the last step, the priority weights for main attributes, sub-attributes and alternatives are combined to determine the priority weights of the alternative suppliers. The supplier with the highest priority weight is selected as the best supplier. Macros in Excel are used to calculate the priority weights of the alternatives based on the questionnaire forms used to facilitate comparisons of main attributes, sub-attributes and alternatives.

1.2 Thesis Outline

The thesis is organized as follows:

Chapter One contains a brief description of the supply chain management and describes the scopes of the study.

Chapter Two concerns definition of supplier selection, classification of supplier selection problems, supplier selection procedure and criteria in detail. Also it presents the approaches used for supplier selection such as categorical models, mathematical programming models and cost based approaches.

Chapter Three contains a detailed literature survey on supplier selection studies.

Chapter Four explains AHP and FAHP in detail. In this thesis, FAHP is utilized to select the best supplier firm.

Chapter Five suggests a FAHP based approach to select the best supplier firm providing the most satisfaction for the criteria determined and discusses the steps of each stage of the procedure in detail.

Chapter Six summarizes the findings of this study and states the future research directions.

CHAPTER TWO
SUPPLIER SELECTION

2.1 Definition

Supplier selection is a multi-criteria problem which includes both qualitative and quantitative factors. In order to select the best suppliers it is necessary to make a trade off between these tangible and intangible factors some of which may conflict (Ghodsypour & O'Brien, 1998).

In most industries the cost of raw materials and component parts constitutes the main cost of a product, such that in some cases it can account for up to 70% (Ghobadian, Stainer & Kiss, 1993). In high technology firms, purchased materials and services represent up to 80% of total product cost (Weber, Current & Benton, 1991). Thus the purchasing department can play a key role in an organization's efficiency and effectiveness because it has a direct effect on cost reduction, profitability and flexibility of a company (Ghodsypour & O'Brien, 2001).

Selecting the right suppliers significantly reduces the purchasing cost and improves corporate competitiveness, which is why many experts believe that the supplier selection is the most important activity of a purchasing department (Dobler, Lee & Burt, 1990; Willis, Huston & Pohlkamp, 1993).

The objective of supplier selection is to identify suppliers with the highest potential for meeting a firm's needs consistently and at an acceptable cost. Selection is a broad comparison of suppliers using a common set of criteria and measures. However, the level of detail used for examining potential suppliers may vary depending on a firm's needs. The overall goal of selection is to identify high-potential suppliers (Kahraman, Cebeci & Ulukan, 2003).

The evaluation of vendors is a complicated decision problem because of the following reasons (Mohanty & Deshmukh, 2001):

- The complexity comes from two main sources. The first is the relative difficulty to conceptualize and structure and numerous components of the evaluation problem into an analytical framework which may facilitate understanding. The second is the nature of the components in this process – some are quantitative whereas others are subjective.

- As the competition in the marketplace increases, there exists a large search space for decision makers.

- There are a multitude of factors/attributes involved in a selection process which are often conflicting and sometimes complementary. Many times, such factors/attributes are non-expressible in commensurable units and some factors/attributes might reflect psychological aspects such as qualitative considerations and intangibles.

2.2 Classification of the Supplier Selection Problem

In today's highly competitive environment, an effective supplier selection process is very important to the success of any manufacturing organization (Liu & Hai, 2005). Basically there are two kinds of supplier selection problems (Ghodsypour & O'Brien, 1998):

1. Supplier selection when there is no constraint. In other words, all suppliers can satisfy the buyer's requirements of demand, quality, delivery, etc.

2. Supplier selection when there are some limitations in suppliers' capacity, quality, etc. In other words, no one supplier can satisfy the buyer's total requirements and the buyer needs to purchase some part of his/her demand from one supplier and the other part from another supplier to compensate for the shortage of capacity or low quality of the first supplier.

In the first kind of supplier selection, one supplier can satisfy all the buyer's needs (Single Sourcing) and the management needs to make only one decision, which supplier is the best, whereas in the second type of supplier selection, as no supplier can satisfy all the buyer's requirements, more than one supplier has to be selected (Multiple Sourcing). In these circumstances management needs to make two decisions: which suppliers are the best, and how much should be purchased from each selected supplier (Ghodsypour & O'Brien, 1998)?

Each strategy has its own advantages and disadvantages. These are discussed below:

Advantages of Single Sourcing:

- The order may be so small that it is not worthwhile to be divided. Splitting the order may increase fixed purchasing costs.

- Concentrating purchases may make possible certain discounts or lower freight rates that could not be had otherwise.

- The supplier will be more cooperative, more interested and more willing to please if it has all of the buyer's business.

- Deliveries may be more easily scheduled.

- Effective supplier relations require considerable resources and time. Therefore the fewer supplier the better.

Advantages of Multiple Sourcing:

- Knowing that competitors are getting some of the business may tend to keep the supplier more alert to the need for giving good prices and service.

- Assurance of supply is increased. In case of fires, accidents, breakdowns, deliveries can still be obtained.

- Supplier dependence is avoided.

- More flexibility is achieved since the unused capacity of all suppliers is available.

- Strategic reasons such as military preparedness and supply security may require multiple sourcing.

- Capacity of a single supplier may not be enough to carry out the current or future needs of the firm (Leenders & Fearon, 2000).

2.3 Supplier Selection Framework

According to De Boer, Labro & Morlacchi (2001) a supplier selection problem typically consists of four phases, (1) finding out exactly what we want to achieve by selecting a supplier (2) defining the criteria (3) pre-qualifying suitable suppliers to (4) making a final choice. The framework is shown in Table 2.1.

Table 2.1 The supplier selection framework (De Boer, 1998)

	New task	**Modified rebuy**	**Straight rebuy**	**Straight rebuy**
		(leverage items)	**(routine items)**	***(strategic/bottleneck)***
Problem definition	Use a supplier or not?	Use more, fewer or other suppliers?	Replacing the current supplier?	How to deal with the supplier?
	Varying importance	Moderate/high importance	Low/moderate importance	High importance
	One-off decision	Repeating decision	Repeating decision	Repeating evaluation
Formulation of criteria	No historical data on suppliers available	Historical data on suppliers available	Historical data on suppliers available	Historical data on suppliers available, yet very few actual selections
	No previously used criteria available	Previously used criteria available	Previously used criteria available	Previously used criteria available
	Varying importance			
Qualification	Small initial set of suppliers	Large set of initial suppliers	Large set of initial suppliers	Very small set of suppliers
	Sorting rather than ranking	Sorting as well as ranking	Sorting rather than ranking	Sorting rather than ranking
	No historical records available	Historical data available	Historical data available	Historical data available
Choice	Small initial set of suppliers	Small to moderate set of initial suppliers	Small to moderate set of initial suppliers	Very small set of suppliers (often only one)
	Ranking rather than sorting	Ranking rather than sorting	Ranking rather than sorting	Historical data available
	Many criteria	Also: how to allocate volume?	Fewer criteria	Evaluation rather selection
	Much interaction	Fewer criteria	Less interaction	Sole sourcing
	No historical records available	Less interaction	Historical data available	
	Varying importance	Historical data available	Model used again	
	Model used once	Model used again	Single sourcing rather than multiple sourcing	

The different positions in the framework have different characteristics that are determinative for the suitability of the various methods. The structure of the framework will be explained in detail below (De Boer et al., 2001).

In order to incorporate complexity and importance into the framework, the industrial marketing literature is combined with Kraljic's (1983) purchasing portfolio approach. Faris et al. (1967) distinguish three typical situations of varying complexity. Peculiar characteristics of these situations are presented in Table 2.2.

Table 2.2 Classification of purchasing situations (Faris et al., 1967)

New task situation	Entirely new product/service; no previous experience
	No (known) suppliers
	High level of uncertainty with respect to the specification
	Extensive problem solving; group decision making
Modified rebuy	New product/service to be purchased from known suppliers
	Existing (modified) products to be purchased from new suppliers
	Moderate level of uncertainty with respect to specification
	Less extensive problem solving
Straight rebuy	Perfect information concerning specification and supplier
	Involves placing an order within existing contracts and agreements

Obviously, new task situations are the most complex, at least in the sense that their level of uncertainty is the highest. The distinction between new task, modified rebuy and straight rebuy facilitates a recognizable "entrance" for the purchaser and at the same time the classification comprises different levels of uncertainty about the purchase and the accompanying supplier selection (De Boer et al., 2001).

A useful framework for covering additional dimensions of complexity as well as importance is Kraljic's (1983) portfolio approach. In this portfolio, the perceived importance and complexity of a purchasing situation is identified in terms of two factors: (a) profit impact and (b) supply risk. Profit impact includes such elements as the (expected) monetary volume involved with the goods and/or services to be purchased and the impact on (future) product quality. Indicators of supply risk may include the availability of the goods/services under consideration and the number of potential suppliers. Depending on the values of these factors, purchases (and therefore the related supplier selection decisions) can be grouped according to Kraljic's classification into strategic, bottleneck, leverage and routine purchases (De Boer et al., 2001). This is illustrated in Table 2.3.

Table 2.3 Purchasing portfolio matrix (Kraljic, 1983)

	Low-supply risk	**High-supply risk**
Low-profit impact	*Routine items*	*Bottleneck items*
	Many suppliers	Monopolistic supply market
	Rationalize	Long-term contracts
	purchasing	
	procedures	
	Systems contracting	Develop alternatives (internally)
	Automate/delegate	Contingency planning
High-profit impact	*Leverage items*	*Strategic items*
	Many suppliers available	Few (difficult to switch) suppliers
	Competitive bidding	Medium/long-term contracts
	Short-term contracts	Supplier
		development/
		partnership
		(develop alternatives externally)
	Active sourcing	Continuous review

The models by Faris et al. (1967) and Kraljic (1983) are used to develop a prescriptive framework of supplier selection situations that not necessarily coincides with supplier selection processes found in practice. Its prime purpose is to offer a purchaser a manageable number of typical, different supplier selection situations with associated ways of carrying out and organizing the supplier selection process (De Boer et al., 2001).

The first distinction made in the framework shown in Table 2.1, is that between one-off and/or first-time supplier selections versus repeated supplier selections. This distinction obviously follows the distinction between new task and rebuy very closely (De Boer et al., 2001).

Within new task situations, we may distinguish between situations of relative high importance and situations of relative low importance. However, irrespective of the importance, the basic sequencing, preparation and execution of the steps in the supplier selection process will be the same. For example, due to the unique character of the situation, the process can hardly be prepared in advance (De Boer et al., 2001).

Within Rebuy situations we may expect more variety in terms of the organization and execution of the steps in the supplier selection process (De Boer et al., 2001). In the following section, the close relation of these variations to the different situations in Kraljic's model will be explained.

In case of a routine item, there are many suppliers that could supply the item. However, because of the low value of the item, it will not pay off to frequently search for and select suppliers. Moreover, usually a whole set of related routine items (e.g. stationary items) is assigned to one (or two) suppliers in order to achieve a highly efficient ordering and administration procedure. The choice of the supplier is fixed for a reasonable period of time. Intermediate changes in the desired or required items are dealt with by the current supplier. Irrespective of such specific changes in the items requested and/or actually purchased, the appropriateness of the supplier is typically reconsidered periodically and if necessary a new (adaptive) selection will take place (De Boer et al., 2001).

In case of bottleneck and strategic items, the choice of the supplier is also more or less fixed. Small changes in the specification of the items are automatically dealt with by the existing supplier. However, the reason for this is very different from that in the routine case. In these cases with a high supply risk, there are virtually no suppliers to choose from immediately, either because of a highly unique specification (i.e. a very strong resource tie between the buying company and the supplier) or because of the scarcity of the material. As a result, the choice set is often much smaller. Decision models are primarily used as means for periodic evaluation (monitoring) of the existing supplier (De Boer et al., 2001).

Leverage items typically involve modified rebuy situations. There are many suppliers to choose from while the high value (and saving potential) of the items justifies proactive search and frequent selection of suppliers. However, the execution of the first steps in the process (problem definition, formulation of criteria and prequalification) is often decoupled from the final choice. The first three steps result in the so-called approved vendor lists. Final (frequent) choices are made from these approved vendor lists (De Boer et al., 2001).

2.4 Supplier Selection Procedure

In today's world of technology and competence, what is important than cost leadership is quality and on-time deliveries. Therefore to survive in the business world, firms must be able to select the right suppliers and handle manufacturing together with them (Mızrak, 2003).

In order to select the right suppliers, the procedure to be followed is (Dobler & Burt, 1996):

1. Develop and maintain a viable supplier base: A regular manufacturing system has many inputs. These inputs consist of hundreds of different raw materials and/or components. Each material/component may be supplied by a single source or by two or more suppliers. This equation gives a huge number of suppliers to be dealt with in each manufacturing organization. Therefore information belonging to each supplier should be kept and a neat supplier base should be created in the organization.

2. Address the appropriate strategic and tactical issues: In some organizations technology and quality may be of greatest importance while in some others on-time deliveries may be given the highest ranking. According to the organization's needs, customer demand and the conditions of the market it is in, each firm should identify its own strategic and tactical decisions.

For example a laptop computer manufacturer may wish to incorporate a larger 'higher resolution display' than currently exists. In order to do so, the display should be innovated. Developing this component will require intense interaction between the buyer and the supplier. In this case quality and the reliability of the supplier are very important. And hence, selecting the right supplier is an important strategic decision.

3. Ensure the potential suppliers are carefully evaluated and that they have the potential to be satisfactory supply partners: After identifying the firms' needs, the suppliers which can not meet the desired criteria are eliminated. The nominee suppliers are chosen by this way.

4. Decide whether to use competitive bidding or negotiation as the basis of source selection: The firm must choose one of the below mentioned procedures from the beginning and act according to this decision.

Competitive Bidding: Each of the potential suppliers is asked for an offer. Competitive bidding is where suppliers know about the others' offers and make changes in their own offers. In the end the one(s) which make the best offer(s) win the contract.

Negotiation: In negotiation the suppliers to be worked with are chosen first. Then the suppliers and the firm negotiate on prices and other conditions.

5. Select the appropriate source: Whether the firm chooses to use competitive bidding or negotiation, the most appropriate suppliers should be selected. At this step many different methods may be applied. Listing and ranking the suppliers, linear programming, goal programming, fuzzy logic goal programming are among these methods.

6. Manage the selected supplier to ensure timely delivery of the required quality at the right price: As the suppliers are chosen and the contracts are made, the contact with the suppliers should be kept from the order time to the delivery of the materials. Accurate and on-time information flow between the suppliers and the buyer should be assured. So that, any unexpected demand or situation can be compensated by the supplier. By this way, materials are delivered at

- the right amount
- the right time
- the required quality
- and the price.

As seen above, supplier selection is not a one-step easy procedure. Since the decision of 'who to buy from' is strategic in nature and affects the companies' overall performance, it should depend on objective and measurable criteria. Also the evaluation and selection are not matter of instance. Including the time frame – past, present and future – brings in more complexity into the decision. Therefore supplier selection should not be a subjective matter. The reasoning behind must be logical and acceptable by everyone in the company. However, if these decisions are based on an objective procedure, no human error would be realized and therefore the risk of deterioration in the firm's performance in purchasing will be minimized (Mızrak, 2003).

2.5 Supplier Selection Criteria

One major aspect of the purchasing function is supplier selection, which includes the acquisition of required material, services and equipment for all types of business enterprises. The first step in any supplier rating procedure is to establish the criteria for supplier selection (Liu & Hai, 2005). The supplier selection literature has long held that product quality, delivery, price and service are the key attributes that are used to assess the performance capabilities of suppliers. The importance of the respective decision criteria has changed over time and while earlier studies reported that delivery and price were most important, later research found that quality had become most prominent (Bharadwaj, 2003).

It must be noted that several factors affect a supplier's performance. Stamm & Golhar (1993), Ellram (1990) and Roa & Kiser (1980) identified, respectively, 13, 18 and 60 criteria for supplier selection.

Another study which considered 23 criteria for supplier selection was carried out by Dickson (1996). As it can be seen from Table 2.4, quality and on-time deliveries are given the highest ranking. Also performance history, warranties and production facilities and capacity are considered to be quite important. Surprisingly, price factor has taken its place as the sixth in the list which shows that quality and delivery are much more important than lower prices in today's world.

Table 2.4 Dickson's supplier selection criteria (Weber et al., 1991)

Rank	Factor	Mean Rating
1	Quality	3,508
2	Delivery	3,417
3	Performance History	2,998
4	Warranties and Claim Policies	2,849
5	Production Facilities & Capacity	2,775
6	Price	2,758
7	Technical Capability	2,545
8	Financial Position	2,514
9	Procedural Compliance	2,488
10	Communication System	2,426
11	Position in Industry	2,412
12	Desire for Business	2,256
13	Management and Organization	2,216
14	Operating Costs	2,211
15	Repair Service	2,187
16	Attitude	2,12
17	Impression	2,054
18	Packaging Ability	2,009
19	Labor Relations Record	2,003
20	Geographical Location	1,872
21	Amount of Past Business	1,597
22	Training Aids	1,537
23	Reciprocal Arrangements	0,61

A study for the Turkish White Goods Industry about the supplier selection problem was done by Cengiz Kahraman, Ufuk Cebeci and Ziya Ulukan. Criteria and measures are developed to be applicable to all the suppliers being considered and to reflect the firm's needs and its supply and technology strategy. According to the authors, selection criteria typically fall into one of four categories: supplier criteria, product performance criteria, service performance criteria or cost criteria (Kahraman, Cebeci & Ulukan, 2003):

- A firm uses supplier criteria to evaluate whether the supplier fits its supply and technology strategy. These considerations are largely independent of the product or service sought. Supplier criteria are developed to measure important aspects of the supplier's business such as financial strength, management approach and capability, technical ability, support resources, and quality systems.

- A firm can use product performance criteria to examine important functional characteristics and measure the usability of the product being purchased. The exact criteria depend on the type of product being considered. A firm may need to examine conformance to specifications in areas such as handling, use in manufacturing, quality, functionality, reliability, maintainability, etc.

- A firm can use service performance criteria to evaluate the benefits provided by supplier services. When considering services, a firm needs to clearly define its expectations since there are few uniform, established service standards to draw upon. Because any purchase involves some degree of service, such as order processing, delivery, and support, a firm should always include service criteria in its evaluation. When assessing the fitness of services, a firm may need to examine the following areas which are customer support, customer satisfiers, follow-up and professionalism.

- Cost criteria recognize important elements of cost associated with the purchase. The most obvious costs associated with a product are "out of pocket" expenses, such as purchase price, transportation cost, and taxes. These are typically considered during selection. Operational expenses, such as transaction processing and cost of rejects, may also be included, although these require more effort to estimate. Although a firm can express any criteria in terms of estimated cost, in some cases, obtaining reliable estimates may be too involved for the level of analysis in selection. A firm should re-evaluate cost in more detail during qualification.

Figure 2.1 shows the “decision hierarchy” for this supplier selection problem. The evaluation criteria consist of three main categories: supplier criteria, product performance criteria and service performance criteria. In the third level, 11 sub-criteria are identified.

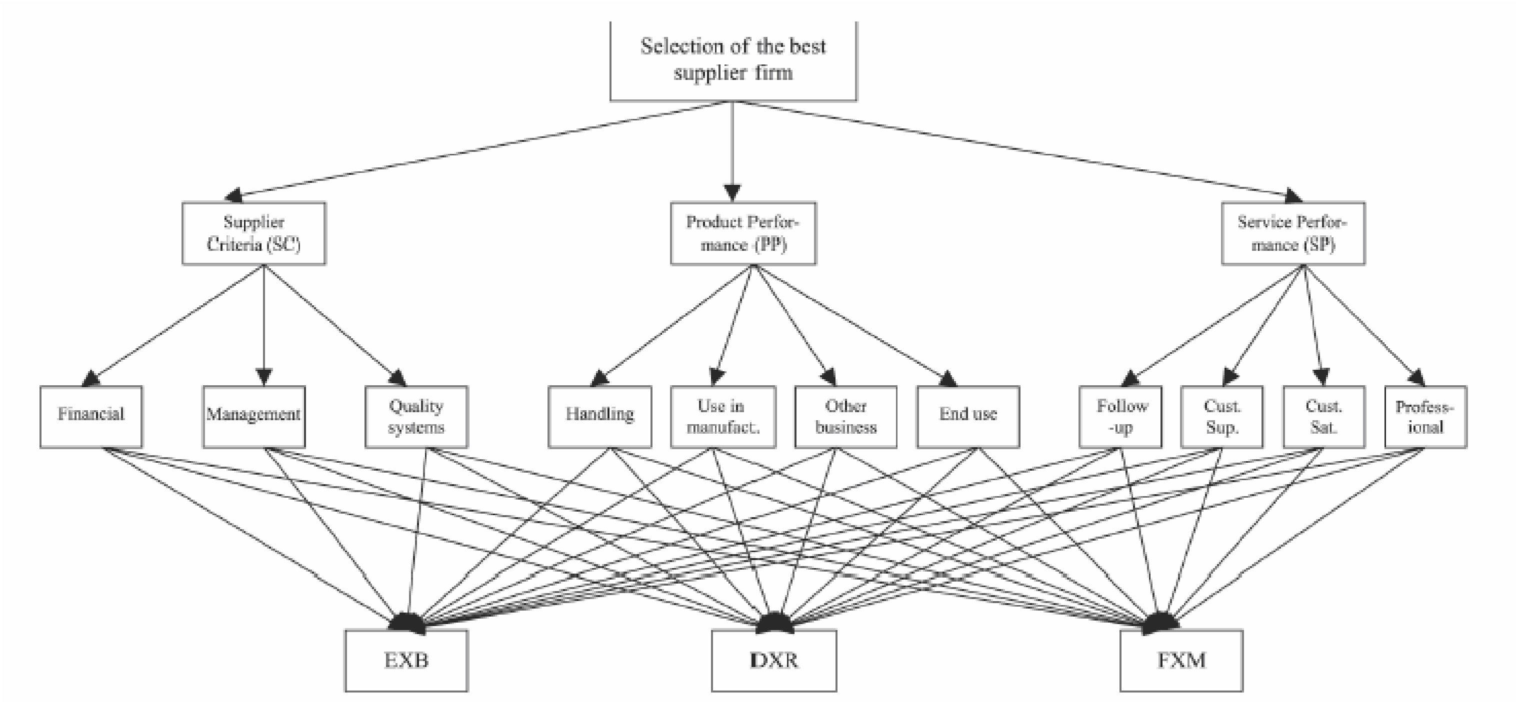

Figure 2.1 The hierarchy for the white goods supplier selection problem (Kahraman, Cebeci & Ulukan, 2003)

2.6 Supplier Selection Methods

This section presents the approaches used in the literature for supplier selection. Currently there are three major groups of methods used in supplier selection which are (a) categorical models, (b) mathematical programming models and (c) cost based approaches.

