KADIR HAS UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

A FUZZY BEST-WORST MULTI-CRITERIA DECISION-MAKING METHOD FOR THIRD PARTY LOGISTICS PROVIDER SELECTION

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A FUZZY BEST-WORST MULTI-CRITERIA DECISION-MAKING METHOD FOR THIRD-PARTY LOGISTICS PROVIDER SELECTION

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ABSTRACT

A FUZZY BEST-WORST MULTI-CRITERIA DECISION MAKING METHOD FOR THIRD-PARTY LOGISTICS PROVIDER SELECTION

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Master of Science in Industrial Engineering

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June, 2016

In recent years, the outsourcing of logistics functions to a third-party has been a major alternative to vertical integration. Third-party logistics provider can serve as a significant source of competitive advantage for firms aiming to focus on their core competencies. In selecting a strategic third-party logistics partner, there are many criteria and potential providers that must be carefully evaluated. Hence, third-party logistics provider selection is a multi-criteria decision-making problem; and it is extremely important that decision makers have a reliable decision support tool to select the best partner.

Several multi-criteria decision making methods have been proposed. Some of these methods like Analytical Hierarchy Process (AHP) and Analytic Network Process (ANP) require decision-makers to use pairwise comparisons in order to determine their preferences. However, due to the large number of criteria and potential providers associated with third-party logistics selection decision, these pairwise comparisons might lead to a reduction in the overall consistency.

This thesis addresses this issue by extending the newly proposed best-worst method to incorporate decision-makers' uncertainty and vagueness while requiring fewer comparisons as compared to a method like Fuzzy AHP. The aim of this thesis is twofold: first, a fuzzy best-worst multi-criteria decision-making method is proposed to handle the issue of larger number of comparisons and uncertainty in judgments. Secondly, the proposed method is applied to a third-party logistics selection problem at a medium-sized company in Turkey.

The results of the study show that the proposed method efficiently handles decision maker's inherent uncertainty while requiring fewer number of comparisons.

Keywords: Logistics service provider, Fuzzy best-worst method, Analytical Hierarchy Process.

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List of Abbreviations

3PL: Third-party logistics

MCDM: Multi-Criteria Decision Making

BWM: Best-Worst Method

DM: Decision Maker

CSCMP: Council of Supply Chain Management Professionals

AHP: Analytical Hierarchy Process

ANP: Analytic Network Process

TurkStat: Turkish Statistical Institute

LODER: Turkish Logistics Association

TL: Turkish Lira

UNECE: United Nations Economic Commission for Europe

CAGR: Compounded Annual Growth Rate

LPI: Logistics Performance Index

TurkLIM: Port Operators Association of Turkey

UBHD: Turkish Ministry of Transportation, Maritime, and Communications

ISPAT: Turkish Ministry of Investment Support and Promotion Agency

Chapter 1: Introduction

In recent years, there has been an increasing demand for improved logistics services. This is primary because, in order to be highly competitive, a firm must develop a distribution network that is efficient and responsive to demand from various customer segments of the market. Nowadays, most firms outsource their logistics activities to third party logistics providers (3PL) in order to concentrate on their competencies, reduce transportation-related costs, delivery times, share risks and gain some level of international competencies (Jharkharia and Shankar 2007). Hence, the logistics performance has a great impact on a firm's profit and competitive advantage; however, it is also a potential cause of bottleneck in a firm's overall supply network.

Selecting the best 3PL is an interesting and important decision that many firms face when they try to select a suitable supply chain configuration (Lieb and Kendrick 2002). In a study conducted by Sohail and Sohal (2003), it was found that 124 firms in Malaysia are satisfied with logistics outsourcing and have seen positive developments from their partnerships. Also, in a study by Zhang et al. (2012), it was found that only about 65% of firms believe that 3PL provider is actually making a significant contribution to their success while 55% of logistics contracts usually end in less than 5 years.

Like many other selection problems, 3PL selection problem involves decision maker(s), a set of criteria and a list of potential providers. Hence, a 3PL provider selection decision can be regarded as a multi-criteria decision-making problem (Güner 2005). Since there is no best approach to selecting a 3PL provider, firms use a variety of approaches and all aim at reducing risks and maximizing overall supply chain surplus.

In recent years, there has been an increased academic interest and publications in the area of 3PL and its selection approach. Berglund et al. (1999) defined 3PL as "*activities carried out by a logistics service provider on behalf of a shipper and as activities consisting of at least management and execution of transportation and warehousing (if warehousing is part of the process)*". Wang (2014) used china's economic data and built a regression model to analyze 4 economic effects of outsourcing. His results show that outsourcing has led to productivity, trade and innovation in China. Işıklar et al. (2007) developed an intelligent decision support system for effectively evaluating and selecting 3PL. Their framework combines case-based reasoning, rule-based reasoning and compromise programming in a fuzzy environment. Ghodsypour and O'Brien (1998) integrated 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. Their model can be applied to supplier selection with and without capacity constraints.

Efendigil et al. (2008) presented a method using a two-phase model based on artificial neural networks and fuzzy logic in a holistic manner to efficiently assist the decision makers in determining the most appropriate third-party reverse logistics provider.

Kahraman et al. (2003) used fuzzy AHP to select the best supplier firm providing the most satisfaction for a white good manufacturer in Turkey.

As seen in these research, there is no best way to evaluate and select a 3PL provider and in fact, it is almost impossible for a given 3PL to excel in all aspects. Due to the high importance attached to 3PL selection decision, firms usually have a list of criteria against which they evaluate potential 3PL providers. Some of these criteria are quantitative and others are qualitative. Some of the existing multi-criteria decision methods such as Analytical Hierarch Process (AHP) and Analytical Network Process (ANP) require decision maker(s) to use pairwise comparisons in order to determine the relative preferences of criterion over one another and also alternatives with respect to each criterion. Due to large numbers of criteria and alternative 3PL providers, there might be large number of pairwise comparisons, and this might lead to a reduction in the overall consistency.

Given these disadvantages, there is a need to develop a methodology that requires fewer comparisons while incorporating uncertainty and vagueness in the decision process.

This research aims to overcome these disadvantages by extending Rezaei (2015) Best-worst method to fuzzy Best-worst method. In summary, the research has two main objectives: To develop a fuzzy best-worst multi-criteria decision-making method and to apply the proposed method to a 3PL selection problem of a company in Turkey.

The rest of the thesis is organized as follows. In chapter 2, related literature is given, a discussion of logistics management, logistics outsourcing in Turkey and some recent publications on 3PL provider selection are presented.

In chapter 3, an overview of the multi-criteria decision making and best-worst multi-criteria decision-making method are presented, the fuzzy set theory and its associated operations are reviewed. The steps of the proposed fuzzy best-worst multi-criteria decision-making method are presented and consistency-related issues are discussed.

In Chapter 4, a case study related to 3PL selection at a medium-sized company in Turkey is presented along with results of the proposed fuzzy best-worst method.

Lastly, chapter 5 presents conclusions and suggestions for future research.

Chapter 2: Literature Review

2.1 Logistics Management

There have been some conflicting definitions of logistics management and in fact, it is sometimes referred to as physical distribution, industrial logistics, supply chain management, channel management, and material management (Coyle et al. 2003). However, one definition proposed by the Council of Supply Chain Management Professionals (CSCMP) has been widely used in many studies (Mentzer et al. 2001; Ayers 2006). They defined logistics management as "*Logistics management is that part of the supply chain that plans, implements, controls, the efficient, effective forward and reverse flows and storage of goods, services, and related information between the point of origin to the point of consumption in order to meet customer's requirements"* (CSCMP, 2009).

Logistics describes the entire process of materials or products moving in and out of a firm. Inbound logistics covers the movement of material received from suppliers. Materials management describes the movement of materials and components within a firm. Physical distribution refers to the movement of goods outward from the end of the assembly line to the customer. Supply chain management is somewhat larger than logistics, and it links logistics more directly with the user's total communications network and with the firm's engineering staff (Tilanus 1997).

The main aim of logistics management is to provide a high level of responsiveness to customers through the management of materials and information flows in the supply chain. Figure 2.1 shows an overview of the logistics system. Logistics services, information systems, and infrastructure/resources are the key components of the logistics system and they are closely linked. These three main components interact to generate value in the supply chain. Logistics services support the movement of materials and products from inputs through production to consumers, as well as associated waste disposal and reverse flows.

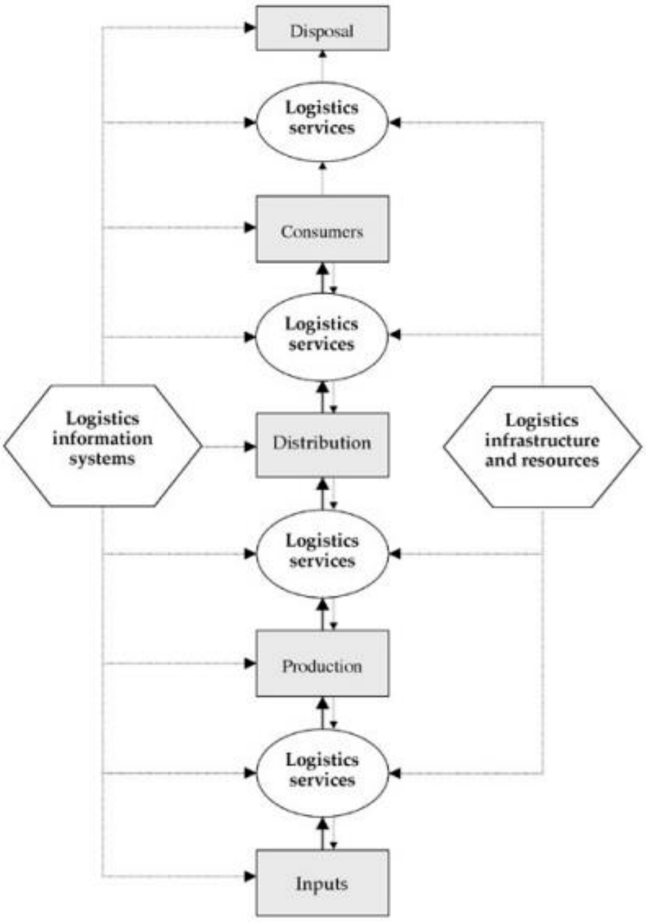

Figure 2.1: An overview of a logistics system (BTRE 2001)

Unlike supply chain, logistics focuses mainly on the flow of services or physical goods from their origin to where they are finally discarded (Stock & Lambert 2001). According to Bowersox et al. (2007), logistics management is the work required to move and position inventory throughout the supply chain.

It serves as a means of integrating other aspects such as order management, inventory, transportation, warehousing, packaging, and material handling; all of which can serve as a potential source of competitive advantage for a firm if properly coordinated (Tan 2001). This integration can serve as a link and synchronize the whole supply chain as a continuous process (Bowersox et al. 2007). Hence, the logistics performance can be regarded as a source of supply chain surplus and competitive advantage for a firm. For example, a company aiming to improve its responsiveness to customers and shareholders has to turn to its logistics activities in order to achieve this goal.

Logistics activities also directly impact customers' satisfaction and thus, affecting overall revenue generated. Sales of goods cannot be achieved if they cannot be delivered to customers at the right time, at the right place and in the right quantity. Without an effective and smooth logistics system, all economic activities in a firm suffer significantly (Lambert et al. 1998).

2.2 An overview of Turkey's Logistics Industry

Being one of the vibrant economies of developing countries, Turkey has been a key player in logistics activities between the east and the west, serving as a junction between the continents of Asia and Europe. According to the Turkish Statistical Institute (TurkStat), the strategic location of Turkey provides access to multiple markets with 1.6 billion people, a combined GDP of USD 27 trillion and more than USD 8 trillion of foreign trade which corresponds to around half of the total global trade. Over the past decades, trade in Turkey has been rising significantly and the region has a huge presence in global trade primarily because of its strategic location. In 2014, almost 1.1% of the global trade volume was conducted by Turkey, and the country's share in global trade is expected to exceed 1.5% by 2025 (TurkStat).

According to the Turkish Logistics Association (LODER), the current size of Turkey's logistics industry can be estimated at USD 80-100 billion and is forecasted to reach USD 108-140 billion by 2017; and global logistics players such as DP World and APM terminals currently operates in Turkey and other top players are keen to invest in Turkey because of the growth potential within the Turkish economy and its proximity to Europe and Asia.

In addition to its faster-growing economy, Turkey's young labor pools contribute to growth in its logistics industry. Turkey has one of the largest and youngest labour pools in Europe with more than 65% of its population aged between 24 and 54; with minimum wage set slightly below €500 (Transportation and Logistics Industry Report 2003).

The logistics industry has been significantly improved by both public and private infrastructure investments. As shown in Figure 2.2, Turkey is currently a key player in road logistics, air logistics, rail logistics, maritime logistics and multi-modal logistics. The Turkish government has set challenging targets to be achieved by 2023 for improving the logistics infrastructure even more (Investment Support and Promotion Agency of Turkey 2014). Some of these targets include:

- Building an additional 15,000 km of dual carriageways and highways.
- Increasing the shares of railway transportation to 10% and 15% in passenger and freight transportation respectively.
- Building an additional 9,000 km of high-speed train lines.

- Constructing new airports with a total annual capacity of 400 million passengers.
- Increasing the share of sea freight transportation to 10% in total freight transportation and containerization by 15%.
- Building three large ports in each sea surrounding Turkey.

Construction of logistics centers/villages is currently being carried out and it will serve to lower the costs of transportation by offering various different modes of transportation within these centers/villages. It is estimated that, by 2023, the total freight carried in the centers/villages will reach a total of USD 500 billion (UDHB).

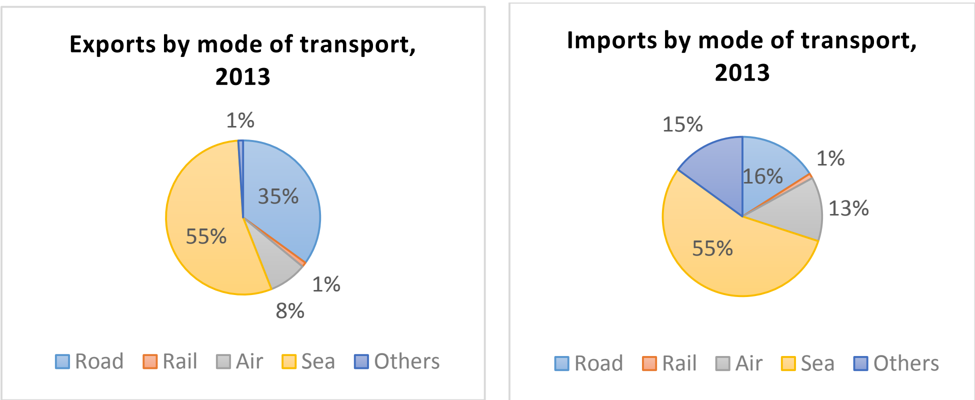

Figure 2.2: Modes of transport in Turkey's logistics industry (TurkStat)

2.2.1 Road Logistics

Since the 1950's, there has been a significant development in Turkey's road network and now, it is considered the most used mode of transportation. Since 2010, 91.7% of passenger and 89.4% of freight are transported by road (TurkStat).

Due to Turkey’s developed road network, cargo handling and transport has been in expansion. The growth of freight and passenger transported via road has been impressive. The tons-km and passenger-km grew with a compound annual growth rate of 3.57% and 4.36%, respectively from 2007 to 2012. As shown in Figure 2.3, the total freight value in net foreign trade transported via roadways in Turkey in recent years has been relatively high. Over the medium term, the freight carried via roadways is expected to continue its growth with a compound annual growth rate of 3% and reach 251.7 million tons-km (UDHB).

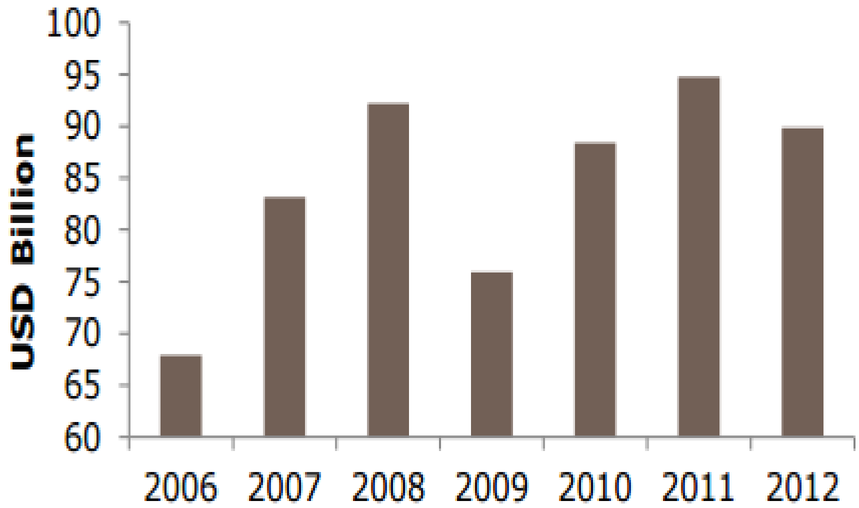

Figure 2.3: Total freight value in net foreign trade transported via roadways in Turkey from 2006-2012 (Turkstat).