2.6.1 Categorical Models

In this approach, suppliers are graded on relevant supplier performance characteristics. In the simple method, the grades are simply added up and the supplier with the highest score is selected. The overall purpose of the approach is to represent the value of a supplier using a common base. All of the different attributes are rated on a particular scale, which enables comparing different suppliers with different characteristics. Scaling, scoring and ranking methods are the easiest and the most applied methods among the supplier selection methods. In scaling and scoring methods, variables or factors are rated numerically whereas in ranking methods, factors are ranked according to the preference of the decision makers (Altinoz, 2001).

To distinguish between attributes with different importance, a weight can be assigned to each of the factors. The suppliers' grades are multiplied by these weights and a weighted score is computed for each (Altinoz, 2001). A typical procedure for conduction of this type of method is explained below (Timmerman, 1987):

1. Identify all criteria relevant to vendor selection.
2. Arrange the identified elements into categories.
3. Assign weights.
4. Develop specific procedures for measuring elements of supplier performance.
5. Assign ratings to each supplier on each criteria based on the performance measures.
6. Calculate the weighted ratings and compare suppliers.

This type of approach is by far the most commonly used of all supplier selection methods. It is easy to understand and requires little in-depth analysis or preparation to construct (Altinoz, 2001).

One difficulty in weighting approaches is deciding the values of the weights that represent the significance of the characteristics. It is not easy to assign weights to a large number of characteristics consistently. There have been methods adapted to make this task easier and more objective. Analytic hierarchy process (AHP) is one of the techniques that have been applied to the supplier selection problem to help with the weighting issue. The technique uses pair-wise comparisons between these elements to assign weights. AHP provides a systematic approach for managers to quantify their subjective evaluations; its systematic approach both makes it easier to process information about vendors and stay consistent while working with the alternatives (Altinoz, 2001). Since fuzzy AHP was applied to the supplier selection problem in this study, AHP will be explained in detail in Chapter 4.

Interpretive structural modeling (ISM) is another technique that has been applied to the supplier selection process. Its main goal is to identify and summarize relationships among supplier characteristics and to form a structural model of the problem (Mandal & Desmukh, 1994).

The categorical method of ranking suppliers suffers from three main shortcomings:

1. The first shortcoming is that although structural methods such as AHP or ISM help stay consistent when assigning weights, a great deal of subjectivity remains embedded in the method (Altinoz, 2001). Timmerman (1987) states that the method is steeped in subjectivity; relevant supplier criteria are subjectively selected, they are subjectively categorized and weighted. Then suppliers are subjectively rated and the results may be subjectively interpreted. When the selection case is small and relatively easy, categorical models do very well in the ease of use criterion. When the cases become more complicated and large numbers of suppliers must be evaluated, this approach falls short.

2. The second shortcoming is that the scope of categorical models is limited. Current constraints at the time of the decision are not taken into account. The relative importance of supplier characteristics change according to the constraints placed on a company. Price may be the top priority today but when an emergency order comes in tomorrow, flexibility and responsiveness of a supplier may outrank price. This means that when weights are being assigned, the decision maker should be taking into account all of these constraints in his head. If the situation is complex and there are many characteristics, the task of remembering and relating all of these constraints and the rules becomes very difficult (Altinoz, 2001).

3. The third shortcoming is also a limitation in scope. The categorical method seeks to find the best supplier or alternative. The method does not consider situations where multiple suppliers may be used and these may offset each other's shortcomings to form a strong supplier base. The categorical method does not identify good fit combinations since it is geared towards ranking suppliers on their own (Altinoz, 2001).

2.6.2 Mathematical Programming Models

Mathematical programming is structuring a model in mathematical notation. The decision makers seek an optimal solution that satisfies a set of constraints (i.e. a capacity limitation or a budgetary limitation) (Schniederjans, 1999).

Supplier selection problems lend themselves well to mathematical programming techniques. The problems usually have several objectives such as minimizing cost or maximizing profit and quality simultaneously. Both the objectives and the rules can be modelled to an extent using math programming (Altinoz, 2001).

Linear or mixed-integer programming is used when there is a single objective that must be maximized or minimized. Goal programming can be used when there are multiple objectives (Altinoz, 2001). Since there are many goals to be achieved in the supplier selection problem, goal programming is designed to deal with these multiple objectives. These objectives are stated as constraints in the model and a combined objective function is created in order to reach the target values (Schniederjans, 1999).

Since mathematical programming is geared towards modelling the constraints in the problem, it is much easier than other approaches to work with a large number of constraints. The methodology also allows current conditions to be explicitly written into the model, although adding or relaxing constraints may not be a simple process. In addition, the models built are not limited to single supplier selection and can easily look for beneficial combinations (Altinoz, 2001).

Unfortunately, the fact that the methodology allows the rules to be modelled does not mean it is easy to model them. A significant problem with using math-programming models is that most of them are too complex for practical use by operating managers (Narasimhan, 1983).

The most significant limitation with using math-programming models is the fundamental assumptions that must be made to apply the method. These are deterministic models that require the figures such as demand or quality levels to be known for certain. They also assume linearity and although there are non-linear math programming techniques, they are rather complex and none have been applied to a supplier selection problem (Altinoz, 2001).

2.6.3 Cost Based Models

Since price has traditionally been a leading factor, selecting suppliers based on cost has been a common approach. A popular application of the cost approach has been calculating the total cost for each purchase. The total cost of working with each supplier is calculated and the cheapest one is picked (Altinoz, 2001). Ellram (1993) explains that a formal total cost approach explicitly recognizes cost factors in addition to price and argues that any total cost approach should include transportation costs, receiving costs, quality costs, purchasing administrative expenses and the price of the item. Ellram (1993) also notes that most firms do not have detailed cost data readily available and they do not have systems for monitoring and tracking total cost. In small cases, the cost based methods may do well in the ease of use criterion but for a thorough analysis, they require considerable work.

Conceptually, the cost approaches are similar to the categorical method. Where the categorical method sums a supplier's value by rating it on relevant characteristics and adding it all up, the cost method does the same by assigning dollar figures to relevant cost categories that the supplier will impact and adds up the costs. The difference is in what they look at. Cost approaches examine measurable cost drivers and thus attempt to avoid the subjectivity that the categorical methods include (Altinoz, 2001).

The limitation in scope that results from not considering any rules, requirements or strategies explicitly is present in the cost approach as well. Some situational constraints and rules may be reflected in the costs (for example, a short lead time constraint may show up in transportation costs) and this is a step forward from the categorical method, but the constraints and rules are still not explicitly considered. Rather the approach assumes that the cost figures will accurately reflect the current conditions. This puts the burden on those calculating the costs to recognize all relevant conditions and rules and figure out how to show their impact in the numbers (Altinoz, 2001).

Although these three categories can be used to classify most supplier selection methods, there are some methods that either do not fit any of these categories or fit more than one category. For example, it is difficult to classify simulation methods since they use costs and other information like lost sales and stock-outs to evaluate suppliers but the analysis is based on rules and logistics techniques (Altinoz, 2001).

CHAPTER THREE
LITERATURE SURVEY OF SUPPLIER SELECTION

3.1 Introduction

During recent years supply chain management and the supplier selection process have received considerable attention in the business management literature. Supplier selection is a multi-criteria problem and there are not a lot of efficient techniques or algorithms that address this problem. The conventional methods that are being used for supplier evaluation like total-cost of ownership models, linear weighted models etc., are very subjective in nature. They are subjective because the buyer assigns values to various factors that are involved in selection of suppliers and the values vary from one buyer to another for the same supplier. So the need for methods/algorithms that are more objective in nature, that involves assigning common set of values to the selection criteria, is to be used.

This section includes a survey of current literature focusing on the problem of supplier selection.

3.2 Categorical Models

Verma & Pullman (1998) examined the difference between managers' rating of the perceived importance of different supplier attributes and their actual choice of suppliers in an experimental setting. An empirical study is designed to evaluate the supplier selection process. Two different data collection and analyses procedures are used. In the first step, a survey instrument containing Likert-type scale questions is used to determine importance of various supplier attributes which are unit cost of components/raw materials, quality of components/raw materials, delivery lead-time, on-time delivery performance and flexibility in changing the order. The respondents are asked to evaluate the relative importance of five broad supplier attributes from 1 (least important) to 5 (most important). In the second step, discrete choice analysis is used for quantifying the relative weights of attributes when actual supplier selection choice is made. Discrete choice analysis is a systematic approach for identifying the relative weights of attributes among which the decision maker tradeoffs when choosing an alternative from a possible set of alternatives.

In this study, the results show that managers perceive “Quality” to be most important supplier attribute, followed by “On Time Delivery” and “Unit Cost of Parts”. It is interesting to note that the first delivery performance measure “On Time Delivery” is rated to be more important than “Unit Cost” but the second measure of delivery performance “Delivery Lead Time” is rated to be less important than “Unit Cost”. Flexibility in changing the order is perceived to be the least important among the five attributes. However the same sample of managers assign more weight to Cost and On Time Delivery attributes than Quality when actually choosing a supplier.

Traditionally, companies consider factors like quality, flexibility, etc. when evaluating supplier performance. However, environmental pressure is increasing and in the long term, environmental issues will become an important factor for a company to consider. Integrating environmental management techniques along the supply chain is an appropriate method of enhancing the environmental performance of an industry.

Humphreys, Wong & Chan (2003) presented a framework of environmental criteria which a company can consider during their supplier selection process. The criteria identified are put into two main groups-quantitative environmental criteria and qualitative environmental criteria. A decision support system which integrates these environmental criteria into the supplier selection process is built and provides guidelines for the purchasing managers to select suppliers from an environmental viewpoint. Finally, the proposed decision support system is computerized in order to provide a fast and convenient tool for the users to assess their suppliers’ environmental performance.

In the long term, the work presented in this paper may help to enhance the competitive position of companies in the supply chain by integrating environmental factors into the supplier selection process.

AHP is one of the extensively used multi-criteria decision-making methods. One of the main advantages of this method is the relative ease with which it handles multiple criteria. In addition to this, AHP is easier to understand and it can effectively handle both qualitative and quantitative data. Therefore it has been extensively applied to supplier selection problems.

Houshyar & Lyth (1992) presented a systematic procedure in making supplier selection decisions. They classify the factors as critical, objective and subjective. The critical factors are the ones, which take a supplier into the choice list or throw out totally. The first step in the procedure is to define all three types of factors. Then the suppliers, which pass the critical factors, are listed. The second step is to evaluate the suppliers in the list in terms of objective and subjective factors using the matrix approach and AHP, respectively. The two different measures are brought together with the desired weights. The last step is to list the suppliers from the highest to the lowest according to their overall scores. Whether to employ single or multiple sourcing is left up to the decision-maker.

Muralidharan, Anantharaman & Deshmukh (2001) proposed a methodology which makes use of estimation of the rating by a group on an individual basis following the principle of anonymity. A statistical analysis is carried out to determine the confidence intervals for the estimates of the composite rating of the vendors. The procedure presented here helps in identifying those members whose opinions may significantly deviate from that of the group.

In the first step, the active participants to be involved in decision making are identified. In the second step, the significant factors/attributes involved in vendor rating are identified. Brainstorming sessions or nominal group technique involving various individuals drawn from different functions could be used for this process. Those factors/criteria that will enable the organization to select the best vendor must be identified by the participants. In the third step, the vendors who are to be rated are identified. This information could be obtained from the vendor database. The variety of information required by the buyer, such as specification details, supply sources, previous prices, items description, vendor performance, etc., can be stored through a database. In the fourth step, AHP model is used to obtain the ratings of the vendor. In the fifth step, confidence interval is established for the rating done by the individuals. In the last step, the vendor's performance is identified with respect to the established confidence limits.

In this study, the above mentioned methodology is applied to a vendor rating problem wherein ten individuals from different functions within the organization are asked to rate the vendors, based on the three significant attributes; namely, quality, delivery and technical facilities. The above procedure can be extended further for continuous evaluation of vendors. According to Muralidharan, Anantharaman and Deshmukh, the vendor's performance must not only be analyzed and rated periodically, but should also be used to motivate the vendors to improve and maintain quality performance. In that case, it would be preferable to have a continuous evaluation of vendors at periodic intervals.

Handfield, Walton, Sroufe & Melnyk (2002) illustrated the use of the Analytical Hierarchy Process (AHP) as a decision support model to help managers understand the trade-offs between environmental dimensions. It is demonstrated how AHP can be used to evaluate the relative importance of various environmental traits and to assess the relative performance of several suppliers along these traits.

Three case studies are carried out in an automotive, paper and apparel manufacturer. The purpose of the pilot tests is to assess how useful the AHP model developed in the Delphi group is in an actual supplier evaluation decision. Finally, it is examined how

AHP can be incorporated into a comprehensive information system supporting Environmentally Conscious Purchasing (ECP).

There are several extensions to the AHP model that may be possible in the future. The first is a system of equations that can help translate supplier environmental performance into cost metrics. The obvious next step is to assimilate supplier environmental performance information into a supplier database that could be used by all purchasing managers and engineers in all divisions of the company.

Liu & Hai (2005) illustrated a new approach based on the use of Saaty's analytic hierarchy process method that was developed to assist in multi-criteria decision-making problems. In order to decide the total ranking of the suppliers, the weighted sum of the selection number of rank vote is compared after determining the weights in a selected rank. Thus the method is called voting analytic hierarchy process.

The six-step procedure for selecting ten suppliers is proposed with a numerical example for the Umbrella Scheme of Malaysia's furniture industry. The problem is to select one of ten candidate suppliers. In the first step, the main criteria and sub-criteria are determined by group decision making. The decision making group consists of sixty respondents who are all managers and supervisors of a company. In the second step, the problem is structured into a hierarchy of four levels. In the third step, the order of criteria and sub-criteria are prioritized. Different orders of criteria and sub-criteria will be selected for the candidates by the managers. The weight of each ranking is determined automatically by the total votes each candidate obtains. In the fourth step, the weights of the criteria and sub-criteria are determined. In the fifth step, the managers are asked to assess the performance of all suppliers on the thirteen factors identified as important for supplier scores. It is agreed that all performance scores are based on an 11-point grade scale. Therefore each supplier can be awarded a 'score' from 0 to 10 on each sub-criterion. In the last step, the total scores of the suppliers are determined. The supplier with the highest supplier rating value is regarded as the best performing supplier and the rest are ranked accordingly.

3.3 Mathematical Programming Models

Mathematical programming is structuring a model in mathematical notation. The decision makers seek an optimal solution that satisfies a set of constraints (i.e. a capacity limitation or a budgetary limitation). In literature, supplier selection problems lend themselves well to mathematical programming techniques. The problems usually have several objectives such as minimizing cost or maximizing profit and quality simultaneously. Both the objectives and rules can be modelled to an extent using math programming.

Weber & Current (1993) proposed a multi-objective approach to supplier selection. The proposed model aims at minimizing the price, maximizing the quality and on time delivery. A linear combination of these objectives becomes the objective function. Mixed integer problem is developed and solved. Two sets of constraints are taken into account: (1) systems' constraints, which are defined as the constraints which are not directly under the control of the purchasing managers such as supplier capacities, demand satisfaction, minimum order quantities established by the suppliers and the total purchasing budget; and (2) policy constraints, including maximum and/or minimum order quantities purchased from a particular supplier, and the maximum and/or minimum number of suppliers to be employed.

Ghodsypour & O’Brien (1998) proposed an integration of an analytical hierarchy process and linear programming to consider both tangible and intangible factors in choosing the best suppliers and placing the optimum order quantities among them such that the total value of purchasing (TVP) becomes maximum. This model can be applied to supplier selection with and without capacity constraints.

This algorithm is applied to a just in time (JIT) manufacturer to choose their best suppliers and assign their optimum quantities to maximise the TVP. In order to solve this problem, two types of calculations are carried out: AHP and linear programming optimisation. In the first step, AHP is used to calculate a rating of suppliers based on three main criteria which are cost, quality and service and six sub-attributes. In the second step, these ratings are applied as coefficients of an objective function in linear programming and the order quantities are allocated between the suppliers. The objective is to maximise the total value of purchasing and the constraints are supplier capacity, buyer's demand and quality. At the end, sensitivity analysis is applied to identify the impact of changes in the priority of criteria on the suppliers' performance and order quantities.

Çebi & Bayraktar (2003) also integrated AHP with a mathematical programming model. The supplier selection problem is structured as an integrated lexicographic goal programming (LGP) and analytic hierarchy process (AHP) model including both quantitative and qualitative conflicting factors. The application process is accomplished in a food company established in Istanbul. Eight raw materials and three suppliers for each raw material, and thus thirteen suppliers in total are taken into consideration in the application process.

Quality, delivery and cost factors are selected as the objective functions in the integrated LGP and AHP model. In addition, a utility function, coefficients representing the supplier scores, is added to the model as the fourth objective function. In order to obtain supplier scores, an AHP model including several important factors that also effects the supplier decisions except quality, delivery, and cost is developed. The AHP model encompasses four criteria which are logistics, technologic, business and relationship and fourteen sub-criteria, which may influence supplier evaluation. The overall objective is supplier evaluation. The reason for including the supplier score objective function to the integrated model is the enhance importance of supplier management. Therefore, maximizing the supplier's score is the other challenging factor that should be taken into account during the decision processes.

After the LGP model is solved, the best compromise purchasing quantity of each raw material from the suppliers are achieved within the conflicting objectives of the firm that are quality maximization, late order percentage minimization, purchasing cost minimization and utilization maximization.

In the future work, some of the criteria and sub-criteria may be eliminated or some other criteria may be included to the AHP model. Additionally, it has to be pointed out that the proposed integrated model can easily be adapted to any kind of applications and can easily be expanded as well.

Wang, Huang & Dismukes (2004) related product characteristics to supply chain strategy and adopted supply chain operations reference (SCOR) model level I performance metrics as the decision criteria. An integrated analytic hierarchy process (AHP) and preemptive goal programming (PGP) based multi-criteria decision-making methodology is then developed to take into account both qualitative and quantitative factors in supplier selection.

AHP, which uses pair-wise comparison, is applied to make the trade-off between tangible and intangible factors and calculate a rating of suppliers. Four main criteria, which are delivery reliability, flexibility and responsiveness, cost and assets are considered. In the second step, the ratings of the suppliers are applied as coefficients of an objective function in PGP and order quantities are allocated among the favorable suppliers such that the manufacturing organization can choose the most favorable and least number of suppliers to achieve maximum efficiency.

3.4 Fuzzy AHP

There are many fuzzy AHP methods proposed by various authors. These methods are systematic approaches to the alternative selection and justification problem by using the concepts of fuzzy set theory and hierarchical structure analysis.

Altinoz (2001) examined supplier selection in general and specifically in the Textile sector. In this study, the concept of business rules in defining selection situations is emphasized. The research findings are formalized in a broadly structured model that can then be applied to specific supplier selection situations. A structured methodology for analyzing selection situations is also developed. In order to test the methodology, a software program is developed and applied to an example.

Feng, Chen & Jiang (2005) proposed a comprehensive evaluation method based on fuzzy decision theory and characteristics of supply chain management for optimal combination and selection among candidate vendors and outsourced parts. In the first step, some useless information is filtered by the judgment of process and production capacities. Useless information is filtered for vendor selection by examining vendors' capabilities. Capability judgment is divided into two ways: process judgment and capacity judgment. The vendors who do not possess the capability enough to complete the task are eliminated in these two steps of judgment. In the second step, a hierarchical fuzzy model for vendor selection is developed. Four main criteria which are cost, quality, potential and time and ten subcriteria are used in the selection process. Finally, the interaction among different order combinations is considered and the corresponding vendors for these outsourced parts are determined.