Moreover, Turkish freight transportation trucks increased from over 929,000 in 2009 to more than 1.1 million in 2012, indicating a 28% increase. Total freight transportation number via road by both Turkish and foreign trucks exceeded 1.5 million in exports and 500,000 in imports. Turkish trucks had a share of 80% in total exports while 70% in total imports (TurkStat). As shown in Table 2.1, some of the key players in Turkey’s road logistics have experienced a tremendous success of the past few years.

Table 2.1: Key players in Turkey's road logistics (Fortune 500 Turkey)

	Overview	Total Revenue in 2011
Omsan Logistics	Founded in 1978, Omsan Logistics headquarter is located in Istanbul. The company is a member of the International Air Transport Association and the International Federation of Freight Forwarders.	TL 530 Million
Ekol Logistics	With headquarter in Istanbul, Ekol Logistics has a combined structure that offers 3PL integrated logistics services globally. Ekol Logistics offers customized solutions tailored specifically for its customers' varied needs.	TL 509 Million
Netlog Logistics	The company employs 3,500 people, owns 2,000 vehicles, 51 storage areas, 12 companies and has transported 4 million tons of freight in 2010. It provides supply chain management, storage and international freight services for textile, automotive, dry food, pharmaceutical and construction industries.	TL 670 Million
Reysaş Transport and Logistics	Founded in 1989, Reysaş Transport and Logistics recently moved their official headquarters from Ankara to Istanbul. The company carries on its operation with more than 1,500 vehicles, both domestically and internationally.	TL 436 Million

As Turkey's growth in the industry becomes more evident, the road network will continue to improve, as well. According to the Ministry of Transport, Maritime Affairs, and Communication, as of 2013, there is 2,127 km of motorways; 31,375 km of state highways and 31,880 km of provincial roads that add up to a total of 65,382 km of road network.

There are bilateral highway transportation agreements with 58 countries from regions that include Europe, the Middle East, and Africa. According to the Ministry of Transport, Maritime Affairs, and Communications, these agreements have enabled transporters to have more business and increased the volume transfers between countries. It is estimated that 50% of the total world trade will be handled around regions neighbouring Turkey and Turkey's export volume is expected to reach USD 1.2 trillion by 2023. The road network in Turkey would be able to meet this rapid growth in freight traffic both within Turkey and in international freight traffic that passes through the country (UDHB).

Currently there is more than 2,100 km of operating motorways. There is an excess of 513 km of ongoing construction. It has been projected that 4,130 km of new motorways will be built by 2035.

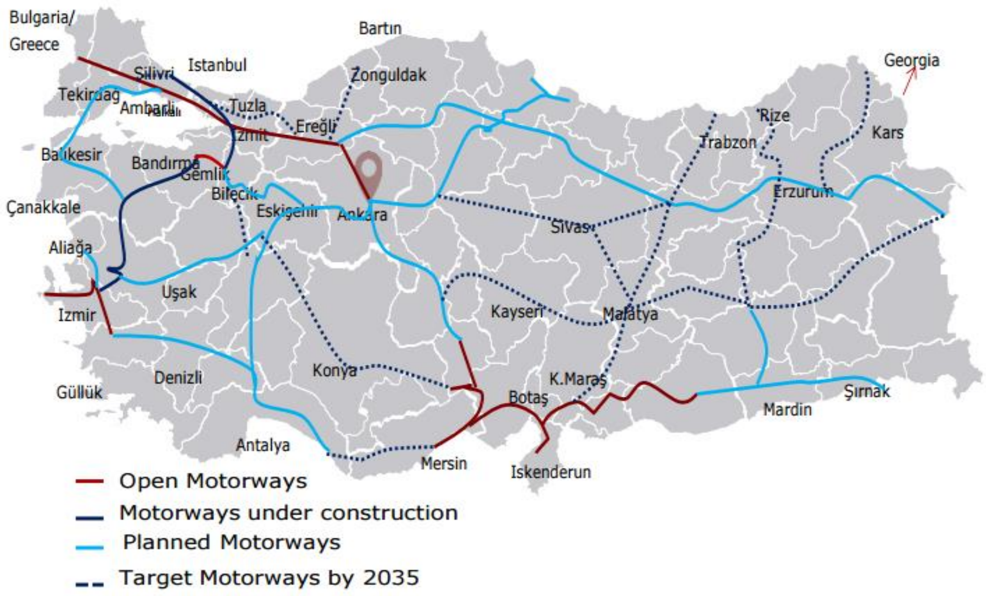

Figure 2.4: The 2023 and 2035 Targets for Turkey’s highway network (UNECE).

Turkey’s major international highways are given in the Table 2.2.

Table 2.2: Turkey’s major international highways (UDHB; UNECE).

International E-ways Network	The E-ways network was started by Agreement on main Traffic Arteries and United Nations Economic Commission for Europe after World War II. There are two main roads that interconnect Turkey with Europe. They are E-80 from the Bulgarian border and E-90 from the Greek border. Turkey provides connection to Asia and the Middle East through its southern and eastern borders. The total length of E-ways is 9,361 kilometers.
Trans-Europe North-South Motorway (TEM)	TEM is the oldest and most developed project in Europe’s transportation history. There are 15 members and 4 observer countries that are part of this project. Turkey connects Europe to Asia and the Middle East with TEM roads. The total length of TEM roads is 6,970 kilometers.
Trans-Eurasia Highways (EATL)	The project EATL plans to connect PanEurope corridors with the main regions of Asia. Turkey’s EATL roadway covers a distance of 5,663 kilometers. Moreover, 208 kilometers to the Filyos and Çandarlı port will connect to the EATL.

2.2.2 Maritime Logistics

Located between Europe and Asia, Turkey’s location enables its ports to handle a huge amount of cargo. The coastal borders of Turkey measures about 8,400 km; and the country attaches great importance to its maritime sector. As shown in Figure 2.2, maritime transportation is the most preferred method of transportation both in Turkey’s exports and imports, with respective shares of 55% and 55% in total. About 85% of the volume of Turkey’s foreign trade transportation has been carried by sea. The amount of cargo handled in Turkish ports was 183.86 million tons in 2004, whereas it reached 348.69 million tons in 2010 with an increase of 69% (Maritime Trade Statistics Report, 2013).

According to the Ministry of Transport, Maritime Affairs, and Communications, about 385 million tons of cargo was handled in Turkish ports in 2013 and the percentages of each cargo type are shown in Figure 2.5 below.

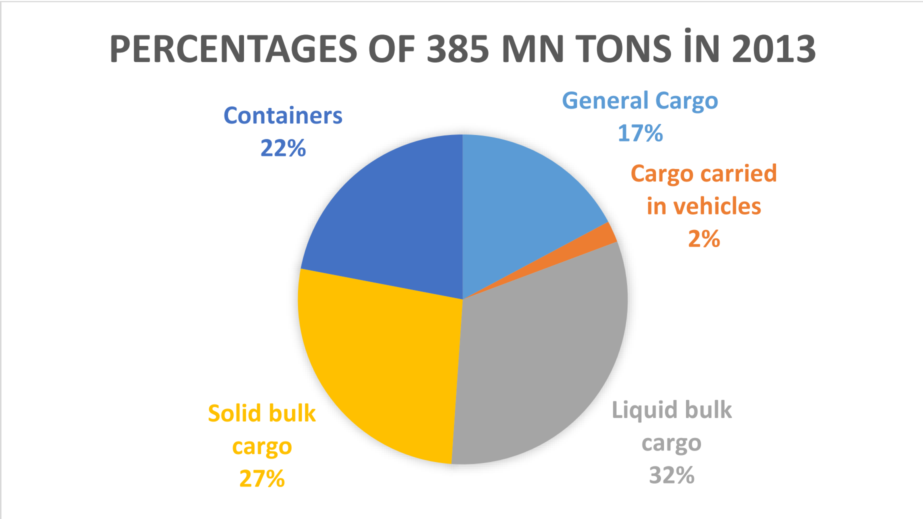

Figure 2.5**:** Freight handling in ports as per type (Percentage of 385 tons).

Turkish ports can handle a variety of cargo, including bulk cargo, general cargo, containers and liquid bulk cargo. The majority of cargo handled was liquid cargo with more than 120 million tons in 2013, followed by solid bulk cargo in excess of 100 million tons, during the same period (Maritime Trade Statistics Report, 2013).

Currently, there are more than 50 ports in Turkey and they are structured in order to serve multiple types of loads (Türklim, 2013). In 2012, containers held in Türklim ports, which are the ports that are members of the Port Operators Association of Turkey, constituted the major share with 87% of total traffic. Total traffic in ports increased at a compounded annual growth rate of 11% from 2004 to 2012. During the same period, traffic in Türklim ports increased at a compounded annual growth rate of 16%. There are 60 customs directorates for sea border crossings, of which 14 directorates are temporary (Türklim, 2013).

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Table 2.3: Major players in Turkey's maritime logistics
(Source: Arkas Holding, Maersk, and Emerging Markets Insight)

Arkas Holding	Arkas Holding operates in many different fields including logistic services that integrate, sea, land, rail and air. Currently, Arkas has a total of 50 offices globally, 13 of which are in Turkey. Arkas is one of the leading companies in the Turkish shipping and logistics sector and is ranked 23rd of Turkey's Most Valuable Brands at a value of USD 347 million.
Maersk Denizcilik	Maersk Line is a division of A.P Moller – Maersk Group and is dedicated to reliable sea and ocean transportation. It is the world's largest container shipping company with over 600 container ships and 3.8 million 20 foot equivalent unit containers. Maersk Denizcilik, which is a division of Maersk Line, opened in Turkey in 2001.

2.2.3 Air Logistics

There have been tremendous developments in Turkey’s civil aviation sector during the last decade. In recent years, the sector has grown ten times faster than the world average. Total air traffic growth expected for Turkey in the reports of international civil aviation organizations like European Organization for the Safety of Air Navigation (EUROCONTROL) and International Air Transport Association (IATA) for 2015 was already reached in 2005; that is, 10 years before the anticipated year. Main causes of this development are liberalization of the sector and economic growth in Turkey (UDHB).

The total air transport market size increased at a compounded annual growth rate of 14% from 2006 to 2011 and reached a value of more than USD 8.8 billion by 2011. The sector has provided about 40,000 new jobs from 2006 to 2011. Currently, there are more than 80 companies actively involved in the air transport sector and even with the increasing cost pressure due to high jet fuel prices, profit margins were stable and reached 13%, in 2011 (Euromonitor International, 2013).

According to Euromonitor International, the air industry will continue to expand at an annual rate of 13% from 2012 to 2017.

As more airports open and existing airport capacities increase, freight carried via air will increase. Future air freight trends also point towards larger growth in this mode of transportation. Air freight industry is expected to continue to grow at a compounded annual growth rate of 9.4% from 2012 to 2016, reaching a total of 3.2 million tons (TAV Airports, Ministry of Customs and

Trade). Some of the major players in Turkey air logistics industry are shown in Table 2.4.

Table 2.4: Major players in Turkey's air logistics

(Source: THY, Pegasus, MNG, Airbus, and Boeing)

Turkish Airlines	Turkish Airlines is the 4th biggest airline company in the world in terms of a number of destinations, flying to over 180 countries. Turkish Airlines made **USD 9 billion** in revenue in 2012.
Pegasus Airlines	Pegasus Airlines was founded in 1990 through the partnership of three different companies. Currently, it has an operating fleet of 42 airplanes and has ordered 75 airbus aircrafts with an option to add 25 more aircraft for **USD 12 billion**.
MNG Airlines	MNG Airlines was founded in 1996 as a subsidiary of MNG Holding. Total freight capacity of the company is 350 million tons and a total revenue of MNG Airlines in 2012 was **USD 100 million**. It has a fleet of 11 aircrafts.

2.3 Outsourcing

Back to the 1970s, outsourcing was initially only involved IT-related issues, but gradually moved on to include other aspects because firms realized that they cannot be experts in more than one or two fields. This conclusion made them get rid of various areas of activity and entrust them to parties. In a survey by Fortune magazine, over 90% of business organizations use external service providers. Initially, outsourcing was mainly used by large companies but as time went by, it has now become a common activity among both large and small enterprises. The large use of outsourcing in the today's markets results from the increased competition among firms, and progressing globalization (Lewin and Johnston 1996).

Outsourcing can generally be regarded as the utilization of external resources. It occurs when tasks, functions or other in-house processes are commissioned to other external providers specializing in a given area on the basis of long-term cooperation. Quelin and Duhamel (2003) defined outsourcing as "*the operation of dedicating a transaction previously governed internally to an external supplier through a contract, and involving the transfer of staff to the vendor for the firm*". According to their definition, strategic outsourcing is characterized by 5 elements:

- A close link between outsourcing processes and the key success factors of a firm.
- The transfer of ownership of a business function previously internalized, often including a transfer of personnel and/or physical assets to the service provider.
- A global contract, longer and higher than a classical subcontracting agreement.
- A long-term commitment between the client and the service provider.
- A contractual definition of service levels and each partner's obligations.

Outsourcing has become a common activity in many industries, most particularly in logistics and supply chain management (Feeney *et al.* 2005). The overall scope of outsourcing is growing continuously, as companies focus on their core competencies and shed tasks perceived as non-core (Lindner 2004). For example, a recent study show that the outsourcing of human resources functions is widespread, with 94% of firms outsourcing at least one major human resource activity, and the majority of firms planning for outsourcing expansion

(Gurchiek 2005). Research assessing the outsourcing of sales, marketing and administrative functions provides similar results, with at least portions of these functions now being outsourced in 15–50 percent of sampled firms (The Outsourcing Institute 2005).

Poor outsourcing practices can also lead to an unintended loss and managers are increasingly feeling pressure to make the right sourcing decision, as the business consequences can be significant (McGovern and Quelch 2005). Good outsourcing decisions can result in lowered costs and competitive advantage, whereas poorly made outsourcing decisions can lead to a variety of problems, such as increased costs, disrupted service and even business failure (Cross 1995). Making the right outsourcing decision requires a clear understanding of the broad array of potential engagement options, risks and benefits, and the appropriateness of each potential arrangement for meeting business objectives.

2.3.1 Logistics Outsourcing

Logistics outsourcing have been in practice for many centuries and in Europe, the origin of some logistics service providers can be traced back to the middle age (Lynch 2000). There has been a significant transformation in international businesses and all firms are looking for potential sources of competitive advantage. The world's trading patterns and physical trade flows are now greatly shaped by trends towards globalization, integrated logistics and the development of Information and Communication Technology (Ronald 1992).

According to a study by Abdur Razzaque and Sheng (1998), a firm can choose between three different options when determining how to effectively and efficiently manage its logistics activities. According to them, these options are:

- Provide the service in-house by making the service.
- Setup a logistics subsidiary or buy a logistics firm.
- Outsource the service and then buy the service from an external provider.

There has been a growing interest in the last option – outsourcing logistics. About 80% of the Fortune 500 companies used third-party logistics services and there is an increasing trend of their logistics operating budgets to 3PL providers (Lieb and Kendrick 2002). Over the past decades, the issue of logistics outsourcing has received considerable attention (Abdur Razzaque and Sheng 1998; Bolumole 2001; Cai et al. 2013; Yang et al. 2016a). Lambert et al. (1999) proposed a more general definition of logistics outsourcing. They defined it as "*the use of a third-party provider for all or part of an organization's logistics operations"*. Most firms utilize their resources focusing on their core competencies that are what they do best, that cannot be easily imitated by other organizations, on the original work and/or work methods. Thus, they have the business or activities other than basic skills done by firms that are experts in the field, the core competence of the business or activity. Table 2.5 shows some of the services provided by 3PLs.

Table 2.5: Services provided by third-party logistics (Rocheleau 2016)

SERVICE CATEGORY	BASIC SERVICE	SOME SPECIFIC VALUE-ADDED SERVICES
Transportation	Inbound, outbound by ship, truck, rail, air.	Tendering, dispatch, freight pay, and contract management.
Warehousing	Storage, facility management.	Cross-dock, in-transit merge, pick/pack, inventory control, and order fulfillment.
Information Technology	Provide and maintain advanced information systems.	Transportation management systems, network modeling and site selection, EDI, and forecasting.
Reverse Logistics	Handle reverse flows	Recycling, customer returns, repair/refurbishment.
Other 3PL Services		Freight forward, purchase order management, and order tracking.
International		Customs brokering, port services, export crating, and consolidation.
Special skills/handling		Parcel/package delivery, temperature controlled, and hazardous materials.

The increasing global markets and the sourcing of parts and/or materials from various countries have led to an increased surge for logistics function (Cooper 1993) and a more sophisticated supply chain (Bradley 1994). The lack of specific skills and infrastructure in such a competitive global market forces firms to turn to the competence of logistics service providers. In recent years, logistics outsourcing has increased rapidly as firms have realized that utilization of third-party logistics provider reduces logistics cost and increases the quality of service. According to the 2016 Third-Party Logistics study, 93% the firms believe their relationships with 3PLs providers have generally been successful; 83% believe the use of 3PLs provider has contributed to improving service to their customers; 75% believe 3PLs has provided new and innovative ways to improve logistics effectiveness; 70% believe the use of 3PLs has contributed to reducing their overall logistics costs; and 73% promise to increasing their use of outsourced logistics services. These findings are indications that logistics outsourcing has become a major source of competitive advantage and as a result, most firms are turning towards it. Wallenberg (2004) and Chopra and Meindl (2007) proposed five points that must be considered by every firm before outsourcing their logistics function. They are:

- Which logistics function to outsource?
- Which third-party will provide the service?
- Will the third-party increase the supply chain surplus relative to performing the activity in-house?
- How much of the supply chain surplus does the third-party get to keep?
- What risks are associated with outsourcing?

2.3.2 Issues Associated with Logistics Outsourcing

According to Chopra and Meindl (2007), three main factors affect the ability of a 3PL to add value to a firm's supply chain. According to them, these factors are scale, uncertainty, and specificity of the assets. When the volume of items is very large, it is likely that the firm can achieve sufficient economies of scale internally. In this case, it is unlikely that the use of 3PL will increase supply chain surplus. Secondly, if the needs of a firm are predictable, there is a limited possibility of increased surplus from a 3PL; and if the needs are uncertain, the 3PL can increase the supply chain surplus through aggregation with other customers if all firms are aware of this action. Lastly, the value added by a 3PL depends on the specificity of a firm's assets; if the assets are specific to a given firm and cannot be combined with others, the 3PL is unlikely to increase surplus because it simply moves assets from one point to another and has no opportunity to aggregate across other customers. As these factor show, a firm gains the most by outsourcing to a 3PL if its needs are small, highly uncertain, and shared by other firms sourcing from the same 3PL.

The aim of using 3PL is to increase the supply chain surplus while providing maximum service level. Determining a suitable 3PL provider depends on the resources/assets of the firm and the trade-off between the advantages and disadvantages generally associated with using 3PL. As Chopra and Meindl (2007) pointed out, these issues are inherently different for various firms. Nevertheless, there are some advantages and disadvantages generally associated with 3PL that most firms, regardless of their nature, must consider when making a selection. These advantages and disadvantages are discussed in subsequent sections.

2.3.2.1 Advantages of Outsourcing Logistics

A firm can either keep it logistics functions in-house or outsource them to an external firm. The goal is to choose an option that will add value to the supply chain. A vast amount of researchers found reasons why most firms prefer to outsource their logistics function rather than performing it in-house (Sohail and Sohal 2003; Aktas and Ulengin 2005; Wallenburg 2004; Cakir 2009). Some of the advantages are:

- **Focus on core competencies:** one of the major reasons most firms are willing to outsource their logistics functions is to be able to focus on their competencies. A firm cannot be an expert in all aspects; and by outsourcing its logistics function to a third-party, it can focus on its expertise – which distinguishes it from other competitors and gives more customers' satisfaction (Simchi-Levi 2005). According to a study by Wilding and Juriado (2004), 50% of 3PL users in the European consumer goods industry indicated that a focus on core competence was very important.

- **Saved time and lower cost:** outsourcing logistics saves a lot of money for many firms. Using a 3PL provider eliminates the need to invest in warehouse space, technology, transportation, and staff to execute the logistics processes (Mentzer et al. 2006; Aktas and Ulengin 2005). A study by Lieb et al. (1993) indicated that current 3PL users had lowered cost up to 30-40% and western European firms have achieved more positive result regarding logistics costs.
- **Improving customer service:** several research point out that one of the reasons for using 3PL service is to improve customers' service in terms of responsiveness. In Singapore, 76.1% of respondents see customer's service as a major reason to outsource logistics (Bhatnagar et al.1999). According to the 2016 Third-Party Logistics Study, 3PL has contributed to improved customer service for 83% of the firms. Because most firms don't have the capacity to provide customers higher responsiveness, they rely on the competence of 3PL to achieve this goal.
- **Improving logistics process:** as a business of its own, 3PL providers have both the expertise and resources to properly handle logistics activities. They generally have the ability to respond to logistical changes/disruptions quickly, which leads to fast delivery and less harm to the supply chain (Byrne 1993). In fact, most 3PL providers have good processes and

technical knowledge that help reduce the risk in the supply chain (Mentzer et al. 2006).

- **Market expansion:** According to Bagchi and Virum (1996), firms can get access to unfamiliar international markets through 3PL providers. Most firms lack specific knowledge of customs, tax regulations and infrastructures of destination countries; and as such, rely on the expertise of 3PL providers. In a study, 40% of Indian firms indicated that their primary goal for using 3PL provider was to gain shares in unfamiliar markets (Sahay and Mohan 2006).
- **Increase inventory turnover:** generally, 3PLproviders help optimize operational activities. They help reduce order cycle times, inventory levels, lead times, and obviously higher customer service (Bhatnagar and Viswanathan 2000). In the study by Sahay and Mohan (2006), 60.6% of Indian 3PL users indicated productivity improvement as the reason for using 3PL.

2.3.2.2 Disadvantages of Outsourcing Logistics

Despite the numerous advantages of outsourcing logistics, there are some potential risks that firms must evaluate when moving logistics function to a third-party. These logistics outsourcing disadvantages have been mentioned in numerous publications and some are discussed below:

- **Loss of control over logistics function:** when logistics functions are outsourced to a third-party, the ability of a firm to control the logistics activities decreases and it becomes difficult to track performance matrices. (Byrne 1993; Lieb and Randall 1996; Sanders et al. 2007).

- **Lack of shared goals:** lack of shared goals in 3PL partnership can be a source of significant problems for both the firm and the 3PL provider (Tsai et al. 2008). This lack of shared goal may result from differences in business visions, styles, and protocol between the two parties (Tsai et al. 2008).
- **Reduced customer/supplier contact:** a firm may lose customer/supplier contact by introducing an intermediary. This loss of contact is important for firms that initially sold directly to customers but then decides to use a third-party to collect orders or deliver out-going shipments (Chopra and Meindl 2007).
- **Uncertainty in service provided:** a study by Lau and Zhang (2006) showed that most 3PL users are uncertain about the level of service they provide to their customers. There is uncertainty about whether 3PLs are capable of meeting user's expectations.

2.3.3 Logistics Outsourcing in Turkey

As seen in section 2.2, the high growth rates in Turkey's logistics industry has attracted global logistics companies. All of the top global logistics companies such as DHL, FedEx, UPS, and TNT are presently operating in Turkey. In a study by Büyüközkan et al. (2008), it was found that in 2006, logistics sector amounted for about $50 billion markets in Turkey. As shown in figure 2.2, road transport is the second larger means of export in Turkey; and there are about 40,000 trucks; thereby giving Turkey the largest fleet in Europe.

According to ISPAT, the logistics industry is an integral portion of Turkey's economy. The Turkey logistics sector's value in 2008 was 60 billion

USD. The current size of 3PL service providers is 22 billion USD. Turkey's current logistics industry size is estimated to be USD 80–100 billion and is forecasted to reach USD 108–140 billion by 2017. The average growth in the fields of transportation, storage, and communication was 6.4% between 2003 and 2013 (LODER).

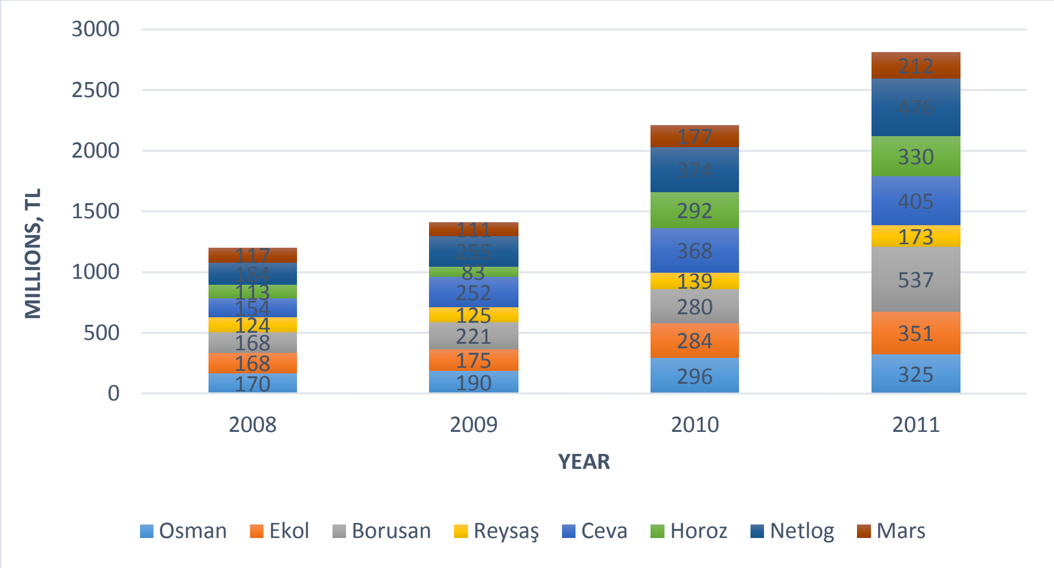

Figure 2.6: Revenues of the major Turkish 3PL firms from 2009-2012 (ISPAT).

As shown in Figure 2.6, most Turkish 3PL companies have experienced huge success over the past few years. There are a large number of logistics provider firms in Turkey, some of which are newly founded small and medium-sized firms with a transportation background. The most important Turkish logistics service providers are Arkas Denizcilik, Omsan, Barsan, Reysas, Borusan, Balnak, Turksped, and Horoz Lojistik. Rapidly growing trade with Turkey has created a promising perspective for the logistics sector, and it is expected to grow in incoming years. Therefore, international logistics companies are increasing their presence in the country (DHL, Logistics in Turkey).

The total revenues of these companies grew with a stunning CAGR of 21% from 2008 to 2012. This shows that the 3PL market is highly profitable and has a significant impact on the country's logistics industry.

According to Logistics Performance Index (LPI) prepared by World Bank, Turkey is ranked 27th with 3.22 point. Turkey moved up from 39th place in 2010 to 27th in 2013, out of the 155 countries in the index. Moreover, it is ranked third in the top 10 upper middle income performing countries (Turkish Customs and Trade Ministry). According to the Emerging Markets Logistics Index prepared by Transport Intelligence, Turkey ranked 11th best country in logistics out of 41 emerging markets (Turkish Customs and Trade Ministry).

2.4 Third-Party Logistics Provider Selection

Through a strategic partnership, firms can combine their respective resources and strengths to achieve their competitive goals, share risks, lower costs, and gain access to more market shares (Carayannis et al. 2000). In recent years, there has been an increased number of partnerships between firms; and one type of such partnerships is 3PL service (Mehta et al. 2006). A 3PL provider may provide the entire logistics functions or some part of it depending on the agreement between both parties. According to Ballou (1999), the importance of partnership between a 3PL provider and a firm depends on the following factors:

- Whether or not the use of the 3PL provider's resources and capability to reduce overall logistics costs.
- Whether using the 3PL provider's capability and agility will improve overall efficiency and customer services.

- Whether or not reducing or avoiding the investment/establishment of a firm's logistics will give more chance to improve its core competencies.

As these show, the evaluation and subsequent selection of a 3PL partner in a logistics value chain has an important strategic outcome to a firm to achieve a higher competitive advantage. Despite the popular nature of partnerships, most businesses fail (Lee and Cavusgil 2006); and the frequently mentioned reason for sure failure is incompatibility of partners.

Choosing the right partners can lead to a significant competitive benefit; whereas failure to establish compatible interests and effective communications can lead to a serious problem. Hence, finding the right partner is an important decision with both quantitative and qualitative data, and requires time. For this reason, one of the aims of this thesis is to propose an easy analytical approach to effectively select such strategic partner for the 3PL relationship.

This problem is MCDM problem by nature since it includes many quantitative and qualitative criteria. Also due to the vagueness in judgements and preferences, it is a fuzzy MCDM problem.

2.4.1 Previous Studies on 3PL Selection

The issue of selecting a perfect 3PL partner has been of great interest to many firms in recent decades and therefore, the MCDM problem has received a lot of attention recently. In the literature, a variety number of techniques are used to evaluate 3PL performance and some MCDM methods are used to select 3PL service provider.

In a recent study by Govindan et al. (2016), the grey decision-making trial and evaluation laboratory (DEMATEL) method was used to develop 3PL provider selection criteria because human judgments are vague and complicated to depict by accurate numerical values. Prakash and Barua (2016) presented an integrated model based on fuzzy analytic hierarchy process (FAHP) for evaluation and prioritization of selection criteria and fuzzy technique for order performance by similarity to ideal solution (FTOPSIS) for the selection and development of reverse logistics partner; and they applied it to the Indian electronics industry. Shi et al. (2016) presented a real-life 3PL service model to illustrate 3PL's innovative aspect; they developed a conceptual model grounded in multiple theories to probe the value propositions of 3PL, and applied structural equation modeling to test the conceptual model based on the survey data from 245 Chinese 3PL providers.

Jharkharia and Shankar (2007) used analytic network process (ANP) to select logistics service provider in a medium-sized and growth-oriented fast-moving-consumer-goods (FMCG) company. Işıklar et al. (2007) proposed an intelligent decision support framework-integrating case-based reasoning (CBR), rule-based reasoning (RBR), and compromise programming techniques in a fuzzy environment, for effective 3PL evaluation and selection. Qureshi et al. (2007) used ANP and TOPSIS to evaluate the performance of logistics solution providers. Zhang (2007) studied the logistics supplier selection based on the analytic hierarchy process (AHP) and data envelopment analysis (DEA). More of these 3PL studies are summarized in Table 2.6.

TABLE 2.6: Summary of methods for 3PL selection.

TECHNIQUES	REFERENCES
Analytical hierarchy process and fuzzy (AHP)	Zhang et al. (2004); Göl and Çatay (2007); Soh (2010); Çakır (2009)
Analytical Network Process (ANP)	Jharkharia and Shankar (2007); Meade and Sarkis (2002)
Analysis of Variance (ANOVA)	Yeung et al. (2006)
Technique for Order Preference by Similarity (TOPSIS)	Bottani and Rizzi (2006)
Case-based Reasoning (CBR)	Yan et al. (2003)
Data Envelope Analysis (DEA)	Haas et al. (2003); Hamdan and Rogers (2008), Azadi and Saen (2011)
Case-based Reasoning (CBR), rule-based reasoning (RBR), and compromise programming in fuzzy environment	Işıklar et al. (2007)
Fuzzy Delphi method and fuzzy TOPSIS	Gupta et al. (2010)
Analytic Network Process and TOPSIS	Murray (2010)
Fuzzy Delphi method, fuzzy interface method, and a fuzzy linear assignment	Liu and Wang (2009)

In the next chapter, an overview of MCDM is presented. Next, the best-worst method is discussed and an overview of the fuzzy set theory and associated operations are presented.

Chapter 3: Methodology

3.1 Overview of Multi-Criteria Decision-Making

Generally, MCDM problems are divided into two classes based upon the solution space of the problem (Nispeling, 2015). For continuous problems with an infinite set of alternatives, Multi-Objective Decision-Making (MODM) methods are used. For discrete problems with a finite number of alternatives, Multi-Attribute Decision-Making (MADM) methods are used. However, in existing literature, MCDM is commonly used to describe MADM (Rezaei 2015).

MADM (hereafter, in line with common practice, MCDM) can be used to evaluate alternatives of different kinds against various criteria; and in this thesis, it will be used to evaluate the performance of some 3PL providers against a set of criteria. MCDM problems are generally shown as a matrix, as follows:

$$W = \{w_1, w_2, w_3, \dots . w_n\} \qquad (3.1)$$

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & C_2 & \dots C_n \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \dots a_{1n} \\ a_{21} & a_{22} & \dots a_{2n} \\ \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \dots a_{mn} \end{bmatrix} \end{array} \qquad (3.2)$$

Where $\{A_1,\ A_{2,} \dots \dots A_m\}$ is a set of feasible alternatives/actions/stimuli, $\{C_1, C_{2,} \dots C_n\}$ is a set of decision criteria and a_{ij} is the score of alternative *i* against criterion C_j. The overall goal is to select the best alternative; that is, the alternative with the best score. There are several methods to determine the overall value of an alternative, V_i. Generally, the score of an alternative can be obtained using a simple additive weighted value function (Keeney and Raiffa 1993), which appears in most MCDM methods:

$$V_i = \sum_{j=1}^{n} w_j a_{ij} \tag{3.3}$$

Since the introduction of MCDM, several methods have been proposed to rank alternatives. Such as the Analytic Hierarchy process (AHP) (Saaty 1990), Analytic Network Process (ANP) (Saaty 2001), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) (Hwang and Yoon 2012).

3.2 Best-Worst Multi-Criteria Decision-Making Method

Best-Worst Method (BWM) is a deterministic multi-criteria decision-making method that was developed by Rezaei (2015). The method uses two vectors of pairwise comparisons to determine the weights of criteria and scores of alternatives. The final score of the alternatives is derived by aggregating the weights from the different sets of criteria with the score of the alternatives. Rezaei (2015) proposed a consistency indicator in order to check the reliability of the comparisons. Compared to other methods like the well-known and used AHP method, the BWM requires fewer number of pairwise comparisons and the method leads to more consistent comparisons, which means that it provides more reliable results (Rezaei 2015). In pairwise comparisons with *n* criteria, each criterion is compared to another criterion and using a specific scale, the relative preferences a_{ij} are determined. For example, the 1/9 to 9 scale[1] can be used. The resulting matrix is shown below:

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots a_{1n} \\ a_{21} & a_{22} & \dots a_{2n} \\ \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \dots a_{nn} \end{bmatrix} \quad (3.4)$$

Where a_{ij} shows the preference of criterion *i* to criterion *j*. $a_{ij} = 1$ shows that *i* and *j* are of equal importance, $a_{ij} > 1$ shows that *i* is more important than *j*, and $a_{ij} = 9$ shows the extreme importance of *i* to *j*. The reverse comparison, that is reciprocal, shows the importance of criterion *j* to criterion *i*, a_{ji}. The reciprocal comparisons require that $a_{ij} = 1/a_{ji}$ and $a_{ii} = 1$, for all *i* and *j*. For the matrix in equation [3.4] to be complete, it requires $(n-1)/2$ pairwise comparisons, where n is the number of criteria and should be at least 2. The matrix in [3.4] is considered fully consistent when: $a_{ik} \times a_{kj} = a_{ij}, \forall i, j$.