To illustrate the analysis process of the proposed model, an example dealing with an important component used in a set of large-size air-separation equipment is described. The component mainly consists of eight parts and four of them are found to be worthy of outsourcing. After judging vendors' process and capacity according to the information data, four candidate vendors are chosen for possible strategic cooperation. At the end, the corresponding vendors for four components are determined.

It should be pointed out that the proposed approach is suitable for the case with limited interdependent parts. If the number of interdependent parts and vendors grows very large, there may be some difficulties in applying this approach. However it can serve as a guide for further research.

Haq & Kannan (2006) proposed a structured model for evaluating vendor selection using the analytical hierarchy process and fuzzy AHP. The study aims to demonstrate how the model can help in solving such decisions in practice. The effectiveness of the AHP model is illustrated using a company in the southern part of India and the results validated using fuzzy AHP. The company plans to build a supply chain for its tire-manufacturing product.

In the study, a conceptual approach for structuring the selection of the best vendor using the AHP is introduced and the AHP decision is compared with fuzzy AHP. In the first step, the hierarchy with four levels is structured. The attributes and sub-attributes involved in the supplier selection are chosen by conducting a survey on the decision making team which includes experts from the industry side. Based on the survey, seven major factors which are quality, delivery, production capability, service, engineering/technical capability, business structure and price and thirty-two sub-factors are determined. The overall objective is “to select the best vendor for the manufacturing plant”. In the second step, the priorities of the elements in each level are determined based on AHP and fuzzy AHP. In the last step, the priority weights for major factors, sub-factors and alternatives are combined to determine the priority weights of the best vendor.

In this study, the finding using the fuzzy AHP approach is found to be consistent with the determined vendor selection. However, the weights of three vendors are found to be quite close with each other, from both methods. Therefore sensitivity analysis should be carried out to determine the robustness of such decisions with respect to variations in the pair-wise rankings.

The most common method used in the solution of fuzzy AHP applications is the extent analysis method proposed by Chang (1992). In the below mentioned studies, the extent analysis method is used to obtain the priority weight vectors of the factors in the hierarchy.

Kahraman, Cebeci & Ulukan (2003) used fuzzy analytic hierarchy process (AHP) to select the best supplier firm providing the most satisfaction for the criteria determined in the white good sector. The purchasing managers of a white good manufacturer established in Turkey are interviewed and the most important criteria taken into account by the managers while they are selecting their supplier firms are determined by a questionnaire. The main attributes determined by the questionnaire are supplier criteria, product performance criteria and service performance criteria. After the main and sub-attributes are determined, the hierarchy is structured. Then the preference weights among the main-attributes, sub-attributes and alternatives are obtained by questionnaires. Firstly, the main attributes are compared with respect to the main goal which is “to select the supplier firm among the alternatives” by the decision making group. Then the sub-attributes are compared with respect to main-attributes by the decision making group. Finally, the supplier firms are compared with respect to the sub-attributes.

Linguistic variables are used in the questionnaires aiming at determining the degrees of preference among the main attributes, sub-attributes and alternatives. The linguistic variables are converted into triangular fuzzy numbers (TFN) and the pair-wise comparison matrices with TFN’s are formed. Then the extent analysis method is used to obtain the priority weight vectors for main attributes, sub-attributes and alternatives. At the end, the priority weights for main attributes, sub-attributes and alternatives are combined to determine the priority weights for the best supplier firm. Further research may be the application of multi-attribute evaluation methods such as ELECTRE, DEA (data envelopment analysis) and TOPSIS to the supplier selection problem and the comparison of the results.

Kahraman, Cebeci & Ruan (2004) used fuzzy analytic hierarchy process to select the best catering firm providing the most customer satisfaction. First a questionnaire is applied to the customers of the catering firms. The customers are asked what the attributes are, while they are selecting their catering firms and what preference they have while they are making pair-wise comparisons among these attributes. Regarding the data derived from the questionnaire, the main and sub-attributes are determined and the decision hierarchy is structured. The decision making group consists of the customers of the catering firms and the five experts from Turkish Chamber of Food Engineers (TCFE). In the second step, the main attributes are compared with respect to the main goal which is "to select the best catering firm among the alternatives" by the decision making group. In the third step, the sub-attributes are compared with respect to main-attributes by the decision making group. In the fourth step, the catering firms are compared with respect to the sub-attributes by the experts from Turkish Chamber of Food Engineers. The meanings of the main and sub-attributes are explained in detail to both the customers of the catering firms and the five experts of TCFE, so that everyone would understand the same thing when they read the questionnaire.

Linguistic variables are used in the questionnaires aiming at determining the degrees of preference among the main attributes, sub-attributes and alternatives. The linguistic variables are converted into triangular fuzzy numbers and the pair-wise comparison matrices with TFN's are formed. Then the extent analysis method is used to obtain the priority weight vectors for main attributes, sub-attributes and alternatives. At the end, the priority weights for attributes, sub-attributes and alternatives are combined to determine the priority weights for the best catering firm. Further research may be the application of multi-attribute evaluation methods such as ELECTRE, DEA (data envelopment analysis) and TOPSIS to the catering selection problem and the comparison of the results.

Chan & Kumar (2005) discussed a fuzzy extended AHP (FEAHP) approach using triangular fuzzy numbers to represent decision makers' comparison judgments and fuzzy synthetic extent analysis method to decide the final priority of different decision criteria. The main objective is the selection of best global supplier for a manufacturing firm. A decision-making group is formed which consists of the experts from each strategic decision area. Detailed discussion on every criterion, attribute and alternative supplier is conducted and five criteria are identified. The main criteria which are considered in the selection of the global supplier are overall cost of the product, quality of the product, service performance of supplier, supplier's profile and risk factor. After further discussion, nineteen attributes with three potential suppliers are determined and then the hierarchy with four levels is structured.

After the construction of the hierarchy the different priority weights of each criteria, attributes and alternatives are calculated using the FEAHP approach. The comparison of the importance of one criterion, attribute or alternative over another can be done with the help of a questionnaire. The preference of one measure over another is decided by the available research, the current business scenario and by the experience of the experts. First the fuzzy evaluation matrix of the criteria is constructed by the pair-wise comparison of the different criterion relevant to the overall objective using TFN's. Then the consistency of the pair-wise judgment of the comparison matrix is checked using the calculation method of consistency index and consistency ratio discussed in Kwong & Bai (2003). Then by using the extent analysis method, the priority weight of the criteria is determined. Later the priority weights of the different attributes and alternatives are determined by following the same procedure.

As a result, based on the different weights of criteria and attributes the final priority weights of the alternative global suppliers are decided. The highest score of the supplier gives the idea about the best global supplier of the manufacturing company for supply of the parts. This study can be extended to incorporate the supplier's capacity constraints and the buyers' aggregate quality and service limitations in the supplier selection process.

Güner (2005) investigated the supplier evaluation and selection problem of a marble-travertine company in Denizli and proposed a solution method. Since there are more than one conflicting criterion in evaluation and selection process, AHP is used in the solution process. In order to deal with uncertainties of the decision problem and eliminate the disadvantages of AHP, linguistic variables and triangular fuzzy numbers are used in pair-wise comparisons.

In the first section of the study, a general supplier selection model is developed for "classical travertine" which is the main product of the company. The criteria and alternatives used in the evaluation are determined via interviews and the problem is solved by using both classical and fuzzy AHP methods. The results obtained are compared and the same supplier is found to be the best alternative in both methods. In the second section, a specific supplier selection problem for a customer order is solved by using fuzzy AHP method with linguistic variables. The result is the same as in the first evaluation.

CHAPTER FOUR
ANALYTICAL HIERARCHY PROCESS
AND
FUZZY ANALYTICAL HIERARCHY PROCESS

4.1 Analytical Hierarchy Process

4.1.1 Definition

The Analytical Hierarchy Process (AHP) is a method developed by Thomas L. Saaty to support multi-criteria decisions where (Saaty, 1980a):

1. Analytic indicates that the problem is broken down into its constitutive elements.

2. Hierarchy indicates that a hierarchy of the constitutive elements is listed in relation to the main goal.

3. Process indicates that data and judgments are processed to reach the final result.

The Analytical Hierarchy Process (AHP) is a systematic procedure for representing the elements of any problem in the form of a hierarchy (Saaty & Kearns, 1985). Generally, the hierarchy has at least three levels: the goal, the criteria, and the alternatives. AHP is designed to solve complex decision problems involving both qualitative and also quantitative criteria.

This method aims at quantifying relative priorities for a given set of alternatives on a ratio scale, based on the judgment of the decision-maker, and stresses the importance of the intuitive judgments of a decision-maker as well as the consistency of the comparison of alternatives in the decision-making process (Saaty, 1980a). Since a decision-maker bases judgments on knowledge and experience, then makes decisions accordingly, the AHP approach agrees well with the behavior of a decision-maker (Al-Harbi, 2001).

AHP is one of the most popular multiple-criteria decision-making tools for formulating and analyzing decisions. The technique is employed for ranking a set of alternatives or for the selection of the best in a set of alternatives. The ranking/selection is done with respect to an overall goal, which is broken down into a set of criteria (Ramanathan, 2006).

Basically, AHP has three underlying concepts: Structuring the complex decision problem as a hierarchy of goal, criteria, and alternatives, pair-wise comparison of elements at each level of the hierarchy with respect to each criterion on the preceding level, and finally vertically synthesizing the judgments over the different levels of the hierarchy (Saaty, 1980a; Tiwari & Banerjee, 2001). In other words, AHP attempts to estimate the impact of each one of the alternatives on the overall objective of the hierarchy (Kablan, 2004).

4.1.2 Application Areas of AHP

AHP is a theory of measurement for dealing with quantifiable and intangible criteria that has been applied to numerous areas, such as decision theory and conflict resolution (Vargas, 1990).

AHP has been applied to numerous decision problems such as energy policy, project selection, measuring business performance and evaluation of advanced manufacturing technology (Kablan, 2004).

Elkarmi & Mustafa (1993) used AHP to select best policies for increasing the utilization of solar energy technologies in Jordan. Mustafa & Ryan (1990) used AHP as a decision supports system for bid evaluation. Eddi & Hang (2001) discussed the applications of AHP for measuring business performance. Tiwari & Banerjee (2001) proposed the use of AHP as a decision support system for the selection of a casting process. Kamal (2001) used AHP to select the most suitable contractor in the prequalification process of a project. Chandra & Schall (1988) used AHP for the economic evaluation of flexible manufacturing system using the Leontif input-output model.

4.1.3 AHP Axioms

AHP is founded on the following set of axioms for deriving a scale from fundamental measurements and for hierarchical composition (Saaty, 1986):

1. Axiom 1: Reciprocal

If element A is ***x*** times important than element B, than element B is 1/***x*** times important than element A.

2. Axiom 2: Homogeneity

Only comparable elements are compared. Homogeneity is essential for comparing similar things, as errors in judgment become large when comparing widely disparate elements.

3. Axiom 3: Independence

The relative importance of elements at any level does not depend on what elements are included at a lower level.

4. Axiom 4: Expectation

The hierarchy must be complete and include all the criteria and alternatives in the subject being studied. No criteria and alternatives are left out and no excess criteria and alternatives are included.

4.1.4 The Procedure for the Application of the AHP

The application of AHP to a decision problem involves four steps (Zahedi, 1986). They can be summarized as structuring of the decision problem into a hierarchical model, making pair-wise comparisons and obtaining the judgment matrix, determining the local weights and consistency of comparisons and aggregation of weights across various levels to obtain the final weights of alternatives.

4.1.4.1 Structuring of the Decision Problem into a Hierarchical Model

It includes decomposition of the decision problem into elements according to their common characteristics and the formation of a hierarchical model having different levels (Ramanathan, 2006). When constructing hierarchies one must include enough relevant detail to (Saaty, 1990):

- Represent the problem as thoroughly as possible, but not so thoroughly as to lose sensitivity to change in the elements.

- Consider the environment surrounding the problem.

- Identify the issues or attributes that contribute to the solution.

- Identify the participants associated with the problem.

The following steps can be considered to form the hierarchy (Chan & Kumar, 2005):

- Define the supplier selection problem.
- Identify the overall objective. What is the firm trying to accomplish?
- Identify the criteria and attributes that must be satisfied to fulfill the overall objectives.
- Identify decision alternatives or outcomes.
- Structure the hierarchy placing the objective at first level, criteria at second level, attributes at third level and decision alternatives at fourth level.

A simple AHP model can be seen in Figure 4.1 that has three levels (goal, criteria and alternatives). Four criteria are represented as C_1, C_2, C_3 and C_4, three alternatives are represented as A_1, A_2 and A_3. Though the simple model with three levels shown in Figure 4.1 is the most common AHP model, more complex models containing more than three levels are also used in the literature. For example, criteria can be divided further into sub-criteria and these sub-criteria can be divided into sub-sub-criteria. Finally alternatives take place in the last level of the hierarchy (Ramanathan, 2006). The hierarchical design given in Figure 4.1 can help the decision maker (DM) understand the problem better as to the importance of each level of the decision problem (Setiawan, 2002).

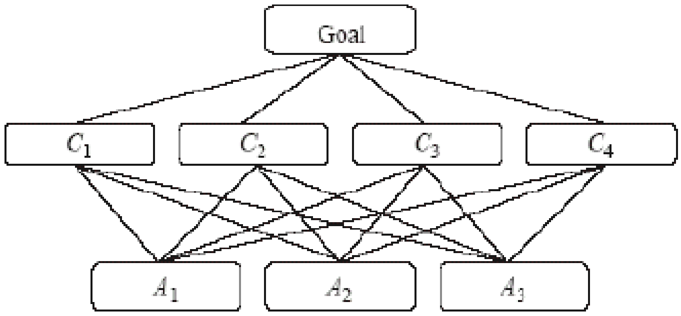

Figure 4.1 A simple AHP model (Ramanathan, 2006)

4.1.4.2 Making Pairwise Comparisons and Obtaining the Judgment Matrix

In this step, the elements of a particular level are compared with respect to a specific element in the immediate upper level. The opinion of a decision-maker (DM) is elicited for comparing the elements (Ramanathan, 2006). A verbal or a corresponding 9-point numerical scale can be used for the comparisons which can be based on objective, quantitative data or subjective, qualitative judgments. Saaty has proposed a numerical scale to represent the degree of "importance" of one alternative (or criterion) compared with another. The scale consists of the discrete numbers in the set of {1/9, 1/8, 1/7, 1/6, 1/5, 1/4, 1/3, 1/2, 1, 2, 3, 4, 5, 6, 7, 8, 9}. The explanation of these values is given in Table 4.1. Usually, an element receiving higher rating is viewed as superior (or more attractive) compared to another one that receives a lower rating (Ramanathan, 2006).

Table 4.1 Saaty's scale of preferences in the pair-wise comparison process (Saaty, 1980a)

Numerical Value	**Linguistic Definition**	**Explanation**
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favor one activity over another
5	Strong Importance	Experience and judgment strongly favor one activity over another
7	Very Strong or Demonstrated Importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate Values	To reflect the compromise between two adjacent judgments

The comparisons are used to form a matrix of pairwise comparisons called the judgment matrix A. Each entry a_{ij} of the judgment matrix are governed by the three rules: $a_{ij} > 0$; $a_{ij} = 1/a_{ji}$ and $a_{ii} = 1$ for all *i*. If the transitivity property holds, i.e., $a_{ij} = a_{ik} \otimes a_{kj}$, for all the entries of the matrix, then the matrix is said to be consistent. If the property does not hold for all the entries, the level of inconsistency can be captured by a measure called consistency ratio (Saaty, 1980b).

4.1.4.3 Determining the Local Weights and Consistency of Comparisons

In this step, local weights of the elements are calculated from the judgment matrices using the eigenvector method (EVM). The normalized eigenvector corresponding to the principal eigenvalue of the judgment matrix provides the weights of the corresponding elements. When EVM is used, consistency ratio (CR) can be computed. For a consistent matrix CR = 0. A value of CR less than 0.1 is considered acceptable because human judgments need not be always consistent, and there may be inconsistencies introduced because of the nature of scale used. If CR for a matrix is more than 0.1, judgments should be elicited once again from the DM till he gives more consistent judgments (Ramanathan, 2006). The calculation of the consistency ratio is introduced in detail in the AHP methodology section.

4.1.4.4 Aggregation of Weights across Various Levels to Obtain the Final Weights of Alternatives

Once the local weights of elements of different levels are obtained as outlined in the previous step, they are aggregated to obtain final weights of the decision alternatives (elements at the lowest level). For example, the final weight of alternative A_1 is computed using the following hierarchical (arithmetic) aggregation rule in traditional AHP (Ramanathan, 2006):

$$\text{Final weight of } A_1 = \sum_j \left[\begin{pmatrix} \text{Local weight of } A_1 \text{ with} \\ \text{respect to criterion } C_j \end{pmatrix} \times \begin{pmatrix} \text{Local weight of} \\ \text{criterion } C_j \end{pmatrix} \right] \quad (1)$$

By definition, the weights of alternatives and importance of criteria are normalized so that they sum to unity. The final weights represent the rating of the alternatives in achieving the goal of the problem (Ramanathan, 2006).

4.1.5 AHP Methodology

AHP is based on a firm theoretical foundation. The basic theory of AHP may be simplified as in the following (Golden et al., 1989; Saaty, 1980a; Saaty, 1990): There are n different and independent alternatives $(A_1, A_2, ..., A_n)$ and they have the weights $(W_1, W_2, ..., W_n)$, respectively. The decision maker (DM) does not know in advance the values of W_i, $i = 1, 2, ..., n$, but DM is capable of making pair-wise comparison between the different alternatives. Also, it is assumed that the quantified judgments provided by the DM on pairs of alternatives (A_i, A_j) are represented in a $n \times n$ matrix as in the following (Kablan, 2004):

$$A = \begin{array}{c} \\ A_1 \\ A_2 \\ . \\ . \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} A_1 & A_2 & \cdots & A_n \end{array} \\ \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \end{array} \qquad (2)$$

a_{ij} $(a_{ij} > 0)$ reflects the value of how "important" alternative i is when it is compared to alternative j. If for example the DM compares alternatives A_1 with alternative A_2, he provides a numerical value judgment a_{12} which should represent the importance intensity of alternative A_1 over alternative A_2. The a_{12} value is supposed to be an approximation of the relative importance of A_1 to A_2, i.e., $a_{12} \approx (W_1 / W_2)$. This can be generalized and the following can be concluded:

1. $a_{ij} \approx (W_i / W_j)$, $i, j = 1,\ 2, \ldots, n.$

2. $a_{ii} = 1,\ i = 1,\ 2, \ldots, n.$

3. If $a_{ij} = \alpha,\ \alpha \neq 0,$ then $a_{ji} = 1/\alpha,\ i = 1,\ 2, \ldots, n.$

4. If A_i is more important than A_j, then $a_{ij} \cong (W_i / W_j) > 1.$

Obviously, it can be assumed that the following statements are true: $a_{ij} = 1/a_{ji}$ for all $i, j = 1,\ 2, \ldots, n$ (third item in the above list) and the diagonal entries are equal to 1. That is, $a_{ii} = 1,$ for all $i = 1,\ 2, \ldots, n$ (second item in the above list).

This implies that matrix A should be a positive and reciprocal matrix with 1's in the main diagonal and hence the DM needs only to provide value judgments in the upper triangle of the matrix. The values assigned to a_{ij} according to Saaty scale are usually in the interval of 1-9 or their reciprocals. Table 4.1 presents Saaty's scale of preferences in the pair-wise comparison process. It can be shown that the number of judgments (L) needed in the upper triangle of the matrix is:

$$L = n(n-1)/2 \tag{3}$$

where n is the size of the matrix A (the number of alternatives (or criteria) to be compared).

The next step is to recover the numerical weights $(W_1,\ W_2,...,W_n)$ of the alternatives using the numerical judgments a_{ij} in the matrix A:

$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} = \begin{pmatrix} W_1/W_1 & W_1/W_2 & \cdots & W_1/W_n \\ W_2/W_1 & W_2/W_2 & \cdots & W_2/W_n \\ . & . & \cdots & . \\ . & . & \cdots & . \\ W_n/W_1 & W_n/W_2 & \cdots & W_n/W_n \end{pmatrix} \tag{4}$$

The matrices given in (4) are multiplied on the right with the weights vector $W = (W_1,\ W_2,...,W_n),$ where W is a column vector. The result of the multiplication of the matrix of pair-wise ratios with W is nW ; hence it follows:

$$AW = nW \tag{5}$$

This is a system of homogenous linear equations. It has a non-trivial solution if and only if the determinant of $A - nI$ vanishes, that is, n is an eigenvalue of A . I is a $n \times n$

identity matrix. Saaty's method computes W as the principal right eigenvector of the matrix A, that is,

$$AW = \lambda_{\max} W \tag{6}$$

where $\lambda_{\max}$ is the principal eigenvalue of the matrix A. If matrix A is a positive reciprocal one, then $\lambda_{\max} \geq n,$ (Saaty, 1980a).

The judgments of the DM are perfectly consistent as long as:

$$a_{ij} a_{jk} = a_{ik},\ i, j, k = 1,\ 2, ..., n, \tag{7}$$

which is equivalent to

$$\left(W_i / W_j\right)\left(W_j / W_k\right) = \left(W_i / W_k\right) \tag{8}$$

a_{ik} is the comparison of alternative i with alternative k, more appropriately, the ratio of the relative weights of alternative i to alternative k in terms of a single criterion. For example, if any criterion A compared to criterion B has a numerical rating of 3 and if criterion B compared to criterion C has a numerical rating of 2, perfect consistency of criterion A compared to criterion C would have a numerical rating of 3 * 2 = 6. If A to C numerical rating assigned by the DM was 4 or 5, some inconsistency would exist among the pair-wise comparison.

The eigenvector method yields a natural measure of consistency. Saaty defined the consistency index (CI) as:

$$CI = (\lambda_{max} - n)/(n-1). \quad (9)$$

For each size of matrix n; random matrices were generated and their mean CI value, called the random index (RI), was computed and tabulated as shown in Table 4.2. Accordingly, Saaty defined the consistency ratio as:

$$CR = CI / RI. \quad (10)$$

Table 4.2 Average random index for corresponding matrix size (Saaty, 1980a)

Matrix size (n)	1	2	3	4	5	6	7	8	9	10
Random index (RI)	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The consistency ratio (CR) is a measure of how a given matrix compares to a purely random matrix in terms of their consistency indices. A value of the consistency ratio $CR \leq 10\%$ is considered acceptable. Larger values of CR require the DM to revise his judgments.

Saaty developed the following steps for the application of the AHP (Saaty, 1980a):

1. State the overall objective of the problem and identify the criteria that influence the overall objective.

2. Structure the problem as a hierarchy of goal, criteria, sub-criteria, and alternatives.

3. Start by the second level of the hierarchy:

   - Do pair-wise comparison of all elements in the second level and enter the judgments in a $n \times n$ matrix.

- Calculate priorities by normalizing the vector in each column of the matrix of judgments and averaging over the rows of the resulting matrix and you have the priority vector.

- Compute the consistency ratio of the matrix of judgments to make sure that the judgments are consistent.

4. Repeat step 3 for all elements in a succeeding level but with respect to each criterion in the preceding level.

5. Synthesize the local priorities over the hierarchy to get an overall priority for each alternative.

4.1.6 Advantages and Disadvantages

4.1.6.1 Main Advantages of AHP

AHP is one of the most widely used decision analysis methods. The main advantages of using the AHP methodology are:

1. AHP is a relatively easy approach to understand and apply (Onesime et al., 2004).

2. The hierarchical structure definition permits to understand all the variables involved and their relationship (Bertolini, Braglia & Carmignani, 2006).

3. The method does not replace the personnel involved in the resolution process but integrates all the judgments with structured links (Bertolini, Braglia & Carmignani, 2006).

4. By breaking a problem down in a logical fashion from the large, descending in gradual steps, to the smaller and smaller, one is able to connect, through simple paired comparison judgments, the small level to the large one (Al-Harbi, 2001).

5. The strength of the AHP lies in its ability to structure a complex, multi-person and multi-attribute problem hierarchically, and then to investigate each level of the hierarchy separately, combining the results as the analysis progresses (Liu & Hai, 2005).

6. AHP provides the simple representation of a multi-criteria problem by comparing multiple alternatives in the form of a pairwise comparison matrix (Setiawan, 2002).

7. The flexibility of the AHP allows the decision makers to make the decision hierarchies to match exactly the requirements of the decision process they are facing (Kyläheiko et al., 2002).

4.1.6.2 Main Disadvantages of AHP

Despite its popularity, AHP methodology has several disadvantages which are:

1. The AHP is mainly used in nearly well structured decision applications (Cheng, 1996).

2. The subjective judgment, selection and preference of decision makers have large influence on the AHP result, i.e., if the judgment is in error, the decision is probably incorrect (Cheng, 1996).

3. Even though the discrete scale of AHP has the advantages of simplicity and ease of use, it is not sufficient to take into account the uncertainty associated with the mapping of one's perception to a number (Kwong & Bai, 2003).

4. The number of judgments to be elicited in AHP increases as the number of alternatives and criteria increase. This is often a tiresome and exerting exercise for the DM (decision maker) (Ramanathan, 2006).

5. The issue of rank reversal is one of the prominent limitations of traditional AHP (Belton & Gear, 1983). The ranking of alternatives determined by the traditional AHP may be altered by the addition or deletion of another alternative for consideration. For example, when a new alternative is added to the list of alternatives, or when an existing alternative is removed, it is possible that their rankings change (Ramanathan, 2006).

Regarding the disadvantages of crisp AHP mentioned above, the supplier selection problem in this thesis was solved by fuzzy analytical hierarchy process (FAHP). The FAHP is the fuzzy extension of AHP to efficiently handle the fuzziness of the data involved in the decision of the best supplier. It is easier to understand and it can effectively handle both qualitative and quantitative data in the multi- attribute decision making problems (Chan & Kumar, 2005). In the following section, fuzzy logic and fuzzy analytic hierarchy process will be explained in detail.

4.2 Fuzzy Analytical Hierarchy Process

4.2.1 Fuzzy Logic

The concept of Fuzzy Logic (FL) was conceived by Lotfi Zadeh, a professor at the University of California at Berkley, and presented not as a control methodology, but as a way of processing data by allowing partial set membership rather than crisp set membership or non-membership. Professor Zadeh reasoned that people do not require precise, numerical information input, and yet they are capable of highly adaptive control. If feedback controllers could be programmed to accept noisy, imprecise input, they would be much more effective and perhaps easier to implement. Unfortunately, U.S.

manufacturers have not been so quick to embrace this technology while the Europeans and Japanese have been aggressively building real products around it (Kaehler, 2004).

Fuzzy logic is a powerful problem-solving methodology with a myriad of applications in embedded control and information processing. Fuzzy provides a remarkably simple way to draw definite conclusions from vague, ambiguous or imprecise information. In a sense, fuzzy logic resembles human decision making with its ability to work from approximate data and find precise solutions (What is fuzzy logic?, n.d.a).

Unlike classical logic which requires a deep understanding of a system, exact equations, and precise numeric values, Fuzzy logic incorporates an alternative way of thinking, which allows modeling complex systems using a higher level of abstraction originating from our knowledge and experience. Fuzzy Logic allows expressing this knowledge with subjective concepts such as very hot, bright red, and a long time which are mapped into exact numeric ranges (What is fuzzy logic?, n.d.a).

According to Albert Einstein, fuzzy logic can be explained by this quote: “So far as the laws of mathematics refer to reality, they are not certain. And so far as they are certain, they do not refer to reality”. Fuzzy logic sometimes appears exotic or intimidating to those unfamiliar with it, but once you become acquainted with it, it seems almost surprising that no one attempted it sooner. In this sense fuzzy logic is both old and new because, although the modern and methodical science of fuzzy logic is still young, the concepts of fuzzy logic reach right down to our bones (What is fuzzy logic?, n.d.b). In Figure 4.2, the difference between precision and significance is mentioned.

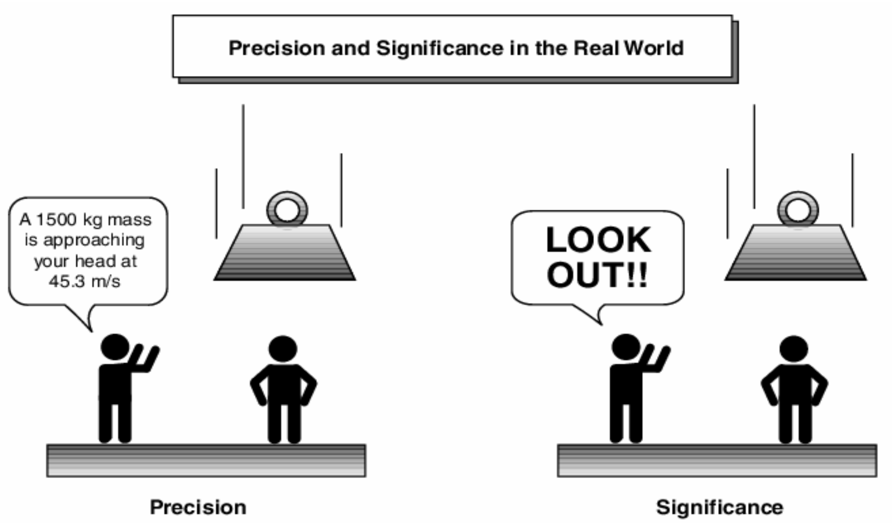

Figure 4.2 Precision and significance in the real world

4.2.2 Fuzzy Decision Making

Decision making is a most important scientific, social and economic endeavor. To be able to make consistent and correct choices is the essence of any decision process imbued with uncertainty. Most issues in life, as trivial as we might consider them, involve decision processes of one form or another. From the moment we wake in the morning to the time we place our bodies at rest at the day's conclusion we make many, many decisions (Ross, 1995).

Keep in mind when dealing with decision making under uncertainty that there is a distinct difference between a good decision and a good outcome. In any decision process we weigh the information about an issue or outcome and choose among two or more alternatives for subsequent action. The information affecting the issue is likely incomplete or uncertain; hence, the outcomes are uncertain, irrespective of the decision made or alternative chosen. We can make a good decision, and the outcome can be adverse. Alternatively, we can make a bad decision, and the outcome can be advantageous. But in the long run, if we consistently make good decisions, advantageous situations will occur more frequently than bad ones (Ross, 1995).

We can see uncertainty violated every day in the business world. A manager makes a good decision, but the outcome is bad and he gets fired. A doctor uses the best established procedures in a medical operation and the patient dies; then she gets sued for malpractice. In all of the similar situations the outcomes have nothing to do with the quality of the decisions or with the process itself. The best we can do is to make consistently rational decisions every time we are faced with a choice with the knowledge that in the long run the “goods” will outweigh the “bads” (Ross, 1995).

The problem in making decisions under uncertainty is that the bulk of the information we have about the possible outcomes, about the value of new information, about the way the conditions change with time (dynamic), about the utility of each outcome-action pair and about our preferences for each action is typically vague, ambiguous, and otherwise fuzzy (Ross, 1995). Therefore fuzzy set theory can be used in decision-making under uncertainty.

4.2.3 Fuzzy AHP

AHP has been widely used to address the multi-criterion decision making problems. However, it has been generally criticized because of the use of a discrete scale of one to nine which cannot handle the uncertainty and ambiguity present in deciding the priorities of different attributes. The relative importance of different decision criteria in supplier selection involves a high degree of subjective judgment and individual preferences. The hierarchy of the decision variables is the subject of a pair-wise comparison of the AHP. In conventional AHP, the pair-wise comparison is established using a nine-point scale which converts the human preferences between available alternatives as equally, moderately, strongly, very strongly or extremely preferred (Chan & Kumar, 2005). Even though the discrete scale of AHP has the advantages of simplicity and ease of use, it is not sufficient to take into account the uncertainty associated with the mapping of one’s perception to a number (Kwong & Bai, 2003). The linguistic assessment of human feelings and judgments are vague and it is not reasonable to represent it in terms of precise numbers. It feels more confident to give interval judgments than fixed value judgments. Hence, triangular fuzzy numbers are used to decide the priority of one decision variable over other (Chan & Kumar, 2005).

Fuzzy set theory has proven advantages within vague, imprecise and uncertain contexts and it resembles human reasoning in its use of approximate information and uncertainty to generate decisions. It was specially designed to mathematically represent uncertainty and vagueness and provide formalized tools for dealing with the imprecision intrinsic to many decision problems. Fuzzy set theory implements classes and grouping of data with boundaries that are not sharply defined (i.e. fuzzy). Fuzzy set theory includes the fuzzy logic, fuzzy arithmetic, fuzzy mathematical programming, fuzzy graph theory and fuzzy data analysis, usually the term fuzzy logic is used to describe all of these. The FEAHP (fuzzy extended AHP) is the fuzzy extension of AHP to efficiently handle the fuzziness of the data involved in the decision of the best supplier. It is easier to understand and it can effectively handle both qualitative and quantitative data in the multi- attribute decision making problems (Chan & Kumar, 2005).

Fuzzy AHP has been applied to numerous decision-making problems such as supplier selection, e-marketplace selection, associate professor selection, evaluation of weapon systems, locating a new convenience store and determining the importance weights for the customer requirements. Fuzzy AHP studies on supplier selection were explained in detail in Chapter Three. Fuzzy AHP applications on other areas will be explained briefly below.

The earliest work in Fuzzy AHP appeared in van Laarhoven and Pedrycz (1983), which compared fuzzy ratios described by triangular membership functions. They presented a fuzzy method to select the best associate professor among the alternatives at a university.

Often fuzzy multiple decision making techniques have been applied to solve the problem of evaluating weapon systems. Cheng & Mon (1994) proposed a new algorithm for evaluating weapon systems by Analytical Hierarchy Process (AHP) based on fuzzy scales, which is a multiple criteria decision making approach in a fuzzy environment. In this study, five anti-aircraft artillery (A.A.A.) of designed patterns were evaluated based on five attributes for judgment which are technological advance of mechanism, large kill capacity, long lifetime of mechanism, high mobility and easy logistic maintenance and 18 sub-attributes. Cheng (1996) proposed a new algorithm for evaluating naval tactical missile systems by the fuzzy Analytical Hierarchy Process based on grade value of membership function. This algorithm was applied to a missile system evaluation and selection problem. Chen (1996) proposed a new method for evaluating weapon systems based on fuzzy number arithmetic operations, where the degrees of satisfiability for each system with respect to each criteria item are ranked by integer numbers and the summation of these rank scores denotes the degree of satisfiability of the system with respect to the criteria and is represented by a triangular fuzzy number. According to Cheng, Yang & Hwang (1999), Chen (1996) used a large number of fuzzy arithmetic operations which caused information (data) loss or more fuzziness and it added to the difficulty and accuracy of decision-making. Therefore they proposed a new method for evaluating weapon systems by analytical hierarchy process (AHP) based on linguistic variable weight and applied it to the evaluation problem of three attack helicopters.

Kuo, Chi & Kao (1999) developed a decision support system using fuzzy sets theory integrated with analytic hierarchy process for locating a new convenience store. The proposed system consisted of four components: (l) hierarchical structure development for fuzzy AHP, (2) weights determination, (3) data collection, and (4) decision making.

The most common method used in the solution of fuzzy AHP applications is the extent analysis method proposed by Chang (1992). Kwong & Bai (2003) proposed a fuzzy AHP with an extent analysis approach to determine the importance weights for the customer requirements. Büyüközkan (2004) proposed a fuzzy-based evaluation methodology to provide managers with a more effective and efficient model for selecting e-marketplaces. To improve the effectiveness of the AHP in contributing to group consensus and decision making, the integration of AHP with fuzzy Delphi method was proposed and it was applied to a Turkish tile manufacturer in Kütahya.

4.2.4 Fuzzy Sets and Membership Function

A fuzzy set is a set containing elements that have varying degrees of membership in the set. This idea is in contrast with classical or crisp sets because members of a crisp set would not to be members unless their membership was full, or complete, in that set (i.e., their membership is assigned a value of 1). Elements in a fuzzy set, because their membership need not be complete, can also be members of other fuzzy sets on the same universe (Ross, 1995).

A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function, which assigns to each object a grade of membership ranging between zero and one (Kahraman, Cebeci & Ruan, 2004). Zadeh extended the notion of binary membership to accommodate various “degrees of membership” on the real continuous interval [0,1] where the endpoints of 0 and 1 conform to no membership and full membership, respectively, just as the indicator function does for crisp sets, but where the infinite number of values in between the endpoints can represent various degrees of membership for an element x in some set on the universe. The sets on the universe X that can accommodate “degrees of membership” were termed by Zadeh as “fuzzy sets” (Ross, 1995).

In fuzzy sets in order for a function to be considered as a membership function, the below mentioned conditions shall be satisfied (Güner, 2005):

1. In interval $(-\infty, a]$, $\mu_{\tilde{C}}(x) = 0$.

2. In interval [a,b], the membership values are monotonically increasing.
3. In interval [b,c], $\mu_{\tilde{C}}(x) = 1$.
4. In interval [c,d], the membership values are monotonically decreasing.
5. In interval $[d, \infty)$, $\mu_{\tilde{C}}(x) = 0$.

4.2.5 Features of the Membership Function

Since all information contained in a fuzzy set is described by its membership function, it is useful to describe various special features of this function (Ross, 1995):

- The *core* of a membership function for some fuzzy set $\underset{\sim}{A}$ is defined as that region of the universe that is characterized by complete and full membership in the set $\underset{\sim}{A}$. That is, the core comprises those elements *x* of the universe such that $\mu_{\underset{\sim}{A}}(x) = 1$.

- The *support* of a membership function for some fuzzy set $\underset{\sim}{A}$ is defined as that region of the universe that is characterized by nonzero membership in the set $\underset{\sim}{A}$. That is, the support comprises those elements *x* of the universe such that $\mu_{\underset{\sim}{A}}(x) > 0$.

- The *boundaries* of a membership function for some fuzzy set $\underset{\sim}{A}$ are defined as that region of the universe containing elements that have a nonzero membership but not complete membership. That is, the boundaries comprise those elements *x* of the universe such that $0 < \mu_{\underset{\sim}{A}}(x) < 1$. These elements of the universe are those with some degree of fuzziness. Figure 4.3 illustrates the regions in the universe comprising the core, support and boundaries of a typical fuzzy set.

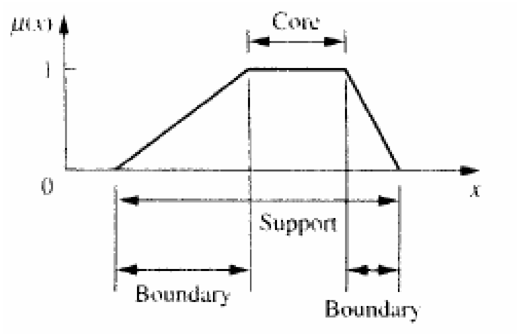

Figure 4.3 Core, support and boundaries of a fuzzy set (Ross, 1995)

- A *normal* fuzzy set is one whose membership function has at least one element x in the universe whose membership value is unity. For fuzzy sets where one and only one element has a membership equal to one, this element is typically referred to as the prototype of the set. Figure 4.4 illustrates typical normal and subnormal fuzzy sets.

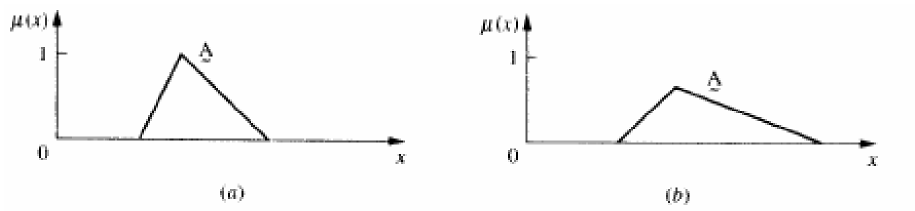

Figure 4.4 Fuzzy sets that are normal (a) and subnormal (b) (Ross, 1995)

- A *convex* fuzzy set is described by a membership function whose membership values are strictly monotonically increasing, or whose membership values are strictly monotonically decreasing, or whose membership values are strictly monotonically increasing then strictly monotonically decreasing with increasing values for elements in the universe. Said another way, if, for any elements x, y and z in a fuzzy set $\underset{\sim}{A}$, the relation $x < y < z$ implies that

$$\mu_{\underset{\sim}{A}}(y) \geq \min\left[\mu_{\underset{\sim}{A}}(x),\ \mu_{\underset{\sim}{A}}(z)\right] \tag{11}$$

then $\underset{\sim}{A}$ is said to be a convex fuzzy set. Figure 4.5 shows a typical convex fuzzy set and a typical nonconvex fuzzy set (Ross, 1995).

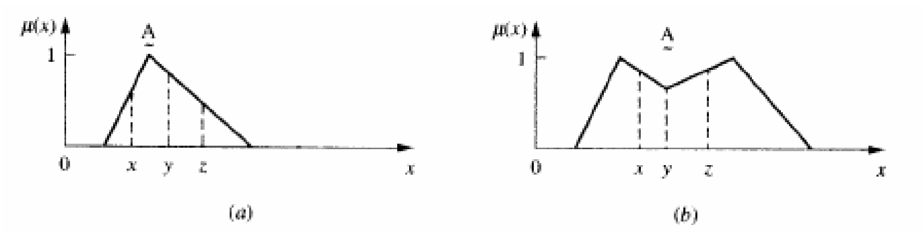

Figure 4.5 Convex, normal fuzzy set (a) and nonconvex, normal fuzzy set (b) (Ross, 1995)

- The *crossover* points of membership function are defined as the elements in the universe for which a particular fuzzy set $\underset{\sim}{A}$ has values equal to 0.5, i.e., for which $\mu_{\underset{\sim}{A}}(x) = 0.5$.

- The *height* of a fuzzy set $\underset{\sim}{A}$ is the maximum value of the membership function, i.e., $\max\left\{\mu_{\underset{\sim}{A}}(x)\right\}$. If the height of a fuzzy set is less than unity, the fuzzy set is said to be subnormal.

- If $\underset{\sim}{A}$ is a convex single-point normal fuzzy set defined on the real line, then $\underset{\sim}{A}$ is often termed a *fuzzy* number.

4.2.6 Algebraic Operations of Fuzzy Numbers

A fuzzy number is simply a fuzzy set which is a subset of a crisp set (Güner, 2005). It is described by a normal, convex membership function on the real line (Ross, 1995). The property "*near 6 feet",* which is used in fuzzy sets, is a simple fuzzy number. In practice, decision makers usually prefer triangular and trapezoidal fuzzy numbers. Also in this thesis, triangular fuzzy numbers were used for the preferences of one criterion over another. For this reason, only the algebraic operations of triangular fuzzy numbers will be explained in this section.