Decision makers in such a case have to do $(n-1)/2$ pairwise comparisons and determine weights of criteria or scores of alternatives. However, judgments made by decision makers are not always completely consistent usually due to larger number of comparisons, complicated questions or lack of knowledge. Hence, to overcome some of these issues, Rezaei (2015) proposed the BWM that uses a new approach, requires less comparison, doesn't use reciprocal comparisons, and as a result produces more consistent results. In the BWM, the pairwise comparisons are grouped into two categories (Nispeling 2015):

[1] Other scales like 1 to 10 or 1 to 100 can also be used.

- Reference comparisons
- Secondary comparison

The comparison a_{ij} is called a reference comparison if i is the most desirable/important or best criterion and/or j is the least desirable/important or worst criterion. It is a secondary comparison when neither i nor j are best or worst criterion and $a_{ij} > 1$. The main focus of the BWM is the reference comparison. It doesn't require secondary comparisons because the relative importance of the secondary comparison can be derived from the reference comparisons. This feature makes the BWM use fewer comparisons $(2n - 3)$ where n is the number of criteria; and as a result, it gives more consistent results. The reference comparisons of the BWM are shown in Figure 3.1.

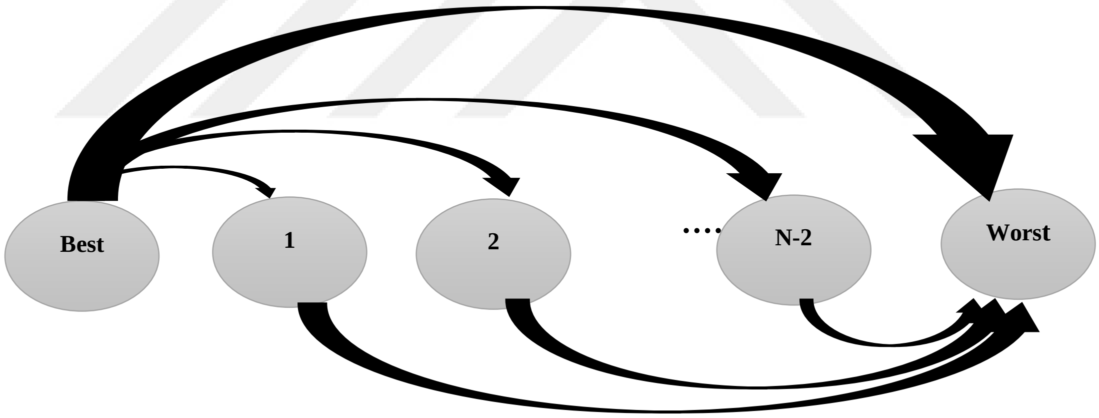

Figure 3.1: Reference comparisons of the BWM (Rezaei 2015).

The BWM consist of 5 steps. These steps are used to determine the weights of criteria and to find the scores of alternatives with respect to each criterion (Rezaei 2015). These steps are presented below for criteria weights. Note that similar calculations are done for finding the scores of alternatives.

STEP 1: Determine a set of decision criteria. In this step, a set of decision criteria $\{C_1, C_2, C_3 \dots \dots C_n\}$ must be defined to reach a decision.

STEP 2: Determine the best and worst criteria among the set of *n* criteria[2]. In this step, the decision maker identifies which criterion is the best and which is the worst among the set of *n* criteria.

STEP 3: Determine the preference of the best criterion over all other. For the deterministic case, this is expressed using a number between 1 and 9; where 1 shows equal importance and 9 shows extreme importance. The resulting vector is called the best-to-others vector and would be: $A_B = (a_{B1}, a_{B2}, \dots a_{Bj} .. a_{Bn})$ where a_{Bj} indicates the preference of the best criterion *B* over criterion *j*. The preference of the best to best, $a_{BB} = 1$.

STEP 4: Determine preference of all other criteria over the worst criteria. The resulting others-to-worst vector is shown as $A_W = (a_{1W}, a_{2W}, .. a_{jW} .., a_{nW})$; where a_{jW} indicates the preference of the criterion *j* over the worst criterion *w*. The preference of the worst to worst, $a_{ww} = 1$.

STEP 5: Determine the weights of the criteria$(\boldsymbol{w_1^*}, \boldsymbol{w_2^*}, \dots \boldsymbol{w_n^*})$. The final step of the BWM presents a model for obtaining the final weights (Rezaei 2015).

For each criterion, the final weight is the one where, for each pair of w_B/w_j and w_j/w_W, we have $\frac{w_B}{w_j} = a_{Bj}$ and $\frac{w_j}{w_W} = a_{jW}$.

[2] If there are more than one best or worst criteria, one of these criteria can be selected arbitrarily.

To determine the optimal weights, we find a solution where the maximum absolute difference between $|w_B - a_{Bj}w_j|$, and $|w_j - a_{jW}w_w|$ for all j is minimized. Considering the non-negativity and sum conditions of weights, the problem can be formulated as follows:

$$\min max_j\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_w|\ \} \tag{3.5}$$

$S.T$

$\sum_j w_j = 1$

$w_j \geq 0, \ \forall_j.$

Problem [3.5] can be transformed into the following problem:

$\min \xi$

$S.T$

$|w_B - a_{Bj}w_j| \leq \xi$

$$|w_j - a_{jW}w_w| \leq \xi \tag{3.6}$$

$$\sum_j w_j = 1$$

$w_j \geq 0, \ \forall_j.$

Problem [3.6] is a linear model. By solving [3.6] the weights $(w_1^*, w_2^*, \ldots w_n^*)$ and ξ can be obtained (Rezaei 2015).

According to Rezaei (2015), the matrix in [3.4] is fully consistent if for all j, $a_{Bj} \times a_{jW} = a_{BW}$, where a_{Bj}, a_{jW} and a_{BW} are respectively the preference of the best criterion over criterion j, the preference of criterion j over the worst criterion and the preference of the best criterion over the worst criterion. However, there is usually some level of inconsistency in the comparisons.

According to Rezaei (2015), ξ in model [3.6] can directly be considered as an indicator of consistency. ξ values close to zero show high level of consistency and consistency decreases as ξ value increase.

Rezaei (2015) tested the method in a small scale decision-making problem (mobile phone selection), but the applicability in larger MCDM problems and incorporation of decision makers' subjective and vague preferences are yet to be determined. Therefore, in this thesis, the BWM is extended to include the decision maker(s)' subjective preferences and vagueness; and it is applied to a real-life MCDM problem – 3PL evaluation and selection.

3.3 Fuzzy Set Theory

A fuzzy set is an extension of a crisp set. Crisp sets only allow full membership or non-membership at all, whereas fuzzy sets allow partial membership. In other words, an element may partially belong to a fuzzy set. Zadeh (1965), proposed to use values from 0 to 1 for showing the degree of membership of the objects in a fuzzy set. Complete non-membership is represented by 0, and complete membership as 1. Values between 0 and 1 represent intermediate degrees of membership.

Fuzzy sets provide a powerful tool to deal with uncertainty and it is widely used in the MCDM problem with linguistic information. Decision maker express their opinions in linguistic terms and then these linguistic information is converted into fuzzy numbers with the help of membership function.

3.3.1 Fuzzy Numbers

A fuzzy number is an generalization of a regular, real number in the sense that it does not refer to one single value but rather to a connected set of possible values, where each possible value has its own weight between 0 and 1. This weight is called the membership function (Nguyen and Walker 2000). A fuzzy number *M* is a convex normalized fuzzy set. A fuzzy number is characterized by a given interval of real numbers, each with a grade of membership between 0 and 1 (Deng 1999).

3.3.2 Triangular Fuzzy Numbers

Triangular Fuzzy Numbers (TFNs) are three real numbers, expressed as (*l*, *m*, *u*). The parameters *l*, *m*, and *u*, respectively, indicate the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event. Among the various shapes of fuzzy number, triangular fuzzy number (TFN) is the most popular one. It is a fuzzy number represented with three points as *A* = (*l*, *m*, *u*), and the degree of membership can be shown as:

$$\mu(x/\tilde{M}) = \begin{cases} 0, & x < l, \\ \dfrac{x-l}{m-l}, & l \le x \le m, \\ \dfrac{u-x}{u-m}, & m \le x \le u, \\ 0, & x > u \end{cases} \tag{3.7}$$

This representation is interpreted as membership functions shown in Figure 3.2.

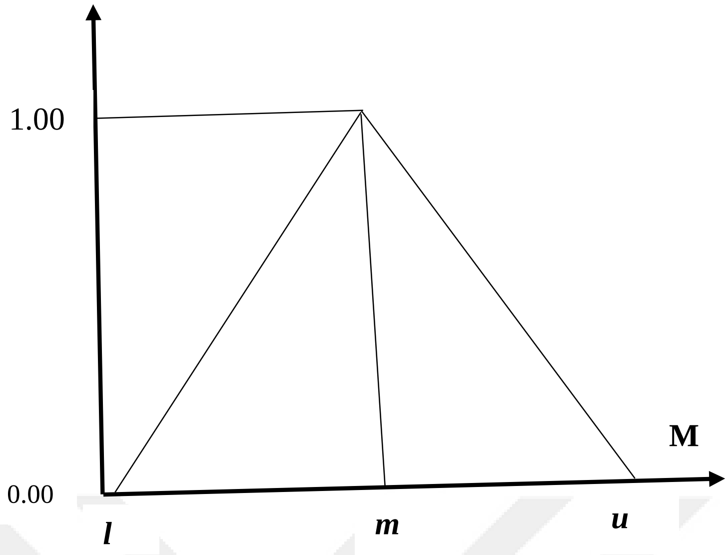

Figure 3.2: A triangular fuzzy number (TFN)

Triangular fuzzy numbers are convenient to work with because of their computational simplicity, and they are useful in promoting representation and information processing in a fuzzy environment. In this research, for simplicity, fuzzy triangular numbers will be used.

3.3.3 Algebraic Operations of Triangular Fuzzy Numbers

When dealing with fuzzy sets in applications, we have to deal with fuzzy numbers. Various operations on TFNs can be defined. But in this section, three important operations usually used are illustrated (Tang & Beynon 2005). Let Ã and B̃ be two positive triangular fuzzy numbers Ã = (a_1, a_2, a_3) and B̃ = (b_1, b_2, b_3). Some algebraic operations can be expressed as follows:

$$Scalar\,summation: \tilde{A}\times\tilde{B} = [a_1+b_1, a_2+b_2, a_3+b_3] \quad (3.8)$$

$$Scalar\,subtraction: \tilde{A}-\tilde{B} = [a_1-b_1, a_2-b_2, a_3-b_3] \quad (3.9)$$

$$Scalar\,multiplication: \tilde{A} \otimes \tilde{B} = [a_1 b_1, a_2 b_2, a_3 b_3] \quad (3.10)$$

$$Scalar\,division: \tilde{A}^{-1} = [1/a_3, 1/a_2, 1/a_1] \quad (3.11)$$

3.4 Proposed Fuzzy Best-Worst Method (FBWM)

In this section, the algorithm of the fuzzy best-worst multi-criteria decision-making method is presented. The proposed method is designed to perfectly handle the decision maker(s)' subjective preferences and vagueness. The 8 steps of the proposed fuzzy best-worst method are as follows[3].

1. **Determination of criteria/alternatives:** The method starts with the determination of a set of $n\ (C_1, C_2, \ldots \ldots C_n)$ decision criteria and a set of $m(A_1, A_2, \ldots \ldots A_m)$ alternatives. These criteria are obtained from both decision makers as well as analysis of literature research related to the problem. The method is designed such that for each criterion, the maximum is better. Therefore, when evaluating alternatives against criteria such as cost and risk level, for example, the highest value is given to the alternative with the lowest cost or risk level. In other words, such criteria are minimizing criteria.
2. **Determination of the best and worst criteria by each decision maker:** In the second step, each decision maker identifies which criterion is best (most desirable) and which is less worst (less desirable). If more than one criterion is identified as best or worst, one is selected arbitrarily.
3. **Determine the preference of the best criterion over all criteria (Best to Other vector):** Each decision maker determines the preference of his/her best criterion over all other criteria using a linguistic scale. This method assumes that the

[3] These steps can be used to determine both weights of criteria and scores of alternatives with respect to each criterion.

decision maker(s) can clearly identify the best and worst criteria and uncertainty is only considered when determining the preference of the best criterion over other criteria and the preference of other criteria over the worst criterion as seen in the next step.

4. **Determine the preference of all other criteria over the worst criterion (Other-to-Worst)**: In this step, each decision maker determines the preference of all other criteria over the worst criteria using a linguistic scale. This proves that the best-worst method requires less comparison as compared to other methods like AHP. It requires $2n - 3$ comparisons, where n is the number of criteria; and similarly for alternatives.

5. **Defuzzification using α-cut:** As stated previously, the decision maker's subjective judgment and vagueness produces uncertain and imprecise relations between criteria as well as alternatives. In addition, the real decision process is usually accompanied by some unclear and potential factors in practice, such as decision maker's degree of confidence and degree of satisfaction with his/her preferences. In the proposed method, decision makers expressed their preferences using linguistic terms and these linguistic terms are converted to corresponding triangular fuzzy numbers. In this case, the confidence value (α) is determined by the decision maker(s) indicating his/her confidence in the judgments. For example, consider a fuzzy performance $\tilde{a}ij$ which is expressed as a triangular fuzzy number (l, m, u), and have the membership function shown in [3.7]. Suppose the interval of confidence level is expressed as α, $\forall\alpha \in (0,1)$ the triangular fuzzy number becomes:

$$\widetilde{M}_x = [l^\alpha, u^\alpha] = [(m - l)\alpha + l, -(u - m)\alpha + u] \qquad (3.12)$$

Next, the interval (l^{α}, u^{α}) is converted to crisp values using the decision maker's degree of satisfaction. The degree of satisfaction is estimated by the index of optimism (λ). Each decision maker defines a λ-function which represents the attitude of the decision maker. It may be optimistic, moderate, or pessimistic expressed on a 0-1 scale. A decision maker with optimistic attitude will take the maximum λ, moderate will take the medium λ and the pessimistic person will take the minimum λ in the range (0, 1). Using the above interval value, the crisp value C_{λ} for a given comparison is calculated as:

$$C_{\lambda} = \lambda u^{\alpha} + (1-\lambda) l^{\alpha} = \lambda[(m-l)\alpha + l] + (1-\lambda)[-(u-m)\alpha + u] \tag{3.13}$$

Here the crisp values of $\tilde{a}_{ij}$ will be represented without the cap as a_{ij}. These values will be used to calculate the weights as shown in the next step.

6. **Determine the weights of the criteria**$(\boldsymbol{w_1^*, w_2^*, \dots w_j \dots w_n^*})$**:** To determine the overall weight of each criterion, we first calculate the weight of each criterion C_j for each decision maker and the consistency indicator ξ. The optimal weight for each criterion is the one where, for each pair w_B/w_j and w_j/w_W, we have $\frac{w_B}{w_j} = a_{Bj}$ and $\frac{w_j}{w_W} = a_{jW}$. In order to find the weights $(w_1^*, w_2^*, \dots w_j \dots w_n^*)$ and the consistency indicator (ξ), a solution should be found by minimizing the maximum among the set of $\{|w_B - a_{Bj} w_j|, [w_j - a_{jW} w_W]\}$. This can be formulated as problem [3.5] and transformed to the minimization problem in [3.6]. By solving problem [3.6] for each decision maker, the weights of the criteria or scores of the alternatives against each criterion can be determined.

As stated earlier, the matrix in [3.4] is fully consistent if for all j, $a_{Bj} \times a_{jW} = a_{BW}$ and the highest inconsistency occurs when $a_{Bj} = a_{jw} = a_{BW}$ and $a_{Bj} \times a_{jw} \neq a_{BW}$. ξ in model [3.6] can directly be considered as an indicator of consistency. ξ values close to zero show high level of consistency and consistency decreases as the ξ value increase (Rezaei 2015).

7. The scores of all alternatives for each decision maker with respect to each criterion can be calculated using the same procedure in steps 2 to 6. That is, each decision maker identifies the best and worst alternatives with respect to a given criterion. The decision maker then determines the preference of the best alternative over all others; and the preference of all other alternatives over the worst alternative. By solving the linear model [3.6] for each decision maker and each criterion, the scores of the alternatives $(A_1, A_2, \ldots \ldots A_m)$ and consistency indicator (ξ) can be determined. Together with the scores of criteria from step 6, the scores from this step are used to calculate the overall scores of the alternatives as shown in the next step.
8. The overall score of each alternative for each decision maker is computed using the weighted value function in [3.14][4].

$$A_i = \sum_{j}^{n} w_j A_{ij} \tag{3.14}$$

[4] A_{ij} Implies the score of alternative *i* against criterion *j* for a given decision maker and w_j is the weight of criterion *j* for a given decision maker.

The overall score of an alternative is obtained by taking the average of the scores for all decision makers. This score is computed for all alternatives and ranked in non-decreasing order for final selection. The alternative with the highest score is selected as the best from the set of alternatives.

Though the existing best-worst method addresses the issue of large comparisons, the major weakness of the method is its inability to adequately handle the inherent uncertainty and imprecision of decision makers' preferences. Hence, in this study, the best-worst method is extended to accurate handle the decision maker's uncertain and imprecise preference relations; and for the first time, it is applied to a 3PL selection problem.

Chapter 4: Case Study

4.1 Overview of the Company

The application of the FBWM approach has been demonstrated in a medium-sized textile company. Founded in 1988, Tek-team's main product is knitted materials. The company produces T-shirts, sweatshirts, jackets, work wears, gastronomy wears and other products from woven and organic fabrics. The company currently has about 300 employees in its 7000 squared meter facility that is equipped with latest technologies of machinery. Since 1997, the company has been exporting its products to customers in Europe. It has outsourced its outbound logistics to carrying and forwarding agents. The company is willing to outsource its entire logistics activities. The opinions of four of its managers (4 DM) were sought in the formation of the FBWM.

4.2 Determination of Criteria and Potential 3PL Providers

The criteria identification is one of the key aspects of MCDM and therefore, the identification of these is an important step in the process. The research framework shown in figure 4.1 shows that both literature and data from the case company are used to identify the criteria for 3PL selection.

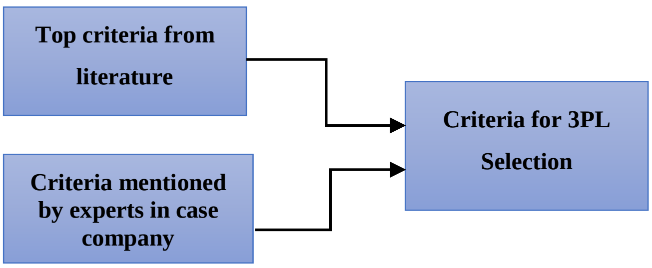

Figure 4.1: Framework for identification of 3PL selection criteria.

Literature related to 3PL selection (Çakir 2009; Göl and Çatay 2007; Çakir et al. 2009) was examined to obtain the most important and common used criteria by academics. The most used and important criteria identified in the literature are shown in Table 4.1.

TABLE 4.1: Most used 3PL selection criteria identified in the literature (Çakir 2009; Göl and Çatay 2007; Çakir et al. 2009).

CRITERIA	DESCRIPTION
Cost of service	Refers to the total cost of logistics sourcing.
Quality of service	The quality of the provider includes many aspects such as on-time delivery, the accuracy of order fulfilment, frequency and cost of loss and damage...etc.
Risk management	The capability of the provider to address any unforeseen problem. It is needed to ensure the continuity of the services.
Technological capabilities	The level of equipment and devices used by the provider, speed and internet compatibility software.
Reputation of the company	The company's logo, facilities, positive and negative experiences of past customers and public recognition.
Delivery time	Competitive delivery time, on-time delivery capabilities, and speed of response to order.
Long-term relationship	Shared risk, rewards, and cooperation between the two companies.
Financial stability	The firm's financial conditions (liquidity).

In addition to the above criteria, the experts and decision makers of the company were asked to provide the criteria they use or find important in the 3PL selection process. A brief questionnaire, shown in Appendix A.1, was presented to 4 managers (4 DM) to identify these criteria. Using the combination of both literature and company knowledge, the following 15 criteria were selected and are being used for the purpose of this study.

Table 4.2: List of criteria gathered from literature review and decision makers.

Criteria	Description
Cost of service (C_1)	Includes the total cost associated with the outsourcing and should be minimized (minimizing criterion).
Reputation of the company (C_2)	The 3PL provider's recognition, clients' satisfaction, financial condition, reliability and customer service.
Quality of service (C_3)	The quality of the 3PL provider includes many aspects such as the accuracy of order fulfilment, the frequency of loss and damage, speed and on-time delivery capability, and technical competence.
Risk management (C_4)	The capability of the 3PL provider to address any unforeseen problem. It includes the insurance coverage provided by the 3PL provider and ability to respond to emergency situations.
Delivery performance (C_5)	There are two dimensions of delivery performance, namely "speed" and "reliability", are important for the satisfaction of the user. It also includes aspects such as document accuracy, transportation safety and shipment error rate.
Size and quality of fixed assets (C_6)	The availability of quality assets such as air-conditioned warehouses and vehicles, which suits the need of the products being transported.
Experience in similar products (C_7)	Prior experience or expertise of the 3PL provider an added advantage to the company.
Employees satisfaction level (C_8)	It is an important criterion, as the presence of dissatisfied employees at the3PL provider's end may lead to a strike, lockouts, sabotage, and other such unwanted activities, which may adversely affect the logistics operations.
Quality of Management (C_9)	Good management of the 3PL provider may not only provide good service to the company but may also foster a long-term relationship between the 3PL provider and the company.
Financial stability (C_{10})	3PL provider's financial conditions (such as liquidity) and financial instability (e.g., whether the supplier involves in other risky businesses).
Information technology capabilities (C_{11})	The IT capabilities of a 3PL provider help in reducing uncertainties and inventory level.

Table 4.2 (Continued): List of criteria gathered from literature review and decision makers

Geographical spread and range of services provided (C_{12})	Wide geographic spread and range of services offered by the 3PL provider are desirable as these create enhanced access to market and much more avenues to the user. It may also enable the user to save some money on distribution and marketing of the product.
Flexibility in billing and payment (C_{13})	Flexibility in billing and payment conditions increases goodwill between the company and the 3PL provider.
Information sharing and mutual trust (C_{14})	Mutual trust-based information sharing between the company and the 3PL provider is necessary not only for the continuation of the agreement but also for the continuous improvement of the service.
Long-term Relationship (C_{15})	Long-term relationships, which include shared risks and rewards, ensure cooperation between the company and the 3PL provider. It also helps in controlling the opportunistic behavior of 3PLs.

Identification of potential providers was done through an interview with the official of the case company and 6 companies were mentioned as potential 3PL service provider.

4.3 Data Collection

According to Sekaran (2006), data can be obtained in two different ways. Either as primary data or as secondary data. Primary data is related to information collected by the researcher on the variables that are subjects of a study. Secondary data can be obtained through sources that already exist such as literature, company records, and government publications. In this study, the data needed to construct the FBWM were collected as primary data through a questionnaire. The questionnaire consisted of two parts requiring the decision makers to express their subjective preferences when comparing criteria, and alternatives with respect to each criterion using fuzzy linguistic variables shown in table 4.3.

Table 4.3: Definition and membership function of fuzzy number for comparing criteria (Ayağ 2005)

Intensity of importance[5]	Fuzzy numbers	Linguistic terms for importance	Triangular membership function
1	$\tilde{1}$	Equally Preferred (EP)	(1, 1, 2)
3	$\tilde{3}$	Moderately Preferred (MP)	(2, 3, 4)
5	$\tilde{5}$	Strongly Preferred (SP)	(4, 5, 6)
7	$\tilde{7}$	Very Strongly Preferred (VSP)	(6, 7, 8)
9	$\tilde{9}$	Extremely More Preferred (EMP)	(8, 9, 10)

In the first part, each decision maker compares his/her best and worst criteria to other criteria in order to determine the optimal weights. In the second part, each decision maker compares the 6 potential 3PL service providers with best/worst alternatives with respect to each of the 15 criteria. For this study, a total of four questionnaires were administered to four managers of the case company.

4.4 Application of FBWM to 3PL Selection

In this section, a detailed application of the FBWM is presented. The steps of the FBWM presented in section 3.4 were used to calculate both the weights of the criteria, and the score of each alternative against each of the 15 criteria. In the next section, the overall weight of each criterion for each decision maker is

[5] Fundamental scale used in pairwise comparison (Saaty, 1990)

calculated; and in the subsequent section, the scores of the alternatives are calculated with respect to each criterion.

4.4.1 Determination of criteria weights

Table 4.4: Best and worst criteria for each of the 4 decision makers.

CRITERIA	BEST	WORST
C1		
C2	DM 2	
C3		
C4		
C5		
C6		DM 2
C7		DM 1, DM 4
C8		DM 3
C9		
C10	DM 3	
C11		
C12		
C13	DM 1	
C14		
C15	DM 4	

As stated in step (1) of section 3.4, the first step of the FBWM was achieved through extensive literature review and consultation with the decision makers in the case company. To achieve step (2) of the methodology, each decision maker (DM) was asked to identify his/her best and worst criteria from the set of 15 criteria. Each of the decision maker identified his/her best and worst criteria as shown in Table 4.4.

Using the fuzzy linguistic variables show in Table 4.4, each decision maker expressed the preference of his/her best criterion over all other criteria, and the preference of all other criteria over the worst criterion. The decision makers' linguistic preferences are shown in Tables B.1 and B.2 of Appendix B;

and are converted to corresponding fuzzy triangular numbers as shown Tables 4.5 and 4.6.

Table 4.5: Preference of best criterion over all other criteria using TFNs.

Best-to-others Vector				
CRITERIA	**DM 1**	**DM 2**	**DM 3**	**DM 4**
C1	(2,3,4)	(2,3,4)	(2,3,4)	(2,3,4)
C2	(4,5,6)	1	(4,5,6)	(4,5,6)
C3	(6,7,8)	(4,5,6)	(2,3,4)	(6,7,8)
C4	(2,3,4)	(4,5,6)	(6,7,8)	(2,3,4)
C5	(2,3,4)	(2,3,4)	(2,3,4)	(2,3,4)
C6	(2,3,4)	(8,9,10)	(6,7,8)	(4,5,6)
C7	(8,9,10)	(2,3,4)	(2,3,4)	(8,9,10)
C8	(4,5,6)	(4,5,6)	(8,9,10)	(2,3,4)
C9	(4,5,6)	(2,3,4)	(8,9,10)	(2,3,4)
C10	(4,5,6)	(6,7,8)	1	(4,5,6)
C11	(2,3,4)	(2,3,4)	(2,3,4)	(6,7,8)
C12	(2,3,4)	(4,5,6)	(4,5,6)	(2,3,4)
C13	1	(6,7,8)	(6,7,8)	(6,7,8)
C14	(6,7,8)	(8,9,10)	(2,3,4)	(2,3,4)
C15	(2,3,4)	(2,3,4)	(4,5,6)	1

Table 4.6: Preference of all other criteria over the worst criterion using TFNs

Others-to-worst Vector				
CRITERIA	**DM 1**	**DM 2**	**DM 3**	**DM 4**
C1	(6,7,8)	(6,7,8)	(6,7,8)	(6,7,8)
C2	(4,5,6)	(8,9,10)	(4,5,6)	(4,5,6)
C3	(2,3,4)	(4,5,6)	(6,7,8)	(2,3,4)
C4	(4,5,6)	(4,5,6)	(2,3,4)	(6,7,8)
C5	(4,5,6)	(4,5,6)	(6,7,8)	(6,7,8)
C6	(2,3,4)	1	(2,3,4)	(4,5,6)
C7	1	(6,7,8)	(6,7,8)	1
C8	(4,5,6)	(2,3,4)	1	(6,7,8)
C9	(4,5,6)	(2,3,4)	(1,1,2)	(6,7,8)
C10	(4,5,6)	(4,5,6)	(8,9,10)	(4,5,6)
C11	(6,7,8)	(6,7,8)	(6,7,8)	(2,3,4)
C12	(6,7,8)	(4,5,6)	(4,5,6)	(6,7,8)
C13	(8,9,10)	(4,5,6)	(2,3,4)	(2,3,4)
C14	(2,3,4)	(1,1,2)	(4,5,6)	(6,7,8)
C15	(2,3,4)	(4,5,6)	(4,5,6)	(8,9,10)

To perform the defuzzification process stated in step (5) of the FBWM in section 3.4, the alpha cut approach proposed by Louis and Wang (1992) was used. The Defuzzification is applied to convert the TFNs to quantifiable values. Since decision makers' confidence and risk tolerance are not the focus of this study, 0.5 is used for both α and λ. These values show that the decision makers are not extremely optimistic or pessimistic about their judgements.

Using equation [3.13], each of the TFN in tables 4.5 and 4.6 are converted to the crisp values in shown tables 4.7 and 4.8 respectively.

Table 4.7: Crisp values for preference of best criterion over all other criteria.

Best-to-others Vector				
CRITERIA	**DM 1**	**DM 2**	**DM 3**	**DM 4**
C1	3	3	3	3
C2	5	1	5	5
C3	7	5	3	7
C4	3	5	7	3
C5	3	3	3	3
C6	3	9	7	5
C7	9	3	3	9
C8	5	5	9	3
C9	5	3	9	3
C10	5	7	1	5
C11	3	3	3	7
C12	3	5	5	3
C13	1	7	7	7
C14	7	9	3	3
C15	3	3	5	1

Table 4.8: Crisp values for preference of other criteria over the worst criterion

Others-to-worst Vector				
CRITERIA	**DM 1**	**DM 2**	**DM 3**	**DM 4**
C1	7	7	7	7
C2	5	9	5	5
C3	3	5	7	3
C4	5	5	3	7
C5	5	5	7	7
C6	3	1	3	5
C7	1	7	7	1
C8	5	3	1	7
C9	5	3	1.25	7
C10	5	5	9	5
C11	7	7	7	3
C12	7	5	5	7
C13	9	5	3	3
C14	3	1.25	5	7
C15	3	5	5	9

Table 4.9: Weight of criteria and consistency indicator (ξ) for each decision

WEIGHTS OF CRITERIA				
CRITERIA	**DM 1**	**DM 2**	**DM 3**	**DM 4**
W1	0.077	0.082	0.083	0.078
W2	0.047	0.2	0.05	0.047
W3	0.035	0.049	0.083	0.034
W4	0.0772	0.049	0.035	0.078
W5	0.0772	0.082	0.083	0.078
W6	0.0772	0.0166	0.035	0.047
W7	0.0168	0.082	0.083	0.017
W8	0.046	0.049	0.018	0.078
W9	0.046	0.082	0.028	0.078
W10	0.046	0.035	0.201	0.047
W11	0.077	0.082	0.083	0.034
W12	0.077	0.049	0.05	0.078
W13	0.191	0.035	0.035	0.034
W14	0.033	0.0274	0.083	0.078
W15	0.077	0.082	0.05	0.194
ξ	0.04	0.048	0.043	0.0408

To determine the weight of the criteria, model [3.6] was solved for each decision maker. Each problem had 27 constraints corresponding to the 27 comparisons. The model gave the weights and consistency indicator (ξ) for each decision maker. The overall weight of the criteria and the resulting consistency indicators are shown in Table 4.9.

4.4.2 Scoring of Alternatives

Using the same procedures as shown in Section 3.4, the score of each alternative against each of the 15 criteria was computed. In the first step, each decision maker identified his/her best and worst alternatives[6] with respect to each criterion as shown in table C.1 of Appendix C.

Next, using the linguistic variables and associated TFNs given in table C.2 of Appendix C, each decision maker expressed his/her preference of the best alternative over all other; and preference of all other alternatives over the worst alternative. The linguistic preferences of decision makers are shown in tables C.3 – C.17 of Appendix C. These linguistic preferences are converted to triangular fuzzy numbers shown in tables C.18 – C.32 of Appendix C. Using the alpha cut method discussed earlier; these fuzzy numbers are converted to quantifiable values and vectors are shown in tables C.33 – C.47 of Appendix C.

For each decision maker, to determine the score of each alternative for each criterion, problem [3.6] was solved for each of the 15 criteria – total of 60 of LPs were solved. The scores of alternatives for each criterion and associated consistency ratios were calculated and the results are shown in tables 4.10 – 4.24.

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[6] Alternatives mentioned in this study refer to the potential 3PL providers.