A tilde "$\sim$" will be placed above a symbol if the symbol represents a fuzzy set. A triangular fuzzy number (TFN), $\tilde{M}$ is shown in Figure 4.6. A TFN is denoted simply as $(l,\ m,\ u)$. The parameters $l,\ m,$ and u denote the smallest possible value, the most promising value and the largest possible value that describe a fuzzy event (Kahraman, Cebeci & Ruan, 2004).

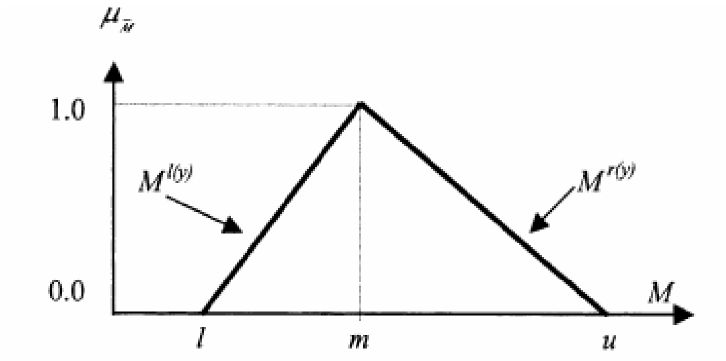

Figure 4.6 A triangular fuzzy number, $\tilde{M}$ (Kahraman, Cebeci & Ruan, 2004)

Each TFN has linear representations on its left and right side such that its membership function can be defined as (Kahraman, Cebeci & Ruan, 2004);

$$\mu_{\tilde{M}} = \begin{Bmatrix} 0, & x < l, \\ (x - l)/(m - l), & l \le x \le m, \\ (u - x)/(u - m), & m \le x \le u, \\ 0, & x > u. \end{Bmatrix} \tag{12}$$

A fuzzy number can always be given by its corresponding left and right representation of each degree of membership (Kahraman, Cebeci & Ruan, 2004):

$$\tilde{M} = (M^{l(y)}, M^{r(y)}) \\ = (l+(m-l)y, u+(m-u)y), \quad y \in [0,1], \tag{13}$$

where l(y) and r(y) denote the left side representation and the right side representation of a fuzzy number, respectively.

One of the most basic concepts of fuzzy set theory which can be used to generalize crisp mathematical concepts to fuzzy sets is the extension principle. Let X be a Cartesian product of universes $X = X_1,...,X_r$, and $\tilde{A}_1,...,\tilde{A}_r$ be r fuzzy sets in $X_1,...,X_r$, respectively. f is a mapping from X to a universe Y, $y = f(x_1,..., x_r)$. Then the extension principle allows us to define a fuzzy set $\tilde{B}$ in Y by Zimmerman (1994):

$$\tilde{B} = \{(y, \mu_{\tilde{B}}(y) | y = f(x_1,...,x_r), (x_1,...,x_r) \in X\}, \tag{14}$$

where

$$\mu_{\tilde{B}}(y) = \begin{cases} \sup\limits_{(x_1,...,x_r) \in f^{-1}(y)} \min \{\mu_{\tilde{A}_1}(x_1),...,\mu_{\tilde{A}_r}(x_r)\}, & if \ f^{-1}(y) \neq \varnothing \\ 0 & ,\text{otherwise} \end{cases} \tag{15}$$

where f^{-1} is the inverse of f.

Assume $\tilde{P}$ = *(a,b,c)* and $\tilde{Q}$ = *(d,e,f)*. *a, b, c, d, e, f* are all positive numbers. With this notation and by the extension principle, some of the extended algebraic operations of triangular fuzzy numbers are expressed in the following (Kahraman, Cebeci & Ulukan, 2003).

Changing sign

$$-(a,b,c) = (-c,-b,-a) \tag{16}$$

or

$$-(d,e,f) = (-f,-e,-d) \tag{17}$$

Addition

$$\tilde{P} \oplus \tilde{Q} = (a+d, b+e, c+f) \tag{18}$$

and

$$k \oplus (a,b,c) = (k+a, k+b, k+c) \tag{19}$$

or

$$k \oplus (d,e,f) = (k+d, k+e, k+f) \tag{20}$$

if k is an ordinary number (a constant).

Subtraction

$$\tilde{P} - \tilde{Q} = (a-f, b-e, c-d) \tag{21}$$

and

$$(a,b,c) - k = (a-k, b-k, c-k) \tag{22}$$

or

$$(d,e,f) - k = (d-k, e-k, f-k) \tag{23}$$

if k is an ordinary number (a constant).

Multiplication

$$\tilde{P} \otimes \tilde{Q} = (ad, be, cf) \tag{24}$$

and

$$k \otimes (a,b,c) = (ka, kb, kc) \tag{25}$$

or

$$k \otimes (d,e,f) = (kd, ke, kf) \tag{26}$$

if k is an ordinary number (a constant).

Taking the inverse

$$(a,b,c)^{-1} = (1/c, 1/b, 1/a) \tag{27}$$

4.3 Fuzzy AHP Methods

In crisp AHP, a discrete scale of one to nine is used to decide the priority of one decision variable over another whereas in fuzzy AHP fuzzy numbers or linguistic variables are used. In practice, decision makers usually prefer triangular or trapezoidal fuzzy numbers. Since fuzzy numbers are used in fuzzy AHP, the solution methods differentiate from crisp AHP. In this section, different solution methods on fuzzy AHP will be explained in detail.

4.3.1 Fuzzy AHP using Fuzzy Arithmetic Operations

Chen (1996) proposed a new method to deal with the performance evaluation of weapon systems using fuzzy arithmetic operations. The proposed method uses simplified fuzzy arithmetic operations of fuzzy numbers rather than the complicated entropy weight calculations. Therefore its execution is much faster than the method with entropy weight calculations.

An efficient algorithm for evaluating weapon systems using fuzzy arithmetic operations is explained below. Assume that there are *n* criteria $\left(i.e.,\ C_1,\ C_2,...,C_n\right)$ and assume that there are *m* systems to be evaluated $\left(i.e.,\ S_1,\ S_2,...,S_m\right)$. Furthermore, assume that the weights of the criteria supplied by the decision maker are represented by a weighting vector W, $W=\left[\tilde{W}_1,\ \tilde{W}_2,...,\tilde{W}_m\right]$, where $\tilde{W}_1,\ \tilde{W}_2,...,\tilde{W}_m$ are triangular fuzzy numbers whose values may be $\tilde{0},\ \tilde{1},\ \tilde{2},...,\tilde{9}$ defined as follows:

$$\begin{aligned}&\tilde{0}=(0,\ 0,0),\quad \tilde{1}=(0,\ 1,2),\quad \tilde{2}=(1,\ 2,3),\quad \tilde{3}=(2,\ 3,4),\quad \tilde{4}=(3,\ 4,5),\\ &\tilde{5}=(4,\ 5,6),\quad \tilde{6}=(5,\ 6,7),\quad \tilde{7}=(6,\ 7,8),\quad \tilde{8}=(7,\ 8,9),\quad \tilde{9}=(8,\ 9,9),\end{aligned} \qquad (28)$$

$\tilde{W}_i$ denotes the weight of the criteria C_i, $1 \le i \le n.$ The computational procedure of the decision-making methodology can be summarized in the following (Chen, 1996):

1. For each criteria, rank the degree of satisfiability for each system with respect to each criteria item by integer numbers 1, 2, 3,..., etc. Summarize the rank score of each system with respect to each criteria item and represent each summarized rank score p by a triangular fuzzy number $\tilde{p}$ parametrized by a triplet $(p-1,\ p, p{+}1)$. Represent the summarized rank of each system with respect to each criteria by a fuzzy rank score matrix A,

$$A = \begin{array}{c} \\ S_1 \\ S_2 \\ \vdots \\ S_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{pmatrix} \tilde{p}_{11} & \tilde{p}_{12} & \cdots & \tilde{p}_{1n} \\ \tilde{p}_{21} & \tilde{p}_{22} & \cdots & \tilde{p}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{p}_{m1} & \tilde{p}_{m2} & \cdots & \tilde{p}_{mn} \end{pmatrix} \end{array} \tag{29}$$

where $\tilde{p}_{ij}$ is a triangular fuzzy number denoting the summarized rank score of system S_i with respect to criteria C_j, $1 \le i \le m,$ and $1 \le j \le n.$

2. Perform the following transformation operations:

$$R = A \odot W^T = \begin{pmatrix} \tilde{p}_{11} \otimes \tilde{w}_1 \oplus \tilde{p}_{12} \otimes \tilde{w}_2 \oplus \cdots \oplus \tilde{p}_{1n} \otimes \tilde{w}_n \\ \tilde{p}_{21} \otimes \tilde{w}_1 \oplus \tilde{p}_{22} \otimes \tilde{w}_2 \oplus \cdots \oplus \tilde{p}_{2n} \otimes \tilde{w}_n \\ \vdots \\ \tilde{p}_{m1} \otimes \tilde{w}_1 \oplus \tilde{p}_{m2} \otimes \tilde{w}_2 \oplus \cdots \oplus \tilde{p}_{mn} \otimes \tilde{w}_n \end{pmatrix} = \begin{pmatrix} R(1) \\ R(2) \\ \vdots \\ R(m) \end{pmatrix} \tag{30}$$

where $\otimes$ and $\oplus$ are fuzzy number multiplication operator and fuzzy number addition operator, respectively, W^T denotes the transpose of the weighting vector W, and R(1), $R(2),..., R(m)$ are triangular fuzzy numbers.

3. Consider a trapezoidal fuzzy number parametrized by a quadruple $(a,\ b,\ c,\ d)$, where e is the defuzzification value of the fuzzy number. The defuzzification value e of a triangular fuzzy number parametrized by $(a,\ b,\ c)$ is equal to:

$$e = \frac{a+b+c+d}{4} \tag{31}$$

Apply Equation (31) to defuzzify the triangular fuzzy numbers $\mathrm{R}(1), R(2),..., R(m)$ into crisp real values $v_1,\ v_2,...,v_m,$ respectively, i.e., if $R(i) = (a_i,\ b_i,\ c_i),$ then let:

$$v_i = \frac{a_i + b_i + b_i + c_i}{4} \tag{32}$$

where $1 \le i \le m.$ If v_j is the smallest value among $v_1,\ v_2,...,v_m,$ then system S_j is the best choice.

4.3.2 Fuzzy AHP based on Entropy Weight

4.3.2.1 Shannon Entropy

The Shannon entropy, *H*, which is applicable only to probability measures, assumes in evidence theory the form

$$H(m) = -\sum_{j=1}^{n} m\left(\{x\}\right)\ \log_2 m\left(\{x\}\right) \tag{33}$$

This function which forms the basis of classical information theory, measures the average uncertainty (in bits) associated with the prediction of outcomes in a random experiment. Cheng (1996) used fuzzy AHP method and the entropy concepts to calculate aggregate weights.

4.3.2.2 The Fuzzy AHP Method based on the Grade Value of Membership Function

Cheng (1996) proposed a new algorithm for evaluating naval tactical missile systems by the fuzzy Analytical Hierarchy Process based on grade value of membership function. The evaluation model in this method can be summarized in the following (Cheng, 1996):

1. Construct a hierarchy structure for the system.

2. Build membership function of judgment criteria: Generally, scores are given to represent judgmental objects by experience of experts. A membership function of judgment criteria for all sub-items is built which is based on an optimal ideal point of experts for practical operation conditions.

3. Compute the performance score g_i: From data of the performance of the system and given fuzzy standard (membership function), the grade of membership function g_i is calculated.

4. Utilize fuzzy AHP method and entropy concepts to calculate aggregate weights: After invoking comparison of the performance scores, symmetric triangular fuzzy numbers are used to implement the scaling scheme in the judgment vector (matrix). The entropies are used in measuring the average uncertainty associated with the prediction of outcomes in a random experiment and in practical applications of maximum entropy principle are mean values of one or more random variables or various marginal probability distributions of an unknown joint distribution. Therefore, the interval arithmetic is used to represent the fuzzy judgment matrix and calculate the aggregate weights by entropy concepts.

The computational procedure of this decision making methodology is summarized as follows (Klir & Yan, 1995):

a) To compare the performance scores, symmetric triangular fuzzy numbers $\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$ are used to indicate the relative strength of the elements in the hierarchy (judgment vector or matrix).

b) To establish the total fuzzy judgment matrix $\tilde{A}$, the fuzzy subjective weight vector $\tilde{W}$ is multiplied with the corresponding column of fuzzy judgment matrix $\tilde{X}$ (the orderly list of fuzzy judgment vectors $\tilde{x}_i$ for every criterion C_i). Thus, the below matrix is obtained.

$$\tilde{A} = \begin{pmatrix} \tilde{w}_1 \times \tilde{x}_{11} & \tilde{w}_2 \times \tilde{x}_{12} & \vdots & \tilde{w}_n \times \tilde{x}_{1n} \\ \tilde{w}_1 \times \tilde{x}_{21} & \tilde{w}_2 \times \tilde{x}_{22} & \vdots & \tilde{w}_n \times \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{w}_1 \times \tilde{x}_{n1} & \tilde{w}_2 \times \tilde{x}_{n2} & \vdots & \tilde{w}_n \times \tilde{x}_{nn} \end{pmatrix} \quad (34)$$

c) Perform fuzzy number multiplications and additions using the interval arithmetic and cuts. Then the below mentioned matrix is obtained.

$$\tilde{A}_\alpha = \begin{pmatrix} \left[a_{11l}^\alpha, a_{11u}^\alpha\right] & \cdots & \left[a_{1nl}^\alpha, a_{1nu}^\alpha\right] \\ \vdots & \ddots & \vdots \\ \left[a_{n1l}^\alpha, a_{n1u}^\alpha\right] & \cdots & \left[a_{nnl}^\alpha, a_{nnu}^\alpha\right] \end{pmatrix} \quad (35)$$

where $a_{ijl}^\alpha = w_{il}^\alpha x_{ijl}^\alpha$, $a_{iju}^\alpha = w_{iu}^\alpha x_{iju}^\alpha$, for $0 < \alpha \leq 1$ and for all *i, j*.

d) Estimate the degree of satisfaction of the judgment $\hat{A}$. When α is fixed, the index of optimism λ will be set by the degree of the optimism of a decision maker. A larger λ indicates a higher degree of optimism. The index of optimism is a linear convex combination, it is defined as:

$$\hat{a}_{ij}^{\alpha} = (1-\lambda) a_{ijl}^{\alpha} + \lambda a_{iju}^{\alpha}, \forall \lambda \in [0,1].$$

Thus we have

$$\hat{A} = \begin{pmatrix} \hat{a}_{11}^{\alpha} & \hat{a}_{12}^{\alpha} & \cdots & \hat{a}_{1n}^{\alpha} \\ \hat{a}_{21}^{\alpha} & \hat{a}_{22}^{\alpha} & \cdots & \hat{a}_{2n}^{\alpha} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{a}_{n1}^{\alpha} & \hat{a}_{n2}^{\alpha} & \cdots & \hat{a}_{nn}^{\alpha} \end{pmatrix} \tag{36}$$

where $\widehat{A}$ is a precise judgment matrix.

e) The entropy can be computed firstly by using the relative frequency of Equation (37) and the entropy formula of Equation (38). i.e.,

$$\begin{pmatrix} \frac{a_{11}}{s_1} & \frac{a_{12}}{s_1} & \cdots & \frac{a_{1n}}{s_1} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{a_{n1}}{s_n} & \frac{a_{n2}}{s_n} & \cdots & \frac{a_{nn}}{s_n} \end{pmatrix} = \begin{pmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1} & f_{n2} & \cdots & f_{nn} \end{pmatrix} \tag{37}$$

where $s_k = \sum_{j=1}^{n} a_{kj}$

$$
\begin{aligned}
H_1 &= -\sum_{j=1}^{n}\left(f_{1j}\right)\log_2\left(f_{1j}\right) \\
H_2 &= -\sum_{j=1}^{n}\left(f_{2j}\right)\log_2\left(f_{2j}\right) \\
&\vdots \\
H_n &= -\sum_{j=1}^{n}\left(f_{nj}\right)\log_2\left(f_{nj}\right)
\end{aligned}
\tag{38}
$$

where (H_i) is the *i*th entropy value. The resultant aggregate weights can be determined by normalizing Equation (38).

The role of uncertainty measures is particularly significant in three fundamental principles for managing uncertainty: the principle of maximum uncertainty, the principle of minimum uncertainty and the principle of uncertainty invariance (Klir & Yan, 1995). Cheng (1996) used the principle of maximum uncertainty to calculate entropy weights. Therefore the alternative with the maximum entropy value (H_n) is chosen as the best alternative.

4.3.3 Fuzzy AHP based on Linguistic Variable Weight

Cheng, Yang & Hwang (1999) proposed a new method for evaluating weapon systems by analytical hierarchy process (AHP) based on linguistic variable weight. Many researchers used fuzzy arithmetic operations with weight and attribute of computing performance score to solve fuzzy multi-attribute decision-making (MADM) problems, such as Chen (1996). They used a large number of fuzzy arithmetic operations, which not only causes information (data) loss or more fuzziness, but also adds to the difficulty and accuracy of decision-making. Therefore, Cheng, Yang & Hwang (1999) used linguistic variable weight method to solve the above problems and to avoid the mistake of decision-making.

This method possesses intuition, in accord with human rethinking-model, and is close to humanized uncertainty of language expression. They used many experts' viewpoints to build the membership function in order to calculate the performance score, and identify expectation of the decision-maker to avoid the constraint of system alternatives and subjective judgments of the decision-maker.

The algorithm for evaluating weapon systems by AHP based on linguistic variable weight can be summarized in the following (Cheng, Yang & Hwang, 1999):

1. Construct the hierarchical organization diagram.

2. Compute the performance score g_i of the sub-factor, and sum up all the scores corresponding to its criteria.

Two methods are mentioned below to obtain the score:

a) The original data are represented by quantity, after consulting many experts' opinions to construct the membership function of the sub-item and use the membership function to compute g_i values.

b) Utilize fuzzy language to construct the look-up table for values and derive its corresponding value to the mean of fuzzy numbers as in Table 4.3, and as shown in Figure 4.7.

Table 4.3 Linguistic value look-up table (Cheng, Yang & Hwang, 1999)

Fuzzy language	**The mean of fuzzy numbers**
Very good	1
Good	0.75
Fair	0.5
Poor	0.25
Very poor	0

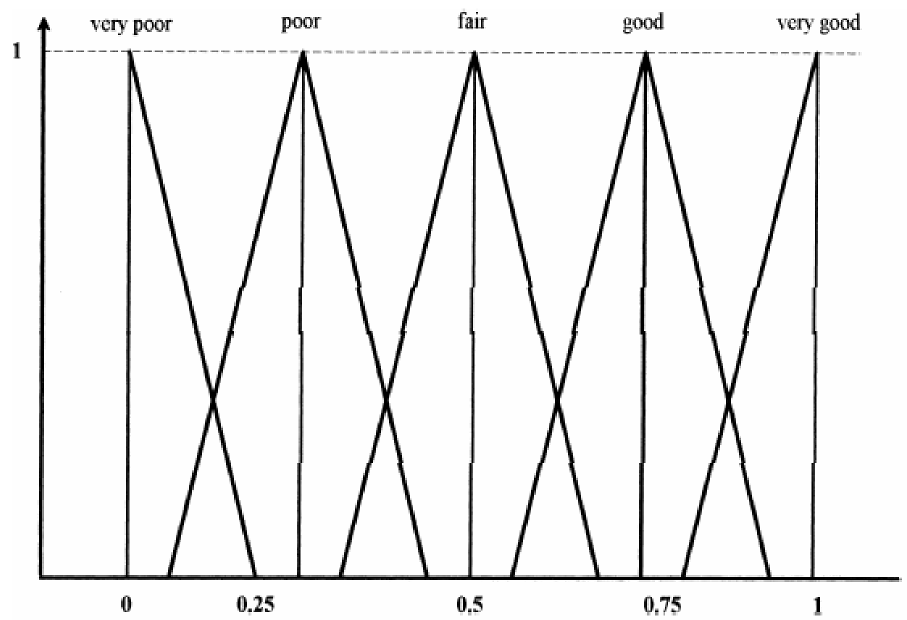

Figure 4.7 Membership functions of linguistic values for criteria ratings (Cheng, Yang & Hwang, 1999)

3. Normalize all total scores for every criteria, i.e.,

$$\begin{matrix} & X_1 & & X_j & & X_n \\ S_1 \\ \vdots \\ S_i \\ \vdots \\ S_m \end{matrix}\begin{pmatrix} X_{11}/t_1 & \dots & X_{1j}/t_j & \dots & X_{1n}/t_n \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ X_{i1}/t_1 & \cdots & X_{ij}/t_j & \dots & X_{in}/t_n \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X_{m1}/t_1 & \dots & X_{mj}/t_j & \dots & X_{mn}/t_n \end{pmatrix} \tag{39}$$

$$= \begin{pmatrix} \mu_1(X_1) & \cdots & \mu_1(X_j) & \cdots & \mu_1(X_n) \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ \mu_i(X_1) & \cdots & \mu_i(X_j) & \cdots & \mu_i(X_n) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mu_m(X_1) & \cdots & \mu_m(X_j) & \cdots & \mu_m(X_n) \end{pmatrix}, \tag{40}$$

$$t_n = \sum_{i=1}^{m} X_{ij} \tag{41}$$

where S_i denotes possible alternatives; X_j denotes attributes with which alternative performances are measured; x_{ij} denotes the performance score of alternative S_i with respect to attribute X_j and $\mu_i\left(x_j\right) \in \left[0,1\right]$.