Table 4.10: Score of alternatives against 'Cost of service'

SCORE OF ALTERNATIVES AGAINST CRITERION 1 (A_{i1})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.038	0.433	0.467	0.174
A2	0.175	0.175	0.112	0.104
A3	0.105	0.105	0.041	0.434
A4	0.175	0.075	0.08	0.038
A5	0.075	0.038	0.187	0.0746
A6	0.433	0.175	0.112	0.174
ξ	0.0911	0.0911	0.095	0.088

Table 4.11: Score of alternatives against 'Reputation of the company'

SCORE OF ALTERNATIVES AGAINST CRITERION 2 (A_{i2})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.433	0.113	0.076	0.031
A2	0.175	0.04	0.177	0.183
A3	0.105	0.465	0.106	0.414
A4	0.075	0.08	0.428	0.11
A5	0.038	0.188	0.036	0.183
A6	0.175	0.113	0.177	0.079
ξ	0.091	0.098	0.104	0.137

Table 4.12: Score of alternatives against 'Quality of service'

SCORE OF ALTERNATIVES AGAINST CRITERION 3 (A_{i3})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.175	0.433	0.175	0.433
A2	0.075	0.038	0.038	0.175
A3	0.433	0.175	0.105	0.038
A4	0.105	0.105	0.175	0.105
A5	0.175	0.175	0.075	0.075
A6	0.038	0.075	0.433	0.175
ξ	0.0911	0.0911	0.0911	0.0911

Table 4.13: Score of alternatives against ‘Risk management’

SCORE OF ALTERNATIVES AGAINST CRITERION 4 (A_{i4})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.174	0.433	0.075	0.038
A2	0.0384	0.175	0.175	0.175
A3	0.434	0.038	0.038	0.433
A4	0.104	0.105	0.105	0.105
A5	0.174	0.175	0.175	0.078
A6	0.0746	0.075	0.433	0.175
ξ	0.088	0.0911	0.0911	0.0911

Table 4.14: Score of alternatives against ‘Delivery Performance’

SCORE OF ALTERNATIVES AGAINST CRITERION 5 (A_{i5})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.038	0.0345	0.174	0.042
A2	0.175	0.394	0.0746	0.083
A3	0.105	0.159	0.0384	0.48
A4	0.433	0.095	0.174	0.116
A5	0.075	0.159	0.434	0.194
A6	0.175	0.159	0.104	0.083
ξ	0.0911	0.083	0.088	0.101

Table 4.15: Score of alternatives against ‘Size and quality of fixed assets’

SCORE OF ALTERNATIVES AGAINST CRITERION 6 (A_{i6})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.168	0.39	0.447	0.175
A2	0.1	0.159	0.168	0.075
A3	0.168	0.095	0.1	0.105
A4	0.447	0.159	0.043	0.175
A5	0.043	0.159	0.072	0.433
A6	0.072	0.035	0.168	0.038
ξ	0.058	0.0828	0.0577	0.0911

Table 4.16: Score of alternatives against ‘Experience in similar product’

SCORE OF ALTERNATIVES AGAINST CRITERION 7 (A_{i7})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.394	0.168	0.038	0.175
A2	0.345	0.168	0.175	0.075
A3	0.159	0.447	0.433	0.433
A4	0.095	0.1	0.075	0.175
A5	0.159	0.072	0.105	0.105
A6	0.159	0.043	0.175	0.038
ξ	0.083	0.0577	0.0911	0.0911

Table 4.17: Score of alternatives against 'Employees satisfaction level'

SCORE OF ALTERNATIVES AGAINST CRITERION 8 (A_{i8})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.0405	0.433	0.427	0.433
A2	0.158	0.175	0.177	0.038
A3	0.419	0.105	0.106	0.175
A4	0.158	0.038	0.177	0.105
A5	0.067	0.175	0.076	0.175
A6	0.157	0.075	0.036	0.075
ξ	0.054	0.0911	0.104	0.0911

Table 4.18: Score of alternatives against 'Quality of management'

SCORE OF ALTERNATIVES AGAINST CRITERION 9 (A_{i9})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.175	0.0175	0.17	0.183
A2	0.038	0.038	0.037	0.11
A3	0.105	0.105	0.102	0.03
A4	0.433	0.433	0.17	0.183
A5	0.075	0.075	0.102	0.079
A6	0.175	0.175	0.42	0.414
ξ	0.0911	0.0911	0.0885	0.137

Table 4.19: Score of alternatives against 'Financial stability'

SCORE OF ALTERNATIVES AGAINST CRITERION 10 (A_{i10})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.168	0.075	0.433	0.175
A2	0.1	0.175	0.038	0.075
A3	0.447	0.433	0.175	0.433
A4	0.072	0.175	0.105	0.175
A5	0.043	0.105	0.075	0.105
A6	0.168	0.038	0.175	0.038
ξ	0.058	0.0911	0.0911	0.0911

Table 4.20: Score of alternatives against 'Information technology capabilities'

SCORE OF ALTERNATIVES AGAINST CRITERION 11 (A_{i11})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.175	0.394	0.46	0.433
A2	0.075	0.159	0.0387	0.175
A3	0.038	0.095	0.0817	0.105
A4	0.105	0.159	0.114	0.038
A5	0.175	0.159	0.19	0.075
A6	0.433	0.0345	0.114	0.175
ξ	0.0911	0.0829	0.111	0.0911

Table 4.21: Score of alternatives against 'Geographical spread and range and services provided'

SCORE OF ALTERNATIVES AGAINST CRITERION 12 (A_{i12})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.433	0.394	0.0432	0.075
A2	0.038	0.159	0.072	0.175
A3	0.175	0.095	0.168	0.433
A4	0.105	0.159	0.1	0.038
A5	0.075	0.159	0.168	0.175
A6	0.175	0.0345	0.447	0.105
ξ	0.0911	0.0829	0.0577	0.0911

Table 4.22: Score of alternatives against 'Flexibility in billing and payments'

SCORE OF ALTERNATIVES AGAINST CRITERION 13 (A_{i13})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.37	0.037	0.465	0.175
A2	0.149	0.17	0.113	0.433
A3	0.0325	0.17	0.04	0.038
A4	0.149	0.42	0.188	0.075
A5	0.149	0.102	0.08	0.105
A6	0.149	0.102	0.113	0.175
ξ	0.0779	0.0885	0.098	0.0911

Table 4.23: Score of alternatives against 'Information sharing and mutual trust'

SCORE OF ALTERNATIVES AGAINST CRITERION 14 (A_{i14})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.136	0.0422	0.433	0.433
A2	0.045	0.48	0.175	0.175
A3	0.409	0.194	0.075	0.075
A4	0.136	0.116	0.105	0.038
A5	0.136	0.083	0.038	0.105
A6	0.136	0.083	0.175	0.175
ξ	0.00	0.101	0.0911	0.0911

Table 4.24: Score of alternatives against 'Long-term relationship'

SCORE OF ALTERNATIVES AGAINST CRITERION 15 (A_{i15})				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.433	0.41	0.095	0.198
A2	0.175	0.153	0.159	0.446
A3	0.038	0.092	0.159	0.085
A4	0.105	0.153	0.394	0.119
A5	0.075	0.153	0.035	0.033
A6	0.175	0.04	0.159	0.119
ξ	0.0911	0.048	0.0829	0.148

Given the weight of each criterion and the scores of each alternative against each criterion for all decision makers, the global score of each alternative for each decision maker can be calculated using the additive weighted value function in equation [3.14].

By doing this for all alternatives and all decision makers, the overall scores of alternatives (A_i) in Table 4.25 were found.

Table 4.25: Overall weighted scores of alternatives for all decision makers

OVERALL SCORES OF ALTERNATIVES				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	0.24	0.25	0.29	0.20
A2	0.12	0.15	0.10	0.20
A3	0.17	0.22	0.13	0.24
A4	0.19	0.15	0.15	0.10
A5	0.10	0.14	0.13	0.12
A6	0.186	0.094	0.204	0.143

4.5 Results and Analysis

In this section, we performed statistical analysis of the FBWM results and rank the alternatives.

Table 4.26: Overview of case study results

ALTERNATIVES	Mean	SD	Minimum	Maximum	Ranking
A1	0.24	0.04	0.20	0.29	1
A2	0.14	0.04	0.10	0.20	5
A3	0.19	0.05	0.13	0.24	2
A4	0.15	0.03	0.10	0.19	4
A5	0.12	0.01	0.10	0.14	6
A6	0.16	0.05	0.09	0.20	3
ξ	0.0848	0.023	0.00	0.148	

As seen in Table 4.26, on average, the first choice of 3PL provider is **(A1)**, followed by **(A3)**, and so on.

As discussed earlier, the consistency indicator plays a key role in MCDM, as it determines the reliability of the result. In this case study, for each decision maker, we have one pair of vectors $(1 \times 14 \; and \; 13 \times 1)$ for comparing the criteria and 15 pairs of vectors $(1 \times 5 \; and \; 4 \times 1)$ for comparing the 6 alternatives against the 15 criteria. Given 4 decision makers, we have 64 pairs of vectors/LPs. As shown in Table 4.26, the average of the 64 consistency ratios is 0.084 and the maximum ξ is 0.148.

As the consistency indicator in this study shows, in addition to the fact that the proposed methodology uses less comparisons as compared to other fuzzy method like FAHP, one of the striking features of the method is the consistency. The FBWM will always produce consistent results (though not fully consistent). Unlike the FAHP, the consistency indicator in the FBWM is used to determine the level of reliability as the FBWM is always reliable. By defining best and worst criteria from a set of criteria, the FBWM places a guide on the comparisons. For example, a decision maker clearly understands that his/her best criteria is at least equally preferred to any other criteria.

The high consistency of the FBWM can also be attributed to the fact that the method uses less comparisons $(2n - 3)$ as compared to method like the FAHP which uses $n(n-1)/2$ comparisons. This is because as the number of comparisons increase, the consistency decreases.

Chapter 5: Conclusion

5.1 Conclusion and Future Research

Due to the increase in global trade and the sourcing of parts/materials for various locations, 3PL selection problem has received vast attention in recent years as firms look for efficient and responsive ways to satisfy demands from various customer segments of the market. In selection process, each alternative is evaluated against a set quantitative and qualitative factors in order to select the best provider. However, decision makers are usually faced with uncertainty and vagueness from subjective perceptions and experiences in the decision-making process. Fuzzy MCDM approach is particularly effective in reducing the uncertainty in the determination of the relative weight given to the different criteria and in determining the impact of each alternative provider on the attributes considered.

In this study, an efficient methodology called Fuzzy Best-worst method (FBWM) was developed and applied to a logistics service provider selection problem at a medium-sized textile company. The proposed methodology uses fewer comparisons as compared to FAHP and it always produce consistent results. In the case study, 6 alternatives were evaluated against 15 selection criteria by a total of 4 decision makers and the methodology found that **(A1)** is the first choice with overall average score of 0.24.

This study raises several important issues that warrant further research. Some of these include:

- Applying the proposed method to other MCDM problems and comparing the solution to other fuzzy methods like FAHP or FTOPSIS.
- Extending the methodology to include more decision makers.
- Combining the methodology with other fuzzy methods.

References

3plstudy.com. (2016). Download the 2016 3rd Party Logistics Study | Third-Party Logistics Study. [online] Available at: http://www.3plstudy.com/downloads/download-the-2016-3rd-party-logistics-study/ [Accessed 4 Jun. 2016].

Abdur Razzaque, M. and Chen Sheng, C., 1998. Outsourcing of logistics functions: a literature survey. International Journal of Physical Distribution & Logistics Management, 28(2), pp.89-107.

Aktas, E. and Ulengin, F., 2005. Outsourcing logistics activities in Turkey. Journal of Enterprise Information Management, 18(3), pp.316-329.

Ayağ, Z., 2005. A fuzzy AHP-based simulation approach to concept evaluation in a NPD environment. IIE transactions, 37(9), pp.827-842.

Ayers, J.B., 2006. Handbook of supply chain management. CRC Press.

Azadi, M. and Saen, R.F., 2011. A new chance-constrained data envelopment analysis for selecting third-party reverse logistics providers in the existence of dual-role factors. Expert Systems with Applications, 38(10), pp.12231-12236.

Bagchi, P.K. and Virum, H., 1996. European logistics alliances: a management model. The International Journal of Logistics Management,7(1), pp.93-108.

Ballou, R.H., 1999. Business Logistics Management. The Planning, Organizing and Controlling of Supply Chain. Prentice-Hall. Upper Saddle River, NJ.

Berglund, M., Van Laarhoven, P., Sharman, G. and Wandel, S., 1999. Third-party logistics: is there a future?. The International Journal of Logistics Management, 10(1), pp.59-70.

Bhatnagar, R. and Viswanathan, S., 2000. Re-engineering global supply chains: alliances between manufacturing firms and global logistics services providers. International Journal of Physical Distribution & Logistics Management,30(1), pp.13-34.

Bhatnagar, R., Sohal, A.S. and Millen, R., 1999. Third party logistics services: a Singapore perspective. International Journal of Physical Distribution & Logistics Management, 29(9), pp.569-587.

Bolumole, Y.A., 2001. The supply chain role of third-party logistics providers. The International Journal of Logistics Management, 12(2), pp.87-102.

Bottani, E. and Rizzi, A., 2006. A fuzzy TOPSIS methodology to support outsourcing of logistics services. Supply Chain Management: An International Journal, 11(4), pp.294-308.

Bowersox, D.J., Closs, D.J. and Cooper, M.B., 2002. Supply chain logistics management (Vol. 2). New York, NY: McGraw-Hill.

Bradley, P., 1994. Contract Logistics: İt's All About Costs, Purchasing. October, 56A3±56A14.

BTRE (2001) Logistics in Australia: A Preliminary Analysis. Bureau of Transport and Regional Economics, Canberra, http://www.btre.gov.au/docs/wp49_contents.htm

Büyüközkan, G., Feyzioğlu, O. and Nebol, E., 2008. Selection of the strategic alliance partner in logistics value chain. International Journal of Production Economics, 113(1), pp.148-158.

Byrne, P.M., 1993. A new road map for contract logistics. Transportation & Distribution, 34(4), pp.58-62.

Cai, X., Chen, J., Xiao, Y., Xu, X. and Yu, G., 2013. Fresh-product supply chain management with logistics outsourcing. Omega, 41(4), pp.752-765.

Cakir, E., 2009. Logistics outsourcing and selection of third party logistics service provider (3PL) via fuzzy AHP. Yüksek Lisans Tezi, Bahçeşehir Üniversitesi Fen Bilimleri Enstitüsü, İstanbul.

ÇAKIR, E., TOZAN, H. and VAYVAY, Ö., 2009. A method for selecting third party logistic service provider using fuzzy AHP. Deniz Bilimleri ve Mühendisliği Dergisi, 5(3).

Carayannis, E.G., Kassicieh, S.K. and Radosevich, R., 2000. Strategic alliances as a source of early-stage seed capital in new technology-based firms. Technovation, 20(11), pp.603-615.

Chai, J., Liu, J.N. and Ngai, E.W., 2013. Application of decision-making techniques in supplier selection: A systematic review of literature. Expert Systems with Applications,40(10), pp.3872-3885.

Chopra, S. and Meindl, P., 2007. Supply chain management. Strategy, planning & operation (pp. 265-275). Gabler.

Cooper, J.C., 1993. Logistics strategies for global businesses. International journal of physical distribution & logistics management, 23(4), pp.12-23.

Coyle, J.J., Bardi, E.J. and Langley, C.J., 1996. The management of business logistics (Vol. 6). St Paul, MN: West Publishing Company.

Cross, J., 1995. IT outsourcing: British Petroleum's competitive approach. Long Range Planning, 28(4), pp.128-128.

Deng, H., 1999, August. Multicriteria analysis with fuzzy pairwise comparison. In Fuzzy Systems Conference Proceedings, 1999. FUZZ-IEEE'99. 1999 IEEE International (Vol. 2, pp. 726-731). IEEE.

Efendigil, T., Önüt, S. and Kongar, E., 2008. A holistic approach for selecting a third-party reverse logistics provider in the presence of vagueness.Computers & Industrial Engineering, 54(2), pp.269-287.

Farzipoor Saen, R., 2009. A mathematical model for selecting third-party reverse logistics providers.International Journal of Procurement Management,2(2), pp.180-190.

Feeny, D., Lacity, M. and Willcocks, L.P., 2005. Outsourcing Providers.

Ghodsypour, S.H. and O'Brien, C., 1998. A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming. International journal of production economics, 56, pp.199-212.

Göl, H. and Çatay, B., 2007. Third-party logistics provider selection: insights from a Turkish automotive company. Supply Chain Management: An International Journal, 12(6), pp.379-384.

Govindan, K., Khodaverdi, R. and Vafadarnikjoo, A., 2016. A grey DEMATEL approach to develop third-party logistics provider selection criteria. Industrial Management & Data Systems, 116(4), pp.690-722.

Güner, H., 2005. Bulanık AHP ve bir isletme için tedarikçi problemine uygulanması.

Gupta, R., Sachdeva, A. and Bhardwaj, A., 2010, October. Selection of 3PL service provider using integrated fuzzy Delphi and fuzzy TOPSIS. InProceedings of the world congress on engineering and computer science (Vol. 2, pp. 20-22).

Gurchiek, K., 2005. Record growth in outsourcing of HR functions. HR Magazine, 50(6), pp.35-36.

Haas, D.A., Murphy, F.H. and Lancioni, R.A., 2003. Managing reverse logistics channels with data envelopment analysis. Transportation Journal, pp.59-69.

Hamdan, A. and Rogers, K.J., 2008. Evaluating the efficiency of 3PL logistics operations.International Journal of Production Economics,113(1), pp.235-244.

Ho, W., Xu, X. and Dey, P.K., 2010. Multi-criteria decision making approaches for supplier evaluation and selection: A literature review.European Journal of Operational Research, 202(1), pp.16-24.

Hung Lau, K. and Zhang, J., 2006. Drivers and obstacles of outsourcing practices in China.International Journal of Physical Distribution & Logistics Management, 36(10), pp.776-792.

Hung Lau, K. and Zhang, J., 2006. Drivers and obstacles of outsourcing practices in China.International Journal of Physical Distribution & Logistics Management, 36(10), pp.776-792.

Hwang, C.L. and Yoon, K., 2012. Multiple attribute decision making: methods and applications a state-of-the-art survey (Vol. 186). Springer Science & Business Media.

Işıklar, G., Alptekin, E. and Büyüközkan, G., 2007. Application of a hybrid intelligent decision support model in logistics outsourcing. Computers & Operations Research, 34(12), pp.3701-3714.

J. Yan, P. E. Chaudhry, and S. S. Chaudhry, “A model of a decision support system based on case-based reasoning for third-party logistics evaluation,” Expert Systems, vol. 20, no. 4, pp. 196–207, 2003.

Jharkharia, S. and Shankar, R., 2007. Selection of logistics service provider: An analytic network process (ANP) approach. Omega, 35(3), pp.274-289.

Kahraman, C., Cebeci, U. and Ulukan, Z., 2003. Multi-criteria supplier selection using fuzzy AHP. Logistics information management, 16(6), pp.382-394.

Keeney, R.L. and Raiffa, H., 1993. Decisions with multiple objectives: preferences and value trade-offs. Cambridge university press.