4. Determine the power of dilation or centralization. Linguistic modifiers will be explained in detail below. When the decision-makers balance the importance of criteria, and determine the power of dilation or centralization, Equation (42) is obtained.

$$\begin{array}{c} \\ S_1 \\ \vdots \\ S_i \\ \vdots \\ S_m \end{array} \begin{array}{c} \begin{array}{ccccc} X_1 & & X_j & & X_n \end{array} \\ \begin{pmatrix} \mu_{11}^{(w_1)} & \cdots & \mu_{1j}^{(w_j)} & \cdots & \mu_{1n}^{(w_n)} \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ \mu_{i1}^{(w_1)} & \cdots & \mu_{ij}^{(w_j)} & \cdots & \mu_{in}^{(w_n)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mu_{m1}^{(w_1)} & \cdots & \mu_{mj}^{(w_j)} & \cdots & \mu_{mn}^{(w_n)} \end{pmatrix} \end{array} \tag{42}$$

Linguistic hedges are special linguistic terms by which other linguistic terms are modified. Linguistic terms such as “very”, “more or less”, “fairly” or “extremely” are examples of linguistic hedges.

A linguistic hedge or a modifier is an operation that modifies the meaning of a term more generally, of a fuzzy set. If $\tilde{A}$ is a fuzzy set, then the modifier *m* generates the (composite) term $\tilde{B} = m\left(\tilde{A}\right)$.

Mathematical models frequently used for modifiers are:

Concentration of a fuzzy set $\tilde{A}$ is shown in Figure 4.8.

$$\mu_{con(\tilde{A})}(u) = \left(\mu_{\tilde{A}}(u)\right)^n, where \text{ n>1.} \quad (43)$$

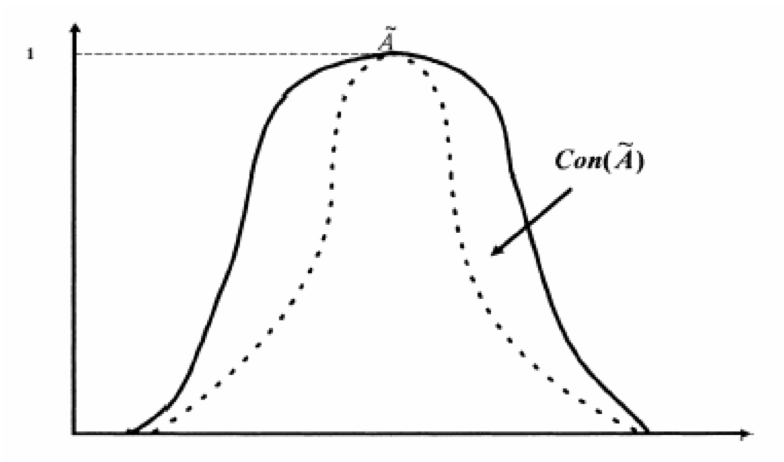

Figure 4.8 Concentration $\tilde{A}$ (Cheng, Yang & Hwang, 1999)

Dilation of a fuzzy set $\tilde{A}$ is shown in Figure 4.9.

$$\mu_{dil(\tilde{A})}(u) = \left(\mu_{\tilde{A}}(u)\right)^{1/n}, where \text{ n>1.} \quad (44)$$

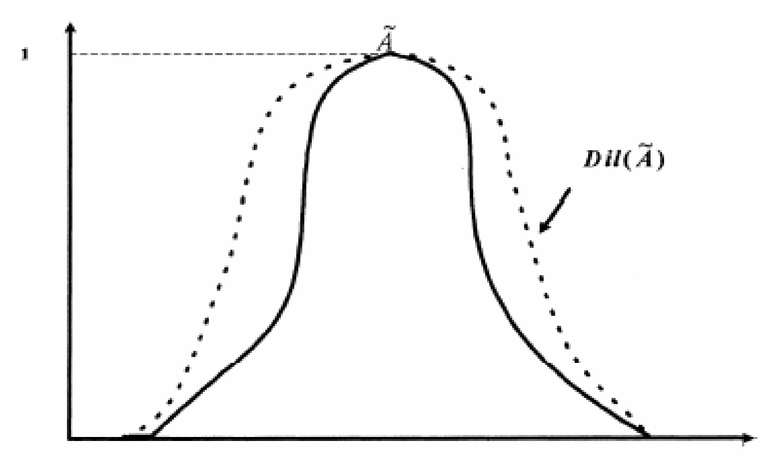

Figure 4.9 Dilation $\tilde{A}$ (Cheng, Yang & Hwang, 1999)

5. Determine the best alternative $\mu_{\tilde{D}}(x_i)$. Equation (45) is used to determine the best alternative which is to maximize the minimum membership value over all the criteria. If alternative i has the same maximum value $\mu_{\tilde{D}} = (x_i)$ in the determining process, the sub-minimum value μ_{ij}^{wj} is taken in the criteria and by Equation (45) the best alternative is determined. Equation (45) is shown in the following.

$$\mu_{\tilde{D}}(x_i) = \max_i \left(\min_j \mu_{ij}^{wj} \right). \qquad (45)$$

4.3.4 Extent Analysis Method

In most of the decision making problems with Fuzzy AHP, the Extent Analysis problem has been used. In this method, there is no need to define α-cuts and thus it is easier to apply to multi-criteria decision making problems.

The extent analysis method is used to consider the extent of an object to be satisfied for the goal, that is, satisfied extent. In the method, the "extent" is quantified by using a fuzzy number. On the basis of the fuzzy values for the extent analysis of each object, a fuzzy synthetic degree value can be obtained, which is defined as follows.

In a supplier selection problem, let $X = \{x_1, x_2, ..., x_n\}$ represent the elements of the alternatives as an object set and let $U = \{u_1, u_2, ..., u_m\}$ represent the elements of the supplier selection criteria as a goal set. According to the method of Chang's (1992) extent analysis, each object is taken and extent analysis for each goal, g_i, is performed respectively. Therefore, m extent analysis values for each object can be obtained, with the following signs:

$$M_{g_i}^{1}, M_{g_i}^{2}, ..., M_{g_i}^{m}, \qquad i = 1, 2, ..., n \tag{46}$$

where all the $M_{g_i}^{j}\ (j = 1, 2, ..., m)$ are TFNs.

The steps of Chang's extent analysis can be given as in the following (Kahraman, Cebeci & Ruan, 2004):

1. The value of fuzzy synthetic extent with respect to *i*th object is defined as

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} \right]^{-1} \tag{47}$$

To obtain $\sum_{j=1}^{m} M_{g_i}^{j}$, perform the fuzzy addition operation of *m* extent analysis values for a particular matrix such that

$$\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{48}$$

and to obtain $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} \right]^{-1}$, perform the fuzzy addition operation of $M_{g_i}^{j}\ (j = 1, 2, ..., m)$ values such that

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right) \tag{49}$$

and then compute the inverse of the vector in Equation (49) such that

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m}M_{g_i}^{j}\right]^{-1}=\left(\frac{1}{\sum_{i=1}^{n}u_i},\frac{1}{\sum_{i=1}^{n}m_i},\frac{1}{\sum_{i=1}^{n}l_i}\right). \tag{50}$$

2. The degree of possibility of $M_2=(l_2,m_2,u_2)\geq M_1=(l_1,m_1,u_1)$ is defined as

$$V(M_2\geq M_1)=\sup_{y\geq x}\left\lfloor \min\left(\mu_{M_1}(x),\mu_{M_2}(y)\right)\right\rfloor \tag{51}$$

and can be equivalently expressed as follows:

$$V(M_2\geq M_1)=hgt(M_1\cap M_2)=\mu_{M_2}(d) \tag{52}$$

$$=\left\{\begin{array}{ll} 1, & \text{if } m_2\geq m_1, \\ 0, & \text{if } l_1\geq u_2, \\ \dfrac{l_1-u_2}{(m_2-u_2)-(m_1-l_1)}, & \text{otherwise,} \end{array}\right\} \tag{53}$$

where d is the ordinate of the highest intersection point D between μ_{M_1} and μ_{M_2}. In Figure 4.10, the intersection between M_1 and M_2 can be seen.

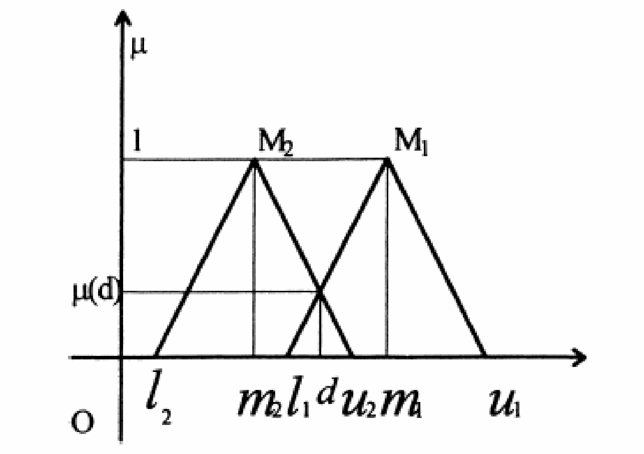

Figure 4.10 The intersection between M_1 and M_2
(Zhu, Ying & Chang, 1999)

To compare M_1 and M_2, we need both the values of $V\left(M_1 \geq M_2\right)$ and $V\left(M_2 \geq M_1\right)$.

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

$$\begin{aligned} &V\left(M \geq M_1, M_2, \ldots, M_k\right) \\ &= V[\left(M \geq M_1\right) \text{and} \left(M \geq M_2\right) \text{and} \ldots \\ &\text{and} \left(M \geq M_k\right)] \\ &= \min V\left(M \geq M_i\right), i=1,2,3,\ldots,k. \end{aligned} \tag{54}$$

Assume that

$$d'\left(A_i\right) = min\ V\left(S_i \geq S_k\right). \tag{55}$$

For $k=1,2,...,n; k \neq i.$ Then the weight vector is given by

$$W' = \left(d'\left(A_1\right), d'\left(A_2\right), \ldots, d'\left(A_n\right)\right)^T, \tag{56}$$

where $A_i \left(i=1,2,\ldots,n\right)$ are n elements.

4. Via normalization, the normalized weight vectors are

$$W=\left(d\left(A_1\right),d\left(A_2\right),\ldots,d\left(A_n\right)\right)^T, \tag{57}$$

where W is a nonfuzzy number.

Also in literature, other Fuzzy AHP methods can be found. Van Laarhoven & Pedrcyz (1983) were the first scientists to use triangular fuzzy numbers and logarithmic regression to calculate the priority weights. Cheng & Mon (1994) used the eigenvector method to calculate the priority weights from fuzzy matrices with the help of α-cuts. But these methods will not be mentioned in this section because they require a lot of mathematical calculations, they cause information (data) loss or more fuzziness and they do not investigate the consistency of the comparison judgments.

4.4 Fuzzy AHP and Consistency

In crisp AHP, the consistency of the pair-wise comparison matrices is calculated. Also in fuzzy AHP, the judgments in all the comparison matrices must be consistent. However most of the time in literature, the consistency of the judgment in the comparison matrices was not calculated in AHP applications using fuzzy numbers or linguistic variables. Kwong & Bai (2003) are one of the few scientists who calculated the consistency of the judgment in all the comparison matrices. Kwong and Bai used a fuzzy AHP method with an extent analysis approach to determine the importance weights for the customer requirements. The triangular fuzzy numbers in the comparison matrices were converted to crisp numbers using Equation (58) and then the consistency of the comparison matrices were calculated as in crisp AHP. The consistency of the judgment in all the comparison matrices in this thesis will be calculated using the same method.

$$M\_crisp = \frac{(4 \otimes m + l + u)}{6} \quad (58)$$

CHAPTER FIVE
DEVELOPMENT OF A FUZZY ANALYTICAL HIERARCHY MODEL FOR SUPPLIER SELECTION IN A WASHING MACHINE COMPANY

5.1 Introduction

In today's highly competitive and interrelated manufacturing environment, materials represent a substantial part of the value of products. In view of the high percentage of the material cost in total cost, the key objective of the purchasing department ought to be purchasing the right quality of a product in the right quantity from the right source at the right time. The right source can provide the right quality of material on time at a reasonable price (Zaim, Sevkli & Tarim, 2003).

Supplier selection and evaluation are very important to the success of a manufacturing firm. This is because the cost and quality of goods and services sold are directly related to the cost and quality of goods and services purchased. Therefore, purchasing and supplier selection have an important role in the supply chain process (Zaim, Sevkli & Tarim, 2003).

Traditionally, vendors are selected from among many suppliers on their ability to meet the quality requirements, delivery schedule and the price offered. In this approach, suppliers aggressively compete with each other. The relationship between buyer and seller is usually adversarial. This traditional purchasing approach places special emphasis on the commercial transaction between supplier and customer. The main purchasing objective in this approach is to obtain the lowest possible price by creating strong competition between suppliers, and negotiating with them. However, in the modern business world, many firms prefer a strategy of few suppliers (Zaim, Sevkli & Tarim, 2003).

Few supplier strategies imply that a buyer wants to have a long-term relationship and the cooperation of a few dedicated suppliers. Using few suppliers can create value to the buyer and yield both lower transaction and production costs. Cooperation between buyer and supplier is the starting point to establish a successful supply chain management and a necessary but insufficient condition. The next level needs coordination and collaboration between buyer and suppliers. Cooperation and collaboration between buyer and supplier includes specified work-flow, sharing information through electronic data interchange and the internet and joint planning and other mechanisms that permit to carry out the just in time (JIT) system and total quality management in the company (Zaim, Sevkli & Tarim, 2003).

After implementing advanced concepts in material management, quality management, logistics and achieving JIT objectives, a company needs to work with specialized suppliers in producing the right quality product. Therefore, the supplier selection process is a multi-objective decision of strategic importance to companies, encompassing many tangible and intangible factors in a hierarchical manner (Zaim, Sevkli & Tarim, 2003).

This thesis is carried out at a washing machine company, which produces washing machines and is located in Manisa. RPM (revolution per minute), cloth capacity and washing programme cards are the most important criteria for a washing machine. The variety of these three criteria is mentioned below:

- RPM: 400 RPM, 500 RPM, 600 RPM, 800 RPM, 1000 RPM, 1200 RPM, 1400 RPM, 1600 RPM
- Cloth Capacity: 4 kgs, 4.5 kgs, 5 kgs, 6 kgs, 7 kgs, 7.5 kgs
- Washing Programme Cards: A1, A2, A3, A4, B1, B2, V1, V2, V3, V4

The production is based on assembly and there are four assembly lines. The capacity of one assembly line is 600 units/shift. So the annual capacity of the washing machine company is 2 million units/year.

This study primarily focuses on the supplier selection process for one the most critical parts used in the production of washing machines. The rest of the thesis is organized as follows: In section 5.2, the importance of the supplier selection process in the white good sector is explained. In section 5.3, Fuzzy AHP procedure for the supplier selection problem is illustrated.

5.2 The Importance of the Supplier Selection Process in the White Good Sector

The selection of suppliers is a very critical multi-attribute decision-making problem in white good sector. The long-term availability of products and services depends on a long-term partnership between the supplier and the manufacturer. The manufacturing company discussed here is new in this sector and it is trying to increase its customer base. That’s why the production facilities and the ability of the supplier to increase its capacity should be taken into account to judge the best supplier. Also due to the white good sector, there are seasonal fluctuations. The supplier’s capacity should be flexible to meet the changes in the market demand. Since the production is based on assembly, all of the raw materials are outsourced. In consideration that the capacity of the factory is 2 million units/year, there are a huge number of raw materials supplied. Therefore supplier selection is one of the most important decision-making problems in the washing machine company.

All of the similar important criteria which can affect the supply of the critical part were discussed with an expert in the Production Planning Department and three critical main attributes were identified. The main attributes determined by the expert were supplier, product performance and service performance. The discussion has been further prolonged to decide the fourteen sub-attributes. The sub-attributes were determined as financial status, management approach, technical ability, quality systems and process, geographical location, production facility and capacity, working with Kanban approach, product price, handling, product quality, follow-up, technical support, lead time and professionalism. The main attributes and sub-attributes have been explained in detail in the following sections.

In this thesis, Extent Analysis Method on fuzzy AHP (Chang, 1992) was developed to solve multi-criteria supplier selection problem. Triangular fuzzy numbers were used in the solution process.

5.3 Fuzzy AHP Procedure for the Supplier Selection Problem

In this supplier selection problem, the relative importance of different decision criteria involves a high degree of subjective judgment and individual preferences. The linguistic assessment of human feelings and judgments are vague and it is not reasonable to represent them in terms of precise numbers. It feels more confident to give interval judgments. That's why triangular fuzzy numbers were used in this problem to decide the priority of one decision variable over another. The triangular fuzzy numbers were determined from reviewing literature (Kahraman, Cebeci & Ulukan, 2003). Then synthetic extent analysis method was used to decide the final priority weights based on triangular fuzzy numbers and so-called as fuzzy extended AHP.

The FEAHP is the fuzzy extension of AHP to efficiently handle the fuzziness of the data involved in the decision of the best supplier. It is easier to understand and it can effectively handle both qualitative and quantitative data in the multi-attribute decision making problems.

In this problem, triangular fuzzy numbers were used for the preferences of one criterion over another. First the decision maker compared the main attributes with respect to the main goal; then he compared the sub-attributes with respect to the main attributes. At the end, he compared the alternatives with respect to each sub-attribute.

By using the extent analysis method, the synthetic extent values of the pairwise comparisons were calculated. Based on this approach, the weight vectors were decided and normalized. At the end, the priority weights for main attributes, sub-attributes and alternatives were combined to determine the priority weights of the alternative suppliers. The supplier with the highest priority weight was selected as the best supplier. Macros in Excel were used to calculate the priority weights of the alternatives based on the questionnaire forms used to facilitate comparisons of main attributes, sub-attributes and alternatives. In the following sections, the main steps of the method will be explained in detail.

5.3.1 Define the Main Attributes and Sub-attributes for Supplier Selection to Design the Fuzzy Analytical Hierarchy Process Tree Structure

First the overall objective of the supplier selection problem has been identified which was “selection of the best supplier firm”. In the white good sector a lot of criteria should be taken into account because the competition is really high. All of the possible important criteria which could affect the supply of the critical part have been discussed with an expert in the Production Planning Department. Also other supplier selection studies in the white good sector using fuzzy AHP were reviewed with the expert (Chan & Kumar, 2005; Kahraman, Cebeci & Ulukan, 2003; Zaim, Sevkli & Tarim, 2003). By combining the attributes determined by the expert and the attributes used in the literature, the main attributes and the sub-attributes in the study were determined.

First three main attributes have been identified. The main attributes determined by the expert were supplier, product performance and service performance. The discussion has been further prolonged to decide the fourteen sub-attributes with three potential suppliers. The sub-attributes determined by the expert were financial status, management approach, technical ability, quality systems and process, geographical location, production facility and capacity, working with Kanban approach, product price, handling, product quality, follow-up, technical support, lead time and professionalism. The main and sub-attributes have been discussed in detail below.

5.3.1.1 Supplier Criteria

Supplier criteria are used to evaluate whether the supplier fits its supply and technology strategy. These considerations are largely independent of the product sought. Supplier criteria are developed to measure important aspects of the supplier's business: financial strength, management approach, technical capability, quality systems, geographical location, capacity and working with Kanban approach. The sub-criterias of the supplier criteria are explained below:

a) Financial status: The firm should require its suppliers to have a sound financial position. Financial strength can be a good indicator of the supplier's long-term stability. A solid financial position also helps ensure that performance standards can be maintained and that products will continue to be available.

b) Management approach: To form a good supplier relationship, companies need to have compatible approaches to management, especially for integrated and strategic relationships. Maintaining a good supplier relationship requires management stability. The firm should have confidence in its supplier's management's ability to run the company. It is also important that the supplier's management be committed to managing its supply base. The supplier's level of quality, service and cost are directly affected by its suppliers" ability to meet its needs.

c) Technical ability: Technology is advancing at a very fast pace in this competitive world to satisfy the customer first and get its appreciation. To provide a consistently high-quality product, promote successful development efforts and ensure future improvements, a firm needs competent technical support from its suppliers. This is particularly important when the firm's supply and technology strategy includes development of a new product or technology.

d) **Quality systems and process:** The supplier's quality systems and processes that maintain and improve quality and delivery performance are the key factors. This sub-criterion may consider the supplier's quality assurance and control procedures, complaint handling procedures, quality manuals, ISO 9001 standard registration status and internal rating and reporting systems.

e) **Geographical location:** It refers to the location of the supplier's firm. In case of urgent situations, the product can be supplied in a shorter time from the nearer supplier. Also the location of the supplier's firm has a direct impact on the price of the product being purchased.

f) **Production facility and capacity:** The production facilities and ability of the supplier to increase its capacity should be taken into account to judge the best one. The potential production capability of each supplier should be analyzed to meet a specified production plan and also to develop a new product according to the market demand.

g) **Working with Kanban approach:** According to the Kanban approach, the supplier firm keeps the stock of the product being purchased. By this way, the firm gets rid of the stock cost. Also according to this approach, the firm only pays for the amount of product it uses.