Lambert, D.M., Stock, J.R. and Ellram, L.M., 1998. Fundamentals of logistics management. McGraw-Hill/Irwin.

Lambert, Douglas M., Margaret A. Emmelhainz, and John T. Gardner. "Building successful logistics partnerships." Journal of Business Logistics 20, no. 1 (1999): 165.

Langley, C.J. and Capgemini, C.J., 2016.Third-Party Logistics Study: The State of Logistics Outsourcing. Capgemini Consulting: 56pp.

Lee, Y. and Cavusgil, S.T., 2006. Enhancing alliance performance: The effects of contractual-based versus relational-based governance. Journal of business research, 59(8), pp.896-905.

Lewin, J.E. and Johnston, W.J., 1996. The effects of organizational restructuring on industrial buying behavior: 1990 and beyond. Journal of business & Industrial marketing, 11(6), pp.93-111.

Lieb, R. and Kendrick, S., 2002, January. The Use of Third-Party Logistics Services by Large American Manufacturers, the 2002 Survey. In Supply Chain Forum: an International Journal (Vol. 3, No. 2, pp. 2-10). Taylor & Francis.

Lieb, R.C. and Randall, H.L., 1996. A comparison of the use of third-party logistics services by large American manufacturers, 1991, 1994, and 1995.Journal of Business Logistics, 17(1), p.305.

Lieb, R.C., Millen, R.A. and Van Wassenhove, L.N., 1993. Third party logistics services: a comparison of experienced American and European manufacturers. International Journal of Physical Distribution & Logistics Management,23(6), pp.35-44.

Linder, J.C., 2004. Transformational outsourcing.MIT Sloan Management Review, 45(2), p.52.

Liou, T.S. and Wang, M.J.J., 1992. Ranking fuzzy numbers with integral value. Fuzzy sets and systems, 50(3), pp.247-255.

Liu, H.T. and Wang, W.K., 2009. An integrated fuzzy approach for provider evaluation and selection in third-party logistics. Expert Systems with Applications, 36(3), pp.4387-4398.

Lynch, C. F., 2000. Managing the outsourcing relationship. Supply Chain Management, Master thesis, Pamukkale University

McGovern, G. and Quelch, J., 2005. Outsourcing marketing. Harvard Business Review, 83(3), pp.22-26.

Meade, L. and Sarkis, J., 2002. A conceptual model for selecting and evaluating third-party reverse logistics providers. Supply Chain Management: An International Journal, 7(5), pp.283-295.

Mehta, R., Polsa, P., Mazur, J., Xiucheng, F. and Dubinsky, A.J., 2006. Strategic alliances in international distribution channels. Journal of Business Research, 59(10), pp.1094-1104.

Mentzer, J.T., Myers, M.B. and Stank, T.P., 2006. Handbook of global supply chain management. Sage Publications.

Murray, M., 2010. Selecting a third party logistics (3PL) provider.

Nguyen, H.T. and Walker, E.A., 2000. A first course in fuzzy logic.Nispeling, T., 2015. Multi-Criteria Supplier Selection in the Edible Oil Industry: The Case of a New Oils & Fats Plant in China (Doctoral dissertation, TU Delft, Delft University of Technology).

Prakash, C. and Barua, M.K., 2016. An analysis of integrated robust hybrid model for third-party reverse logistics partner selection under fuzzy environment. Resources, Conservation and Recycling, 108, pp.63-81.

Quélin, B. and Duhamel, F., 2003. Bringing together strategic outsourcing and corporate strategy:: Outsourcing motives and risks.European management journal, 21(5), pp.647-661.

Qureshi, M.N., Kumar, D. and Kumar, P., 2007. Performance evaluation of 3PL Services provider using AHP and TOPSIS: a case study. The Icfai Journal of Supply Chain Management, 4(3), pp.20-38.Review, 4 (4), pp. 90-96.

Rezaei, J., 2015. Best-worst multi-criteria decision-making method. Omega,53, pp.49-57.

Rezaei, J., 2015. Best-worst multi-criteria decision-making method: Some properties and a linear model. Omega.Rocheleau, J. (2016). Who's Who in Logistics Online 3PL Guide - Armstrong & Associates. [online] Armstrong & Associates. Available at: http://www.3plogistics.com/product/whos-who-in-logistics-online-guide/ [Accessed 4 Jun. 2016].

RONALD, H.B., 1992. Business logistics management: planning, organizing, and controlling the supply chain.

Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. European journal of operational research, 48(1), pp.9-26.

Saaty, T.L., 2001. Decision making with dependence and feedback: The analytic network process. Pittsburgh. RWS Publications, 7, pp.557-570.

Sahay, B.S. and Mohan, R., 2006. 3PL practices: an Indian perspective. International Journal of Physical Distribution & Logistics Management,36(9), pp.666-689.

Sanders, N.R., Locke, A., Moore, C.B. and Autry, C.W., 2007. A multidimensional framework for understanding outsourcing arrangements. Journal of Supply Chain Management, 43(4), pp.3-15.

Sekaran, U., 2006. Research methods for business: A skill building approach. John Wiley & Sons.

Shi, Y., Zhang, A., Arthanari, T., Liu, Y. and Cheng, T.C.E., 2016. Third-party purchase: An empirical study of third-party logistics providers in China.International Journal of Production Economics, 171, pp.189-200.

Simchi-Levi, D., 2005. Designing and managing the supply chain. Mcgraw-Hill College.

Soh, S., 2010. A decision model for evaluating third-party logistics providers using fuzzy analytic hierarchy process. African Journal of Business Management, 4(3), p.339.

Sohail, M.S. and Sohal, A.S., 2003. The use of third party logistics services: a Malaysian perspective. Technovation, 23(5), pp.401-408.

Stock, J.R. and Lambert, D.M., 2001. Strategic logistics management (Vol. 4). Boston, MA: McGraw-Hill/Irwin.

Tan, K.C., 2001. A framework of supply chain management literature. European Journal of Purchasing & Supply Management, 7(1), pp.39-48.

Tang, Y.C. and Beynon, M.J., 2005. Application and development of a fuzzy analytic hierarchy process within a capital investment study. Journal of Economics and Management, 1(2), pp.207-230.

Tilanus, B. ed., 1997. Information systems in logistics and transportation. London: Pergamon.

Tsai, M.C., Liao, C.H. and Han, C.S., 2008. Risk perception on logistics outsourcing of retail chains: model development and empirical verification in Taiwan. Supply Chain Management: An International Journal, 13(6), pp.415-424.

Turkey's Transportation and Logistics Industry Report, 2003 (http://www.invest.gov.tr/en-US/infocenter/publications/Documents/TRANSPORTATION-LOGISTICS-INDUSTRY.pdf)

Turkstat.gov.tr. (2016). : Welcome to Turkish Statistical Institute(TurkStat)'s Web Pages::... [online] Available at: http://www.turkstat.gov.tr [Accessed 15 May. 2016].

Wallenburg, C.M., 2004. Kundenbindung in der Logistik: eine empirische Untersuchung zu ihren Einflussfaktoren. Haupt.

Wang, T., 2014. An Empirical Study of the Economic Effects of Outsourcing-----Based on China's Economic Development Data. International Journal of Business and Social Science, 5(11).

Wilding, R. and Juriado, R., 2004. Customer perceptions on logistics outsourcing in the European consumer goods industry. International Journal of Physical Distribution & Logistics Management, 34(8), pp.628-644.

Yan, J. and Peggy, E., 2003. Article_. *Expert Systems*, *20*(4), p.197.

Yang, Q., Zhao, X., Yeung, H.Y.J. and Liu, Y., 2016. Improving logistics outsourcing performance through transactional and relational mechanisms under transaction uncertainties: Evidence from China. International Journal of Production Economics, 175, pp.12-23.

Yang, Q., Zhao, X., Yeung, H.Y.J. and Liu, Y., 2016. Improving logistics outsourcing performance through transactional and relational mechanisms under transaction uncertainties: Evidence from China. International Journal of Production Economics, 175, pp.12-23.

Yeung, J.H.Y., Selen, W., Sum, C.C. and Huo, B., 2006. Linking financial performance to strategic orientation and operational priorities: An empirical study of third-party logistics providers.International Journal of Physical Distribution & Logistics Management, 36(3), pp.210-230.

Zadeh, L.A., 1965. Information and control. Fuzzy sets, 8(3), pp.338-353.

Zhang, G., Shang, J. and Li, W., 2012. An information granulation entropy-based model for third-party logistics providers evaluation. International Journal of Production Research, 50(1), pp.177-190.

Zhang, H., Li, X., Liu, W., Li, B. and Zhang, Z., 2004, October. An application of the AHP in 3PL vendor selection of a 4PL system. In Systems, Man and Cybernetics, 2004 IEEE International Conference on (Vol. 2, pp. 1255-1260). IEEE.

Zhang, Z.H., 2007. A probe on logistics strategic partner selecting model with preference DEA based on AHP. Journal of Chinese Market, 8, pp.66-67.

Appendices

Appendix A: Questionnaire

A.1 Questionnaire for criteria identification

The survey aims at identifying criteria used by the company to select a suitable third-party logistics service provider. It is not only meant to identify the most important criteria but also the less tangible criteria that may be considered when selecting a third-party logistics service provider.

Literatures relating to third-party logistics provider selection were examined and they produced a vast amount of selection criteria. The most important and frequently mentioned criteria are listed below. **Could you indicate which of these you think should be taken into account when selecting a third-party logistics service provider**?

CRITERIA	DESCRIPTION
Cost of service	Refers to the total cost of logistics sourcing.
Quality of service	Quality of the provider includes many aspects such as on-time delivery, accuracy of order fulfilment, frequency and cost of loss and damage...etc.
Risk management	The capability of the provider to address any unforeseen problem. It is needed to ensure the continuity of the services.
Technological capabilities	The level of equipment and devices used by the provider, speed and internet compatibility software.
Reputation of the company	The company's logo, facilities, positive and negative experiences of past customers and public recognition.
Delivery time	Competitive delivery time, on-time delivery capabilities, and speed of response to order.
Long-term relationship	Shared risk, rewards, and cooperation between the two companies.
Financial stability	The firm's financial conditions (liquidity).

Could you also indicate, if any, which criterion/criteria you think should be consider that have not been mentioned above (as many as possible).

Criteria

Thanks for your response!!!

APPENDIX B: Vectors for evaluating criteria

Table B.1: Decision makers' linguistic preferences for best criterion over all other.

Best-to-others vector				
CRITERIA	**DM 1**	**DM 2**	**DM 3**	**DM 4**
C1	MP	MP	MP	MP
C2	SP	EP	SP	SP
C3	VSP	SP	MP	VSP
C4	MP	SP	VSP	MP
C5	MP	MP	MP	MP
C6	MP	EMP	VSP	SP
C7	EMP	MP	MP	EMP
C8	SP	SP	EMP	MP
C9	SP	MP	EMP	MP
C10	SP	VSP	EP	SP
C11	MP	MP	MP	VSP
C12	MP	SP	SP	MP
C13	EP	VSP	VSP	VSP
C14	VSP	EMP	MP	MP
C15	MP	MP	SP	EP

Table B.2: Decision makers' linguistic preferences for all other criteria over the worst criterion.

Others-to-worst Vector				
CRITERIA	**DM 1**	**DM 2**	**DM 3**	**DM 4**
C1	VSP	VSP	VSP	VSP
C2	SP	EMP	SP	SP
C3	MP	SP	VSP	MP
C4	SP	SP	MP	VSP
C5	SP	SP	VSP	VSP
C6	MP	EP	MP	SP
C7	EP	VSP	VSP	EP
C8	SP	MP	EP	VSP
C9	SP	MP	EP	VSP
C10	SP	SP	EMP	SP
C11	VSP	VSP	VSP	MP
C12	VSP	SP	SP	VSP
C13	EMP	SP	MP	MP
C14	MP	EP	SP	VSP
C15	MP	SP	SP	EMP

APPENDIX C: Vectors for evaluating alternatives

Table C.1: Decision makers' best and worst alternatives with respect to each criterion

CRITERIA		DM 1	DM 2	DM 3	DM 4
C1	BEST	A6	A1	A1	A3
	WORST	A1	A5	A3	A4
C2	BEST	A1	A3	A4	A3
	WORST	A5	A2	A5	A1
C3	BEST	A3	A1	A6	A1
	WORST	A6	A2	A2	A3
C4	BEST	A3	A1	A6	A3
	WORST	A2	A3	A3	A1
C5	BEST	A4	A2	A5	A3
	WORST	A1	A1	A3	A1
C6	BEST	A4	A1	A1	A5
	WORST	A5	A6	A4	A6
C7	BEST	A1	A3	A3	A3
	WORST	A2	A6	A1	A6
C8	BEST	A3	A1	A1	A1
	WORST	A1	A4	A6	A2
C9	BEST	A4	A4	A6	A6
	WORST	A2	A2	A2	A3
C10	BEST	A3	A3	A1	A3
	WORST	A5	A6	A2	A6
C11	BEST	A6	A1	A1	A1
	WORST	A3	A6	A2	A4
C12	BEST	A1	A1	A6	A3
	WORST	A2	A6	A1	A4
C13	BEST	A1	A4	A1	A2
	WORST	A3	A1	A3	A3
C14	BEST	A3	A2	A1	A1
	WORST	A2	A1	A5	A4
C15	BEST	A1	A1	A4	A2
	WORST	A3	A6	A5	A5

Table C.2: Definition and membership function of fuzzy number for comparing alternatives (Ayağ 2005)

Intensity of importance	Fuzzy numbers	Linguistic terms for importance	Triangular membership function
1	$\tilde{1}$	Equally Important (EI)	(1, 1, 2)
3	$\tilde{3}$	Moderately Important (MI)	(2, 3, 4)
5	$\tilde{5}$	Very Important (VI)	(4, 5, 6)
7	$\tilde{7}$	Absolutely Important (AI)	(6, 7, 8)
9	$\tilde{9}$	Extremely More Important (EMI)	(8, 9, 10)

Table C.3: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 1.

BO VECTOR, C1				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	EMI	EI	EI	MI
A2	MI	MI	VI	VI
A3	VI	VI	EMI	EI
A4	MI	AI	AI	EMI
A5	AI	EMI	MI	AI
A6	EI	MI	VI	MI
OW VECTOR, C1				
A1	EI	EMI	EMI	MI
A2	VI	AI	MI	VI
A3	VI	VI	EI	EMI
A4	AI	MI	MI	EI
A5	MI	EI	VI	MI
A6	EMI	AI	VI	VI

Table C.4: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 2.

BO VECTOR, C2				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	EI	VI	AI	EMI
A2	MI	EMI	MI	MI
A3	VI	EI	VI	EI
A4	AI	AI	EI	VI
A5	EMI	MI	EMI	MI
A6	MI	VI	MI	AI
OW VECTOR, C2				
A1	EMI	MI	VI	EI
A2	MI	EI	MI	AI
A3	VI	EMI	MI	EMI
A4	MI	MI	EMI	VI
A5	EI	AI	EI	MI
A6	AI	VI	AI	AI

Table C.5: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 3.

BO VECTOR, C3				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	MI	EI	MI	EI
A2	AI	EMI	EMI	MI
A3	EI	MI	VI	EMI
A4	VI	VI	MI	VI
A5	MI	MI	AI	AI
A6	EMI	VI	EI	MI
OW VECTOR, C3				
A1	AI	EMI	MI	EMI
A2	MI	EI	EI	VI
A3	EMI	AI	VI	EI
A4	VI	VI	AI	VI
A5	MI	MI	MI	MI
A6	EI	MI	EMI	AI

Table C.6: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 4.

BO VECTOR, C4				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	MI	EI	AI	EMI
A2	EMI	MI	MI	MI
A3	EI	EMI	EMI	EI
A4	VI	VI	VI	VI
A5	MI	MI	MI	AI
A6	AI	AI	EI	MI
OW VECTOR, C4				
A1	MI	EMI	MI	EI
A2	EI	MI	VI	MI
A3	EMI	EI	EI	EMI
A4	VI	VI	VI	VI
A5	MI	AI	VI	MI
A6	MI	MI	EMI	AI

Table C.7: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 5

BO VECTOR, C5				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	EMI	EMI	MI	EMI
A2	MI	EI	AI	AI
A3	VI	MI	EMI	EI
A4	EI	VI	MI	VI
A5	AI	MI	EI	MI
A6	MI	MI	VI	AI
OW VECTOR, C5				
A1	EI	EI	MI	EI
A2	AI	EMI	MI	MI
A3	VI	AI	EI	EMI
A4	EMI	VI	VI	VI
A5	MI	VI	EMI	AI
A6	AI	VI	VI	MI

. Table C.8: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 6.

BO VECTOR, C6				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	MI	EI	EI	MI
A2	VI	MI	MI	AI
A3	MI	VI	VI	VI
A4	EI	MI	EMI	MI
A5	EMI	MI	AI	EI
A6	AI	EMI	MI	EMI
OW VECTOR, C6				
A1	MI	EMI	EMI	AI
A2	MI	VI	VI	MI
A3	MI	MI	MI	VI
A4	EMI	AI	EI	VI
A5	EI	AI	MI	EMI
A6	MI	EI	VI	EI

Table C.9: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 7.