5.3.1.2 Product Performance Criteria

Product performance criteria can be used to examine important characteristics of the product being purchased. The exact criteria depend on the type of the product being considered. The sub-criterias of the product performance criteria are explained below:

a) **Product price:** In today's highly competitive and interrelated manufacturing environment, materials represent a substantial part of the value of products. In view of the high percentage of the material cost in the total cost, the key objective of the purchasing department ought to be purchasing the product with the minimum price to increase the profitability.

b) **Handling:** It includes the effectiveness of the transportation, storage and packaging function. The packaging of the product being purchased is very important. If this function is not effective, the material can get damaged during transportation. Also if the packaging of the product is effective, it will take less stock in the warehouse of the firm.

c) **Product Quality:** The quality of the product being purchased is very important. The quality of the product being sold is directly related to the quality of the product being purchased. The quality of the product being purchased can be measured in terms of the rejection rate of the product. The rejection rate of the product is defined in terms of the number of parts rejected by the customers in fixed time period because of some quality problems. It includes the defective parts detected in the incoming quality control and in the production line.

5.3.1.3 Service Performance Criteria

Service performance criteria can be used to evaluate the benefits provided by the supplier’s services. When considering services, a firm needs to clearly define its expectations since there are few uniform service standards to draw upon. Service performance criteria should always be included in the supplier selection criteria because any purchase involves some degree of service, such as order processing, delivery and support. When assessing the fitness of services of the supplier firms, follow-up, technical support, lead time and professionalism will be used. The sub-criterias of the service performance criteria are explained below:

a) **Follow-up:** The supplier firm should keep the customer informed about the production and delivery of the product being purchased. If there is a delay in the shipment of the product, the customer shall be informed. So that it can find another solution on time. Also according to the Kanban approach, the supplier firm shall keep track of the firm’s stock and inform the firm about it.

b) **Technical support:** The supplier firm should give technical support for problems occurring during the production of the product. Sometimes changes in the structure of the material can be required. The supplier firm shall give full technical support in such cases.

c) **Lead time:** The ability of the supplier to follow up the predefined delivery schedule is always the prime criteria for selection in this fast moving world. The lead time of the product being purchased directly affects the delivery schedule of the product being produced.

d) **Professionalism:** This includes the knowledge, accuracy, attitude and reliability of the contact people in the supplier firm.

After the main attributes, sub-attributes and alternatives were determined, the hierarchy of the supplier selection problem was structured. Figure 5.1 shows the structuring of the supplier selection problem hierarchy of four levels. The top level of the hierarchy represents the ultimate goal of the problem which is selection of the best supplier firm. The second level of the hierarchy is grouped under three categories, which are supplier attribute, product performance attribute and service performance attribute. At the third level, these main attributes are decomposed into various sub-attributes that may affect the supplier’s choice. Finally, the bottom level of the hierarchy represents the three alternative suppliers.

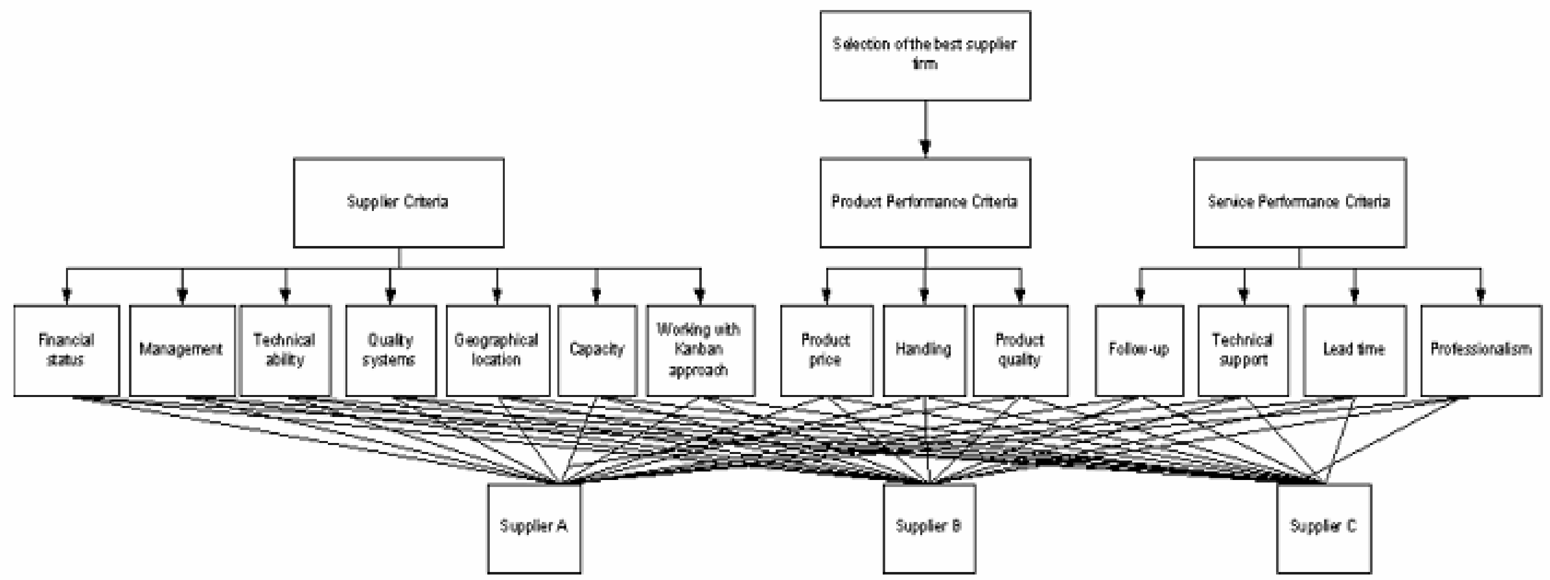

Figure 5.1 The hierarchy of the supplier selection problem

5.3.2 Calculate the Weights of the Main Attributes, Sub-attributes and Alternatives

After the construction of the hierarchy, the different priority weights of each main attribute, sub-attribute and alternative were calculated using the Fuzzy AHP approach. The comparison of the importance of one main attribute, sub-attribute and alternative over another were achieved by the help of the questionnaires in Appendix A1 and A2. The questionnaires facilitate the answering of pairwise comparison questions. The preference of one measure over another was decided by the available research and the experience of the expert.

First the expert compared the main attributes with respect to the main goal; then the expert compared the sub-attributes with respect to the main attributes. At the end, the expert compared the supplier firms with respect to each sub-attribute. In each row of the matrix in the questionnaire, the expert compared the attribute with the one matching across it and determined the importance of the attribute over the other by help of the question and the linguistic variables. Then the expert put the letter "X" in the intersection cell under the importance level he preferred.

If an attribute on the left was more important than the one matching on the right, he put the letter "X" to the left of the importance *"Equal"* under the importance level he preferred. If an attribute on the left was less important than the one matching on the right, he put the letter "X" to the right of the importance *"Equal"* under the importance level he preferred.

The expert used the linguistic variables to make the pairwise comparisons. Then the linguistic variables were converted to triangular fuzzy numbers. Table 5.1 shows the linguistic variables and their corresponding triangular fuzzy numbers. The pairwise comparison matrices of main attributes, sub-attributes and alternatives with triangular fuzzy numbers can be found in Appendix A3 and A4.

Table 5.1 The linguistic variables and their corresponding fuzzy numbers

Equally preferred (EP)	(1,1,1)
Weakly preferred (WP)	(2/3,1,3/2)
Fairly strongly preferred (FSP)	(3/2,2,5/2)
Very strongly preferred (VSP)	(5/2,3,7/2)
Absolutely preferred (AP)	(7/2,4,9/2)

After the pairwise comparison matrices were formed, the consistency of the pairwise judgment of each comparison matrix was checked using the calculation method of consistency index and consistency ratios in crisp AHP.

Each triangular fuzzy number, $M = (l, m, u)$ in the pair-wise comparison matrix was converted to a crisp number using $M\_crisp = (4 \otimes m + l + u) / 6$. After the fuzzy comparison matrices were converted into crisp matrices, the consistency of each matrix was checked by the method in crisp AHP. After calculation, the consistency ratio of each comparison matrix was found to be under 0.10. So we can conclude that the consistency of the pairwise judgments in all matrices is acceptable.

Then the priority weights of each main attribute, sub-attribute and alternative were calculated using FAHP method. As an example, the calculation of the priority weights of the main attributes will be explained in detail below.

Table 5.2 The fuzzy evaluation matrix with respect to the goal with linguistic variables

	Supplier	**Product performance**	**Service performance**
Supplier			WP
Product performance	WP		FSP
Service performance			

Table 5.3 The fuzzy evaluation matrix with respect to the goal with triangular fuzzy numbers

	Supplier	**Product performance**	**Service performance**
Supplier	(1,1,1)	(2/3,1,3/2)	(2/3,1,3/2)
Product performance	(2/3,1,3/2)	(1,1,1)	(3/2,2,5/2)
Service performance	(2/3,1,3/2)	(2/5,1/2,2/3)	(1,1,1)

In table 5.2, the fuzzy evaluation matrix with respect to the goal with linguistic variables can be found. By using the values in Table 5.1, the linguistic variables in the comparison matrix were converted to triangular fuzzy numbers. The fuzzy evaluation matrix with respect to the goal with triangular fuzzy numbers can be seen in Table 5.3. In order to find the priority weights of the main attributes, first the fuzzy synthetic extent values of the attributes were calculated by using Equation (47). The different values of fuzzy synthetic extent of the three different main attributes were denoted by S_S, S_{PP}, S_{SP}.

$$S_S = (2.34,\ 3,\ 4) \otimes (1/12.17,\ 1/9.5, 1/7.58) = (0.19,\ 0.32, 0.53) \tag{59}$$

$$S_{PP} = (3.17,\ 4,\ 5) \otimes (1/12.17,\ 1/9.5, 1/7.58) = (0.26,\ 0.42, 0.66) \tag{60}$$

$$S_{SP} = (2.07,\ 2.5,\ 3.17) \otimes (1/12.17,\ 1/9.5, 1/7.58) = (0.17,\ 0.26, 0.42) \tag{61}$$

The degree of possibility of S_I over S_J ($i \neq j$) was determined by using Equation (52) and (53).

$$V(S_S \geq S_{PP}) = \frac{(0.26 - 0.53)}{(0.32 - 0.53) - (0.42 - 0.26)} = 0.73 \tag{62}$$

$$V(S_S \geq S_{SP}) = 1 \tag{63}$$

$$V(S_{PP} \geq S_S) = 1 \tag{64}$$

$$V(S_{PP} \geq S_{SP}) = 1 \tag{65}$$

$$V(S_{SP} \geq S_S) = \frac{(0.19 - 0.42)}{(0.26 - 0.42) - (0.32 - 0.19)} = 0.79 \tag{66}$$

$$V(S_{SP} \geq S_{PP}) = \frac{(0.26 - 0.42)}{(0.26 - 0.42) - (0.42 - 0.26)} = 0.50 \tag{67}$$

With the help of Equation (55), the minimum degree of possibility was stated as below:

$$d'(S) = \min\ (0.73,\ 1) = 0.73 \tag{68}$$

$$d'(PP) = \min\ (1,\ 1) = 1 \tag{69}$$

$$d'(SP) = \min\ (0.79,\ 0.50) = 0.50 \tag{70}$$

Therefore the weight vector was given as $W' = (0.73,\ 1,\ 0.50)$. After normalization process, the weight vector of the main attributes which are supplier attribute, product performance attribute and service performance attribute was found to be $W_G = (0.33,\ 0.45,\ 0.22)^{\mathrm{T}}$.

We can conclude that the most important attribute in the supplier selection process is product performance attribute because it has the highest priority weight. Supplier attribute is the next preferred attribute.

The same calculations were applied to the other pairwise comparison matrices and the priority weights of each main attribute, sub-attribute and alternative were calculated. The priority weights of each main attribute, sub-attribute and alternative can be found in Table 5.4.

Table 5.4 Priority vectors for the decision hierarchy

Variables in Level 1	Level 1 Priorities	Variables in Level 2	Level 2 Priorities	Variables in Level 3	Level 3 Priorities
Supplier Criteria (S)	0.33	Financial Status (FS)	0.18	Supplier A	0.16
				Supplier B	0.84
				Supplier C	0
		Management (M)	0	Supplier A	1
				Supplier B	0
				Supplier C	0
		Technical Ability (TA)	0.22	Supplier A	0.58
				Supplier B	0.42
				Supplier C	0
		Quality Systems (QS)	0.31	Supplier A	0.58
				Supplier B	0.42
				Supplier C	0
		Geographical Location (GL)	0.04	Supplier A	0
				Supplier B	0
				Supplier C	1
		Capacity (C)	0.25	Supplier A	0.58
				Supplier B	0.42
				Supplier C	0
		Working with Kanban Approach (WWKA)	0	Supplier A	0.33
				Supplier B	0.22
				Supplier C	0.45
Product Performance Criteria (PP)	0.45	Product Price (PP)	0.16	Supplier A	0.45
				Supplier B	0.22
				Supplier C	0.33
		Handling (H)	0	Supplier A	0.58
				Supplier B	0.42
				Supplier C	0
		Product Quality (PQ)	0.84	Supplier A	0.45
				Supplier B	0.33
				Supplier C	0.22
		Follow-up (F)	0	Supplier A	0.45
				Supplier B	0.22

Service Performance Criteria (SP)	0.22			Supplier C	0.33
		Technical Support (TS)	0.23	Supplier A	0.45
				Supplier B	0.33
				Supplier C	0.22
		Lead Time (LT)	0.69	Supplier A	0.58
				Supplier B	0.42
				Supplier C	0
		Professionalism (P)	0.08	Supplier A	0.58
				Supplier B	0.42
				Supplier C	0

5.3.3 Compute the Overall Score of Each Supplier and Choose the Best Supplier

In the last step, the priority weights of the main attributes and sub-attributes were combined to determine priority weights of the alternative suppliers. In Table 5.5, each column of the matrix was multiplied by the priority weight at the top of the column and then those values were added up for each row. At the end, the priority weights of the alternatives with respect to supplier attribute were calculated.

The same calculations have been applied to the sub-attributes of product performance attribute and service performance attribute and the priority weights of the alternatives with respect to product performance and service performance attributes have been calculated. The priority weights can be seen in Table 5.6 and 5.7.

Table 5.5 Sub-attributes of supplier criteria

	FS	**M**	**TA**	**QS**	**GL**	**C**	**WWKA**	**Alternative priority weight**
Weight	0.18	0	0.22	0.31	0.04	0.25	0	
Alternative								
Supplier A	0.16	1	0.58	0.58	0	0.58	0.33	0.48
Supplier B	0.84	0	0.42	0.42	0	0.42	0.22	0.48
Supplier C	0	0	0	0	1	0	0.45	0.04

Table 5.6 Sub-attributes of product performance criteria

	PP	H	PQ	Alternative priority weight
Weight	0.16	0	0.84	
Alternative				
Supplier A	0.45	0.58	0.45	0.45
Supplier B	0.22	0.42	0.33	0.31
Supplier C	0.33	0	0.22	0.24

Table 5.7 Sub-attributes of service performance criteria

	F	TS	LT	P	Alternative priority weight
Weight	0	0.23	0.69	0.08	
Alternative					
Supplier A	0.45	0.45	0.58	0.58	0.55
Supplier B	0.22	0.33	0.42	0.42	0.40
Supplier C	0.33	0.22	0	0	0.05

At the end, the priority weights of the alternatives with respect to the main attributes were combined and the priority weights of the alternatives were determined. The priority weights of the alternative suppliers can be seen in Table 5.8.

Table 5.8 Main-attributes of the goal

	S	PP	SP	Alternative priority weight
Weight	0.33	0.45	0.22	
Alternative				
Supplier A	0.48	0.45	0.55	**0.48**
Supplier B	0.48	0.31	0.40	**0.39**
Supplier C	0.04	0.24	0.05	**0.13**

In order to shorten the solution process for the supplier selection problem, macros in Excel were used to calculate the priority weights of the alternatives based on the questionnaire forms used to facilitate comparisons of main attributes, sub-attributes and alternatives. The expert filled out the questionnaire forms in Appendix 1 and 2. Then macros in Excel made all of the calculations mentioned above to calculate the priority weights of the alternative firms. The priority weights for the alternatives were found to be (0.48, 0.39, 0.13). According to the final score, Supplier A is the most preferred supplier because it has the highest priority weight and Supplier B is the next recommended alternative supplier.

CHAPTER SIX
CONCLUSION

Today's markets and the technological and competitive forces within them are changing at an ever-increasing rate. To respond to these forces, radical changes in organizations have become necessary. Supply chain management is a key strategic factor for increasing organizational effectiveness and for better achieving organizational goals such as enhanced competitiveness, better customer care and increased profitability. Supply chain is a network of facilities and distribution options that perform the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these products to customers. The strength of the chain is as strong as the weakest part of the chain. Therefore, parts of the chain are very important. One important factor of the supply chain is the supplier selection in the purchasing process.

Supplier selection is a broad comparison of suppliers using a common set of criteria and measures. The objective of supplier selection is to identify suppliers with the highest potential for meeting a firm's needs consistently and at an acceptable cost. Supplier selection is one of the most important decision making problems because selecting the right suppliers significantly reduces the purchasing costs and improves corporate competitiveness.

The main interest of this thesis was to present a fuzzy analytic hierarchy based approach to select the best supplier firm providing the most customer satisfaction for the criteria determined for a washing machine company.

In the first phase, the main attributes and sub-attributes for supplier selection are defined and the hierarchy is structured. The main attributes and sub-attributes are determined based on literature survey and the experience of the expert in the Production Planning Department. The main attributes determined by the questionnaire are supplier, product performance and service performance. Then the main attributes are decomposed into various sub-attributes. Supplier attribute is decomposed into (a) financial status, (b) management approach, (c) technical ability, (d) quality systems and process, (e) geographical location, (f) production facility and capacity and (g) working with Kanban approach. Product performance attribute is decomposed into (a) product price, (b) handling and (c) product quality. Service performance attribute is decomposed into (a) follow-up, (b) technical support, (c) lead time and (d) professionalism.

In the second phase, the weights of the main attributes, sub-attributes and alternatives are calculated. The linguistic assessment of human feelings and judgments are vague and it is not reasonable to represent them in terms of precise numbers. It feels more confident to give interval judgments. Therefore linguistic variables and triangular fuzzy numbers are used for the preferences of one criterion over another. The comparison of the importance of one main attribute, sub-attribute and alternative over another is achieved by the help of the questionnaire.

In the first step, the decision maker compares the main attributes with respect to the overall goal which is “selection of the best supplier firm.” Based on the priority weights of the main attributes, product performance is found to be the most important attribute affecting decision-makers’ supplier selection. Supplier attribute is determined as the second important attribute.

In the second step, the decision maker compares the sub-attributes with respect to the main attributes. First the expert compares the sub-attributes of supplier attribute. Quality systems is found to be the most important sub-attribute with respect to supplier attribute. Capacity is the second most important sub-attribute. Then the expert compares the sub-attributes of product performance attribute. Product quality is found to be the most important sub-attribute with respect to product performance attribute. Product price is the second most important sub-attribute which shows that the manufacturer firm gives more importance to the quality of the material than its price. At the end, the expert compares the sub-attributes of service performance attribute. Service performance attribute has relatively less effect compared with others on the evaluation of the supplier. Lead time is determined as the most important sub-attribute with respect to service performance attribute. Technical support is the second most important sub-attribute.

In the third step, the expert compares the alternatives with respect to the fourteen sub-attributes.

In the last phase of the study, the priority weights for main attributes, sub-attributes and alternatives are combined to determine the priority weights of the alternative suppliers.

In order to shorten the solution process of the problem, macros in Excel are written to determine the priority weights of the alternatives. The priority weights of the alternative firms are calculated based on the questionnaire forms used to facilitate comparisons of main attributes, sub-attributes and alternatives. The priority weights of the alternative suppliers calculated by the macros in Excel can be seen in Table 5.9.

Table 5.9 Main-attributes of the goal

	Supplier	**Product Performance**	**Service Performance**	**Alternative priority weight**
Weight	0.33	0.45	0.22	
Alternative				
Supplier A	0.48	0.45	0.55	**0.48**
Supplier B	0.48	0.31	0.40	**0.39**
Supplier C	0.04	0.24	0.05	**0.13**

The priority weights for the alternative suppliers are found to be (0.48, 0.39, 0.13). According to the final score, Supplier A is the most preferred supplier because it has the highest priority weight and Supplier B is the next recommended alternative supplier.

The results obtained from the fuzzy AHP implementation are discussed with the expert from the Production Planning Department and they are found to be competent with the actual case. Since environmental factors which affect the performance of suppliers may change over time, the supplier evaluation should be considered a dynamic decision process and the whole evaluation process should be repeated over time. The desire of the company is to establish the long-term relationship with its suppliers and not to change the suppliers frequently.

The fuzzy analytic hierarchy approach (FAHP) presented in this study is proved to be simple and less time taking as compared to other existing decision making systems. The FAHP has the ability to capture the vagueness of human thinking style and effectively solve multi-attribute decision making problems.

During the supplier selection process, many qualitative and quantitative criteria are taken into consideration in order to be successful in supplier management. In this study, it is concluded that using linguistic variables to make the pairwise comparisons between attributes gives more accurate and practical solutions. Also the decision maker can make more accurate and easier pairwise comparisons by using linguistic variables such as “absolutely important”, “weakly important”, “equally important” and etc. Based on the thoughtfulness, flexibility and efficiency of the proposed approach, we can conclude that it can directly tap the subjectivity and preferences of the decision makers and thus give good results in the supplier evaluation and selection process.

In this study, macros in Excel are used to calculate the priority weights of the alternative firms. It has several advantages. The supplier selection problem can be solved in a shorter and more accurate way. It permits making hand-made errors while making the mathematical calculations. Also future changes in the preferences of the main attributes, sub-attributes or alternatives can be easily reflected on the priority weights of the alternatives without calculating all of the steps from the beginning once more.

There are many other methods to use in comparing supplier firms. These are multi-attribute evaluation methods such as ELECTRE, DEA and TOPSIS. These methods have been recently developed to use in a fuzzy environment. Future research of the FAHP application may be the application of these methods to the supplier selection problem and the comparison of the results.

Also this study can be extended to incorporate the supplier's capacity constraints in the supplier selection process. Thus an integrated AHP and mathematical programming model can be proposed to determine the best suppliers and the optimal order quantities from the chosen suppliers.

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APPENDIX A1

QUESTIONNAIRE FORMS USED TO FACILITATE COMPARISONS OF MAIN AND SUB-ATTRIBUTES

With respect to the overall goal "selection of the best supplier firm"

Q1. How important is *supplier* when it is compared with *product*?

Q2. How important is *supplier* when it is compared with *service*?

Q3. How important is *product* when it is compared with *service*?

Table A1.1 Questionnaire form used to facilitate comparisons of main attributes

With respect to: the Best supplier firm		**Importance (or preference) of one main-attribute over another**									
Questions	**Attributes**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Attributes**
Q1	**Supplier**						**X**				**Product**
Q2	**Supplier**				**X**						**Service**
Q3	**Product**			**X**							**Service**

With respect to the main attribute "supplier"

Q4. How important is *financial status* when it is compared with *management*?

Q5. How important is *financial status* when it is compared with *technical ability*?

Q6. How important is *financial status* when it is compared with *quality systems*?

Q7. How important is *financial status* when it is compared with *geographical location*?

Q8. How important is *financial status* when it is compared with *capacity*?

Q9. How important is *financial status* when it is compared with *working with Kanban approach*?

Q10. How important is *management* when it is compared with *technical ability*?

Q11. How important is *management* when it is compared with *quality systems*?

Q12. How important is *management* when it is compared with *geographical location*?

Q13. How important is *management* when it is compared with *capacity*?

Q14. How important is *management* when it is compared with *working with Kanban approach*?

Q15. How important is *technical ability* when it is compared with *quality systems*?

Q16. How important is *technical ability* when it is compared with *geographical location*?

Q17. How important is *technical ability* when it is compared with *capacity*?

Q18. How important is *technical ability* when it is compared with *working with Kanban approach*?

Q19. How important is *quality systems* when it is compared with *geographical location*?

Q20. How important is *quality systems* when it is compared with *capacity*?

Q21. How important is *quality systems* when it is compared with *working with Kanban approach*?

Q22. How important is *geographical location* when it is compared with *capacity*?

Q23. How important is *geographical location* when it is compared with *working with Kanban approach*?

Q24. How important is *capacity* when it is compared with *working with Kanban approach*?

Table A1.2 Questionnaire form used to facilitate comparisons of sub-attributes of supplier

With respect to: Supplier		Importance (or preference) of one sub-attribute over another									
Questions	Sub-attributes	Absolute	Very strong	Fairly Strong	Weak	Equal	Weak	Fairly Strong	Very strong	Absolute	Sub-attributes
Q4	Financial Status			X							Management
Q5	Financial Status						X				Technical Ability
Q6	Financial Status							X			Quality Systems
Q7	Financial Status				X						Geographical Location
Q8	Financial Status						X				Capacity
Q9	Financial Status			X							Kanban Approach
Q10	Management							X			Technical Ability
Q11	Management								X		Quality Systems
Q12	Management						X				Geographical Location
Q13	Management							X			Capacity
Q14	Management						X				Kanban Approach
Q15	Technical Ability						X				Quality Systems
Q16	Technical Ability			X							Geographical Location
Q17	Technical Ability						X				Capacity
Q18	Technical Ability			X							Kanban Approach
Q19	Quality Systems		X								Geographical Location
Q20	Quality Systems				X						Capacity
Q21	Quality Systems			X							Kanban Approach
Q22	Geographical Location							X			Capacity
Q23	Geographical Location				X						Kanban Approach
Q24	Capacity		X								Kanban Approach

With respect to the main attribute "product"

Q25. How important is *product price* when it is compared with *handling*?

Q26. How important is *product price* when it is compared with *product quality*?

Q27. How important is *handling* when it is compared with *product quality*?

Table A1.3 Questionnaire form used to facilitate comparisons of sub-attributes of product

With respect to: Product		Importance (or preference) of one sub-attribute over another									
Questions	**Sub-attributes**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Sub-attributes**
Q25	**Product Price**			X							**Handling**
Q26	**Product Price**							X			**Product Quality**
Q27	**Handling**								X		**Product Quality**

With respect to the main attribute "service"

Q28. How important is *follow-up* when it is compared with *technical support*?

Q29. How important is *follow-up* when it is compared with *lead time*?

Q30. How important is *follow-up* when it is compared with *professionalism*?

Q31. How important is *technical support* when it is compared with *lead time*?

Q32. How important is *technical support* when it is compared with *professionalism*?

Q33. How important is *lead time* when it is compared with *professionalism*?

Table A1.4 Questionnaire form used to facilitate comparisons of sub-attributes of service

With respect to: Service		**Importance (or preference) of one sub-attribute over another**									
Questions	**Sub-attributes**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Sub-attributes**
Q28	**Follow-up**							**X**			**Technical Support**
Q29	**Follow-up**								**X**		**Lead Time**
Q30	**Follow-up**						**X**				**Professionalism**
Q31	**Technical Support**							**X**			**Lead Time**
Q32	**Technical Support**				**X**						**Professionalism**
Q33	**Lead Time**			**X**							**Professionalism**

APPENDIX A2
QUESTIONNAIRE FORMS USED TO FACILITATE COMPARISONS OF ALTERNATIVES

With respect to the sub-attribute "financial status"

Q34. How important is *supplier A* when it is compared with *supplier B*?

Q35. How important is *supplier A* when it is compared with *supplier C*?

Q36. How important is *supplier B* when it is compared with *supplier* C?

Table A2.1 Questionnaire form used to facilitate comparison of alternatives with respect to financial status

With respect to: Financial status		**Importance (or preference) of one alternative over another**									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q34	**Supplier A**							**X**			**Supplier B**
Q35	**Supplier A**			**X**							**Supplier C**
Q36	**Supplier B**		**X**								**Supplier C**

With respect to the sub-attribute "management"

Q37. How important is *supplier A* when it is compared with *supplier B*?

Q38. How important is *supplier A* when it is compared with *supplier C*?

Q39. How important is *supplier B* when it is compared with *supplier* C?

Table A2.2 Questionnaire form used to facilitate comparison of alternatives with respect to management

With respect to: Management		**Importance (or preference) of one alternative over another**									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q37	**Supplier A**		**X**								**Supplier B**
Q38	**Supplier A**			**X**							**Supplier C**
Q39	**Supplier B**						**X**				**Supplier C**

With respect to the sub-attribute "technical ability"

Q40. How important is *supplier A* when it is compared with *supplier B*?

Q41. How important is *supplier A* when it is compared with *supplier C*?

Q42. How important is *supplier B* when it is compared with *supplier* C?

Table A2.3 Questionnaire form used to facilitate comparison of alternatives with respect to technical ability

With respect to: Technical ability		**Importance (or preference) of one alternative over another**									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q40	**Supplier A**				**X**						**Supplier B**
Q41	**Supplier A**		**X**								**Supplier C**
Q42	**Supplier B**			**X**							**Supplier C**

With respect to the sub-attribute "quality systems"

Q43. How important is *supplier A* when it is compared with *supplier B*?

Q44. How important is *supplier A* when it is compared with *supplier C*?

Q45. How important is *supplier B* when it is compared with *supplier* C?

Table A2.4 Questionnaire form used to facilitate comparison of alternatives with respect to quality systems

With respect to: Quality systems		**Importance (or preference) of one alternative over another**									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q43	**Supplier A**				**X**						**Supplier B**
Q44	**Supplier A**		**X**								**Supplier C**
Q45	**Supplier B**			**X**							**Supplier C**

With respect to the sub-attribute "geographical location"

Q46. How important is *supplier A* when it is compared with *supplier B*?

Q47. How important is *supplier A* when it is compared with *supplier C*?

Q48. How important is *supplier B* when it is compared with *supplier* C?

Table A2.5 Questionnaire form used to facilitate comparison of alternatives with respect to geographical location

With respect to: Geographical location		**Importance (or preference) of one alternative over another**									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q46	**Supplier A**					**X**					**Supplier B**
Q47	**Supplier A**								**X**		**Supplier C**
Q48	**Supplier B**								**X**		**Supplier C**

With respect to the sub-attribute "capacity"

Q49. How important is *supplier A* when it is compared with *supplier B*?

Q50. How important is *supplier A* when it is compared with *supplier C*?

Q51. How important is *supplier B* when it is compared with *supplier* C?

Table A2.6 Questionnaire form used to facilitate comparison of alternatives with respect to capacity

With respect to: Capacity		**Importance (or preference) of one alternative over another**									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q49	**Supplier A**				**X**						**Supplier B**
Q50	**Supplier A**		**X**								**Supplier C**
Q51	**Supplier B**			**X**							**Supplier C**

With respect to the sub-attribute "working with Kanban approach"

Q52. How important is *supplier A* when it is compared with *supplier B*?

Q53. How important is *supplier A* when it is compared with *supplier C*?

Q54. How important is *supplier B* when it is compared with *supplier* C?

Table A2.7 Questionnaire form used to facilitate comparison of alternatives with respect to working with Kanban approach

With respect to: Kanban approach		**Importance (or preference) of one alternative over another**									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q52	**Supplier A**				**X**						**Supplier B**
Q53	**Supplier A**						**X**				**Supplier C**
Q54	**Supplier B**							**X**			**Supplier C**

With respect to the sub-attribute "product price"

Q55. How important is *supplier A* when it is compared with *supplier B*?

Q56. How important is *supplier A* when it is compared with *supplier C*?

Q57. How important is *supplier B* when it is compared with *supplier* C?

Table A2.8 Questionnaire form used to facilitate comparison of alternatives with respect to product price

With respect to: Product price		**Importance (or preference) of one alternative over another**									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q55	**Supplier A**			X							**Supplier B**
Q56	**Supplier A**				X						**Supplier C**
Q57	**Supplier B**						X				**Supplier C**

With respect to the sub-attribute "handling"

Q58. How important is *supplier A* when it is compared with *supplier B*?

Q59. How important is *supplier A* when it is compared with *supplier C*?

Q60. How important is *supplier B* when it is compared with *supplier* C?

Table A2.9 Questionnaire form used to facilitate comparison of alternatives with respect to handling

With respect to: Handling		**Importance (or preference) of one alternative over another**									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q58	**Supplier A**				X						**Supplier B**
Q59	**Supplier A**		X								**Supplier C**
Q60	**Supplier B**			X							**Supplier C**

With respect to the sub-attribute "product quality"

Q61. How important is *supplier A* when it is compared with *supplier B*?

Q62. How important is *supplier A* when it is compared with *supplier C*?

Q63. How important is *supplier B* when it is compared with *supplier* C?

Table A2.10 Questionnaire form used to facilitate comparison of alternatives with respect to product quality

With respect to: Product quality		Importance (or preference) of one alternative over another									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q61	**Supplier A**				**X**						**Supplier B**
Q62	**Supplier A**			**X**							**Supplier C**
Q63	**Supplier B**				**X**						**Supplier C**

With respect to the sub-attribute "follow-up"

Q64. How important is *supplier A* when it is compared with *supplier B*?

Q65. How important is *supplier A* when it is compared with *supplier C*?

Q66. How important is *supplier B* when it is compared with *supplier* C?

Table A2.11 Questionnaire form used to facilitate comparison of alternatives with respect to follow-up

With respect to: Follow-up		Importance (or preference) of one alternative over another									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q64	**Supplier A**			**X**							**Supplier B**
Q65	**Supplier A**				**X**						**Supplier C**
Q66	**Supplier B**						**X**				**Supplier C**

With respect to the sub-attribute “technical support”

Q67. How important is *supplier A* when it is compared with *supplier B*?

Q68. How important is *supplier A* when it is compared with *supplier C*?

Q69. How important is *supplier B* when it is compared with *supplier* C?

Table A2.12 Questionnaire form used to facilitate comparison of alternatives with respect to technical support

With respect to: Technical support		Importance (or preference) of one alternative over another									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q67	**Supplier A**				**X**						**Supplier B**
Q68	**Supplier A**			**X**							**Supplier C**
Q69	**Supplier B**				**X**						**Supplier C**

With respect to the sub-attribute “lead time”

Q70. How important is *supplier A* when it is compared with *supplier B*?

Q71. How important is *supplier A* when it is compared with *supplier C*?

Q72. How important is *supplier B* when it is compared with *supplier* C?

Table A2.13 Questionnaire form used to facilitate comparison of alternatives with respect to lead time

With respect to: Lead time		Importance (or preference) of one alternative over another									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q70	**Supplier A**				**X**						**Supplier B**
Q71	**Supplier A**		**X**								**Supplier C**
Q72	**Supplier B**			**X**							**Supplier C**

With respect to the sub-attribute "professionalism"

Q73. How important is *supplier A* when it is compared with *supplier B*?

Q74. How important is *supplier A* when it is compared with *supplier C*?

Q75. How important is *supplier B* when it is compared with *supplier* C?

Table A2.14 Questionnaire form used to facilitate comparison of alternatives with respect to professionalism

With respect to: Professionalism		Importance (or preference) of one alternative over another									
Questions	**Aletrnatives**	**Absolute**	**Very strong**	**Fairly Strong**	**Weak**	**Equal**	**Weak**	**Fairly Strong**	**Very strong**	**Absolute**	**Aletrnatives**
Q73	**Supplier A**				**X**						**Supplier B**
Q74	**Supplier A**		**X**								**Supplier C**
Q75	**Supplier B**			**X**							**Supplier C**

APPENDIX A3

FUZZY EVALUATION MATRICES OF MAIN AND SUB-ATTRIBUTES WITH TRIANGULAR FUZZY NUMBERS

Table A3.1 Evaluation of the main attributes with respect to the goal

Main goal	Supplier	Product	Service
Supplier	(1, 1, 1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
Product	(2/3, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
Service	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(1, 1, 1)

Table A3.2 Evaluation of the sub-attributes with respect to product

Product	Product price	Handling	Product quality
Product price	(1, 1, 1)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Handling	(2/5, 1/2, 2/3)	(1, 1, 1)	(2/7, 1/3, 2/5)
Product quality	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(1, 1, 1)

Table A3.3 Evaluation of the sub-attributes with respect to service

Service	Follow-up	Technical support	Lead time	Professionalism
Follow-up	(1, 1, 1)	(2/5, 1/2, 2/3)	(2/7, 1/3, 2/5)	(2/3, 1, 3/2)
Technical support	(3/2, 2, 5/2)	(1, 1, 1)	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)
Lead time	(5/2, 3, 7/2)	(3/2, 2, 5/2)	(1, 1, 1)	(3/2, 2, 5/2)
Professionalism	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(1, 1, 1)

Table A3.4 Evaluation of the sub-attributes with respect to supplier

Supplier	Financial status	Management	Technical ability	Quality systems	Geographical location	Capacity	Kanban approach
Financial status	(1, 1, 1)	(3/2, 2, 5/2)	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(3/2, 2, 5/2)
Management	(2/5, 1/2, 2/3)	(1, 1, 1)	(2/5, 1/2, 2/3)	(2/7, 1/3, 2/5)	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)
Technical ability	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(1, 1, 1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(2/3, 1, 3/2)	(3/2, 2, 5/2)
Quality systems	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(2/3, 1, 3/2)	(1, 1, 1)	(5/2, 3, 7/2)	(2/3, 1, 3/2)	(3/2, 2, 5/2)
Geographical location	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(2/7, 1/3, 2/5)	(1, 1, 1)	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)
Capacity	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(1, 1, 1)	(5/2, 3, 7/2)
Kanban approach	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)	(2/7, 1/3, 2/5)	(1, 1, 1)

APPENDIX A4
FUZZY EVALUATION MATRICES OF ALTERNATIVES WITH TRIANGULAR FUZZY NUMBERS

Table A4.1 Evaluation of the alternatives with respect to financial status

Financial status	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/5, 1/2, 2/3)	(3/2, 2, 5/2)
Supplier B	(3/2, 2, 5/2)	(1, 1, 1)	(5/2, 3, 7/2)
Supplier C	(2/5, 1/2, 2/3)	(2/7, 1/3, 2/5)	(1, 1, 1)

Table A4.2 Evaluation of the alternatives with respect to management

Managament	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(5/2, 3, 7/2)	(3/2, 2, 5/2)
Supplier B	(2/7, 1/3, 2/5)	(1, 1, 1)	(2/3, 1, 3/2)
Supplier C	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)	(1, 1, 1)

Table A4.3 Evaluation of the alternatives with respect to technical ability

Technical ability	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/3, 1, 3/2)	(5/2, 3, 7/2)
Supplier B	(2/3, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
Supplier C	(2/7, 1/3, 2/5)	(2/5, 1/2, 2/3)	(1, 1, 1)

Table A4.4 Evaluation of the alternatives with respect to quality systems

Quality systems	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/3, 1, 3/2)	(5/2, 3, 7/2)
Supplier B	(2/3, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
Supplier C	(2/7, 1/3, 2/5)	(2/5, 1/2, 2/3)	(1, 1, 1)

Table A4.5 Evaluation of the alternatives with respect to geographical location

Geographical location	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(1, 1, 1)	(2/7, 1/3, 2/5)
Supplier B	(1, 1, 1)	(1, 1, 1)	(2/7, 1/3, 2/5)
Supplier C	(5/2, 3, 7/2)	(5/2, 3, 7/2)	(1, 1, 1)

Table A4.6 Evaluation of the alternatives with respect to capacity

Capacity	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/3, 1, 3/2)	(5/2, 3, 7/2)
Supplier B	(2/3, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
Supplier C	(2/7, 1/3, 2/5)	(2/5, 1/2, 2/3)	(1, 1, 1)

Table A4.7 Evaluation of the alternatives with respect to Kanban approach

Kanban approach	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
Supplier B	(2/3, 1, 3/2)	(1, 1, 1)	(2/5, 1/2, 2/3)
Supplier C	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(1, 1, 1)

Table A4.8 Evaluation of the alternatives with respect to product price

Product price	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(3/2, 2, 5/2)	(2/3, 1, 3/2)
Supplier B	(2/5, 1/2, 2/3)	(1, 1, 1)	(2/3, 1, 3/2)
Supplier C	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1, 1, 1)

Table A4.9 Evaluation of the alternatives with respect to handling

Handling	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/3, 1, 3/2)	(5/2, 3, 7/2)
Supplier B	(2/3, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
Supplier C	(2/7, 1/3, 2/5)	(2/5, 1/2, 2/3)	(1, 1, 1)

Table A4.10 Evaluation of the alternatives with respect to product quality

Product quality	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)
Supplier B	(2/3, 1, 3/2)	(1, 1, 1)	(2/3, 1, 3/2)
Supplier C	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)	(1, 1, 1)

Table A4.11 Evaluation of the alternatives with respect to follow-up

Follow-up	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(3/2, 2, 5/2)	(2/3, 1, 3/2)
Supplier B	(2/5, 1/2, 2/3)	(1, 1, 1)	(2/3, 1, 3/2)
Supplier C	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1, 1, 1)

Table A4.12 Evaluation of the alternatives with respect to technical support

Technical support	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)
Supplier B	(2/3, 1, 3/2)	(1, 1, 1)	(2/3, 1, 3/2)
Supplier C	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)	(1, 1, 1)

Table A4.13 Evaluation of the alternatives with respect to lead time

Lead time	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/3, 1, 3/2)	(5/2, 3, 7/2)
Supplier B	(2/3, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
Supplier C	(2/7, 1/3, 2/5)	(2/5, 1/2, 2/3)	(1, 1, 1)

Table A4.14 Evaluation of the alternatives with respect to professionalism

Professionalism	Supplier A	Supplier B	Supplier C
Supplier A	(1, 1, 1)	(2/3, 1, 3/2)	(5/2, 3, 7/2)
Supplier B	(2/3, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
Supplier C	(2/7, 1/3, 2/5)	(2/5, 1/2, 2/3)	(1, 1, 1)