BO VECTOR, C7				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	EI	MI	EMI	MI
A2	EMI	MI	MI	AI
A3	MI	EI	EI	EI
A4	VI	VI	AI	MI
A5	MI	AI	VI	VI
A6	MI	EMI	MI	EMI
OW VECTOR, C7				
A1	EMI	VI	EI	MI
A2	EI	VI	AI	MI
A3	AI	EMI	EMI	EMI
A4	VI	MI	MI	AI
A5	MI	MI	VI	VI
A6	VI	EI	MI	EI

Table C.10: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 8.

BO VECTOR, C8				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	EMI	EI	EI	EI
A2	MI	MI	MI	EMI
A3	EI	VI	VI	MI
A4	MI	EMI	MI	VI
A5	AI	MI	AI	MI
A6	MI	AI	EMI	AI
OW VECTOR, C8				
A1	EI	EMI	EMI	EMI
A2	VI	VI	AI	EI
A3	EMI	VI	VI	AI
A4	VI	EI	MI	VI
A5	MI	AI	VI	AI
A6	MI	MI	EI	MI

.

Table C.11: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 9.

BO VECTOR, C9				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	MI	MI	MI	MI
A2	EMI	EMI	EMI	VI
A3	VI	VI	VI	EMI
A4	EI	EI	MI	MI
A5	AI	AI	VI	AI
A6	MI	MI	EI	EI
OW VECTOR, C9				
A1	VI	MI	AI	AI
A2	EI	EI	EI	VI
A3	MI	VI	VI	EI
A4	EMI	EMI	AI	MI
A5	MI	MI	MI	AI
A6	AI	AI	EMI	EMI

Table C.12: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 10.

BO VECTOR, C10				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	MI	AI	EI	MI
A2	VI	MI	EMI	AI
A3	EI	EI	MI	EI
A4	AI	MI	VI	MI
A5	EMI	VI	AI	VI
A6	MI	EMI	MI	EMI
OW VECTOR, C10				
A1	VI	MI	EMI	AI
A2	MI	AI	EI	MI
A3	EMI	EMI	AI	EMI
A4	MI	VI	VI	VI
A5	EI	MI	MI	MI
A6	MI	EI	AI	EI

Table C.13: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 11.

BO VECTOR, C11				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	MI	EI	EI	EI
A2	AI	MI	EMI	MI
A3	EMI	VI	AI	VI
A4	VI	MI	VI	EMI
A5	MI	MI	MI	AI
A6	EI	EMI	VI	MI
OW VECTOR, C11				
A1	MI	EMI	EMI	EMI
A2	MI	AI	EI	MI
A3	EI	VI	VI	VI
A4	VI	VI	VI	EI
A5	AI	AI	MI	MI
A6	EMI	EI	VI	AI

Table C.14: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 12.

BO VECTOR, C12				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	EI	EI	EMI	AI
A2	EMI	MI	AI	MI
A3	MI	VI	MI	EI
A4	VI	MI	VI	EMI
A5	AI	MI	MI	MI
A6	MI	EMI	EI	VI
OW VECTOR, C12				
A1	EMI	EMI	EI	MI
A2	EI	AI	MI	AI
A3	MI	VI	VI	EMI
A4	VI	AI	MI	EI
A5	MI	MI	MI	AI
A6	AI	EI	EMI	VI

Table C.15: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 13.

BO VECTOR, C13				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	EI	EMI	EI	MI
A2	MI	MI	VI	EI
A3	EMI	MI	EMI	EMI
A4	MI	EI	MI	AI
A5	MI	VI	AI	VI
A6	MI	VI	VI	MI
OW VECTOR, C13				
A1	EMI	EI	EMI	AI
A2	VI	AI	MI	EMI
A3	EI	AI	EI	EI
A4	AI	EMI	AI	MI
A5	MI	VI	MI	VI
A6	MI	VI	VI	AI

Table C.16: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 14.

BO VECTOR, C14				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	MI	EMI	EI	EI
A2	EMI	EI	MI	MI
A3	EI	MI	AI	AI
A4	MI	VI	VI	EMI
A5	MI	AI	EMI	AI
A6	MI	AI	MI	MI
OW VECTOR, C14				
A1	MI	EI	EMI	EMI
A2	EI	EMI	AI	AI
A3	EMI	AI	MI	MI
A4	MI	VI	MI	EI
A5	MI	MI	EI	VI
A6	MI	MI	VI	AI

Table C.17: Linguistic preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 15.

BO VECTOR, C15				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	EI	EI	VI	MI
A2	MI	MI	MI	EI
A3	EMI	VI	VI	AI
A4	VI	MI	EI	VI
A5	AI	MI	EMI	EMI
A6	MI	EMI	MI	VI
OW VECTOR, C15				
A1	EMI	EMI	MI	MI
A2	VI	VI	VI	EMI
A3	EI	MI	VI	AI
A4	MI	VI	EMI	MI
A5	MI	VI	EI	EI
A6	AI	EI	AI	VI

Table C.18: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 1.

BO VECTOR, C1				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(8,9,10)	1	1	(2,3,4)
A2	(2,3,4)	(2,3,4)	(4,5,6)	(4,5,6)
A3	(3,5,6)	(4,5,6)	(8,9,10)	1
A4	(2,3,4)	(6,7,8)	(6,7,8)	(8,9,10)
A5	(6,7,8)	(8,9,10)	(2,3,4)	(6,7,8)
A6	1	(2,3,4)	(4,5,6)	(2,3,4)
OW VECTOR, C1				
A1	1	(8,9,10)	(8,9,10)	(2,3,4)
A2	(4,5,6)	(6,7,8)	(2,3,4)	(4,5,6)
A3	(4,5,6)	(4,5,6)	1	(8,9,10)
A4	(6,7,8)	(2,3,4)	(2,3,4)	1
A5	(2,3,4)	1	(4,5,6)	(2,3,4)
A6	(8,9,10)	(6,7,8)	(4,5,6)	(4,5,6)

Table C.19: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 2.

BO VECTOR, C2				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	1	(4,5,6)	(6,7,8)	(8,9,10)
A2	(2,3,4)	(8,9,10)	(2,3,4)	(2,3,4)
A3	(4,5,6)	1	(4,5,6)	1
A4	(6,7,8)	(6,7,8)	1	(4,5,6)
A5	(8,9,10)	(2,3,4)	(8,9,10)	(2,3,4)
A6	(2,3,4)	(4,5,6)	(2,3,4)	(6,7,8)
OW VECTOR, C2				
A1	(8,9,10)	(2,3,4)	(4,5,6)	1
A2	(2,3,4)	1	(2,3,4)	(6,7,8)
A3	(4,5,6)	(8,9,10)	(2,3,4)	(8,9,10)
A4	(2,3,4)	(2,3,4)	(8,9,10)	(4,5,6)
A5	1	(6,7,8)	1	(2,3,4)
A6	(6,7,8)	(4,5,6)	(6,7,8)	(6,7,8)

Table C.20: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 3.

BO VECTOR, C3				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(2,3,4)	1	(2,3,4)	1
A2	(6,7,8)	(8,9,10)	(8,9,10)	(2,3,4)
A3	1	(2,3,4)	(4,5,6)	(8,9,10)
A4	(4,5,6)	(4,5,6)	(2,3,4)	(4,5,6)
A5	(2,3,4)	(2,3,4)	(6,7,8)	(6,7,8)
A6	(8,9,10)	(6,7,8)	1	(2,3,4)
OW VECTOR, C3				
A1	(6,7,8)	(8,9,10)	(2,3,4)	(8,9,10)
A2	(2,3,4)	1	1	(4,5,6)
A3	(8,9,10)	(6,7,8)	(4,5,6)	1
A4	(4,5,6)	(4,5,6)	(6,7,8)	(4,5,6)
A5	(2,3,4)	(2,3,4)	(2,3,4)	(2,3,4)
A6	1	(2,3,4)	(8,9,10)	(6,7,8)

Table C.21: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 4.

BO VECTOR, C4				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(2,3,4)	1	(6,7,8)	(8,9,10)
A2	(8,9,10)	(2,3,4)	(2,3,4)	(2,3,4)
A3	1	(8,9,10)	(8,9,10)	1
A4	(4,5,6)	(4,5,6)	(4,5,6)	(4,5,6)
A5	(2,3,4)	(2,3,4)	(2,3,4)	(6,7,8)
A6	(6,7,8)	(6,7,8)	1	(2,3,4)
OW VECTOR, C4				
A1	(2,3,4)	(8,9,10)	(2,3,4)	1
A2	1	(2,3,4)	(6,7,8)	(2,3,4)
A3	(8,9,10)	1	1	(8,9,10)
A4	(4,5,6)	(4,5,6)	(4,5,6)	(4,5,6)
A5	(2,3,4)	(6,7,8)	(4,5,6)	(2,3,4)
A6	(2,3,4)	(2,3,4)	(8,9,10)	(6,7,8)

Table C.22: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 5.

BO VECTOR, C5				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(8,9,10)	(8,9,10)	(2,3,4)	(8,9,10)
A2	(2,3,4)	1	(6,7,8)	(6,7,8)
A3	(4,5,6)	(2,3,4)	(8,9,10)	1
A4	1	(4,5,6)	(2,3,4)	(4,5,6)
A5	(6,7,8)	(2,3,4)	1	(2,3,4)
A6	(2,3,4)	(2,3,4)	(4,5,6)	(6,7,8)
OW VECTOR, C5				
A1	1	1	(2,3,4)	1
A2	(6,7,8)	(8,9,10)	(2,3,4)	(2,3,4)
A3	(4,5,6)	(6,7,8)	1	(8,9,10)
A4	(8,9,10)	(4,5,6)	(4,5,6)	(4,5,6)
A5	(2,3,4)	(4,5,6)	(8,9,10)	(6,7,8)
A6	(6,7,8)	(4,5,6)	(4,5,6)	(2,3,4)

Table C.23: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 6.

BO VECTOR, C6				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(2,3,4)	1	1	(2,3,4)
A2	(4,5,6)	(2,3,4)	(2,3,4)	(6,7,8)
A3	(2,3,4)	(4,5,6)	(4,5,6)	(4,5,6)
A4	1	(2,3,4)	(8,9,10)	(2,3,4)
A5	(8,9,10)	(2,3,4)	(6,7,8)	1
A6	(6,7,8)	(8,9,10)	(2,3,4)	(8,9,10)
OW VECTOR, C6				
A1	(2,3,4)	(8,9,10)	(8,9,10)	(6,7,8)
A2	(2,3,4)	(4,5,6)	(4,5,6)	(2,3,4)
A3	(2,3,4)	(2,3,4)	(2,3,4)	(4,5,6)
A4	(8,9,10)	(6,7,8)	1	(4,5,6)
A5	1	(6,7,8)	(2,3,4)	(8,9,10)
A6	(2,3,4)	1	(4,5,6)	1

Table C.24: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 7.

BO VECTOR, C7				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	1	(2,3,4)	(8,9,10)	(2,3,4)
A2	(8,9,10)	(2,3,4)	(2,3,4)	(6,7,8)
A3	(2,3,4)	1	1	1
A4	(4,5,6)	(4,5,6)	(6,7,8)	(2,3,4)
A5	(2,3,4)	(6,7,8)	(4,5,6)	(4,5,6)
A6	(2,3,4)	(8,9,10)	(2,3,4)	(8,9,10)
OW VECTOR, C7				
A1	(8,9,10)	(4,5,6)	1	(2,3,4)
A2	1	(4,5,6)	(6,7,8)	(2,3,4)
A3	(6,7,8)	(8,9,10)	(8,9,10)	(8,9,10)
A4	(4,5,6)	(2,3,4)	(2,3,4)	(6,7,8)
A5	(2,3,4)	(2,3,4)	(4,5,6)	(4,5,6)
A6	(4,5,6)	1	(2,3,4)	1

Table C.25: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 8.

BO VECTOR, C8				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(8,9,10)	1	1	1
A2	(2,3,4)	(2,3,4)	(2,3,4)	(8,9,10)
A3	1	(4,5,6)	(4,5,6)	(2,3,4)
A4	(2,3,4)	(8,9,10)	(2,3,4)	(4,5,6)
A5	(6,7,8)	(2,3,4)	(6,7,8)	(2,3,4)
A6	(2,3,4)	(6,7,8)	(8,9,10)	(6,7,8)
OW VECTOR, C8				
A1	1	(8,9,10)	(8,9,10)	(8,9,10)
A2	(4,5,6)	(4,5,6)	(6,7,8)	1
A3	(8,9,10)	(4,5,6)	(4,5,6)	(6,7,8)
A4	(4,5,6)	1	(2,3,4)	(4,5,6)
A5	(2,3,4)	(6,7,8)	(4,5,6)	(6,7,8)
A6	(2,3,4)	(2,3,4)	1	(2,3,4)

Table C.26: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 9.

BO VECTOR, C9				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(2,3,4)	(2,3,4)	(2,3,4)	(2,3,4)
A2	(8,9,10)	(8,9,10)	(8,9,10)	(4,5,6)
A3	(4,5,6)	(4,5,6)	(4,5,6)	(8,9,10)
A4	1	1	(2,3,4)	(2,3,4)
A5	(6,7,8)	(6,7,8)	(4,5,6)	(6,7,8)
A6	(2,3,4)	(2,3,4)	1	1
OW VECTOR, C9				
A1	(4,5,6)	(2,3,4)	(6,7,8)	(6,7,8)
A2	1	1	1	(4,5,6)
A3	(2,3,4)	(4,5,6)	(4,5,6)	1
A4	(8,9,10)	(8,9,10)	(6,7,8)	(2,3,4)
A5	(2,3,4)	(2,3,4)	(2,3,4)	(6,7,8)
A6	(6,7,8)	(6,7,8)	(8,9,10)	(8,9,10)

Table C.27: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 10.

BO VECTOR, C10				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(2,3,4)	(6,7,8)	1	(2,3,4)
A2	(4,5,6)	(2,3,4)	(8,9,10)	(6,7,8)
A3	1	1	(2,3,4)	1
A4	(6,7,8)	(2,3,4)	(4,5,6)	(2,3,4)
A5	(8,9,10)	(4,5,6)	(6,7,8)	(4,5,6)
A6	(2,3,4)	(8,9,10)	(2,3,4)	(8,9,10)
OW VECTOR, C10				
A1	(4,5,6)	(2,3,4)	(8,9,10)	(6,7,8)
A2	(2,3,4)	(6,7,8)	1	(2,3,4)
A3	(8,9,10)	(8,9,10)	(6,7,8)	(8,9,10)
A4	(2,3,4)	(4,5,6)	(4,5,6)	(4,5,6)
A5	1	(2,3,4)	(2,3,4)	(2,3,4)
A6	(2,3,4)	1	(6,7,8)	1

Table C.28: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 11.

BO VECTOR, C11				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(2,3,4)	1	1	1
A2	(6,7,8)	(2,3,4)	(8,9,10)	(2,3,4)
A3	(8,9,10)	(4,5,6)	(6,7,8)	(4,5,6)
A4	(4,5,6)	(2,3,4)	(4,5,6)	(8,9,10)
A5	(2,3,4)	(2,3,4)	(2,3,4)	(6,7,8)
A6	1	(8,9,10)	(4,5,6)	(2,3,4)
OW VECTOR, C11				
A1	(2,3,4)	(8,9,10)	(8,9,10)	(8,9,10)
A2	(2,3,4)	(6,7,8)	1	(2,3,4)
A3	1	(4,5,6)	(4,5,6)	(4,5,6)
A4	(4,5,6)	(4,5,6)	(4,5,6)	1
A5	(6,7,8)	(6,7,8)	(2,3,4)	(2,3,4)
A6	(8,9,10)	1	(4,5,6)	(6,7,8)

Table C.29: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 12.

BO VECTOR, C12				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	1	1	(8,9,10)	(6,7,8)
A2	(8,9,10)	(2,3,4)	(6,7,8)	(2,3,4)
A3	(2,3,4)	(4,5,6)	(2,3,4)	1
A4	(4,5,6)	(2,3,4)	(4,5,6)	(8,9,10)
A5	(6,7,8)	(2,3,4)	(2,3,4)	(2,3,4)
A6	(2,3,4)	(8,9,10)	1	(4,5,6)
OW VECTOR, C12				
A1	(8,9,10)	(8,9,10)	1	(2,3,4)
A2	1	(6,7,8)	(2,3,4)	(6,7,8)
A3	(2,3,4)	(4,5,6)	(4,5,6)	(8,9,10)
A4	(4,5,6)	(6,7,8)	(2,3,4)	1
A5	(2,3,4)	(2,3,4)	(2,3,4)	(6,7,8)
A6	(6,7,8)	1	(8,9,10)	(4,5,6)

Table C.30: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 13.

BO VECTOR, C13				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	1	(8,9,10)	1	(2,3,4)
A2	(2,3,4)	(2,3,4)	(4,5,6)	1
A3	(8,9,10)	(2,3,4)	(8,9,10)	(8,9,10)
A4	(2,3,4)	1	(2,3,4)	(6,7,8)
A5	(2,3,4)	(4,5,6)	(6,7,8)	(4,5,6)
A6	(2,3,4)	(4,5,6)	(4,5,6)	(2,3,4)
OW VECTOR, C13				
A1	(8,9,10)	1	(8,9,10)	(6,7,8)
A2	(4,5,6)	(6,7,8)	(2,3,4)	(8,9,10)
A3	1	(6,7,8)	1	1
A4	(6,7,8)	(8,9,10)	(6,7,8)	(2,3,4)
A5	(2,3,4)	(4,5,6)	(2,3,4)	(4,5,6)
A6	(2,3,4)	(4,5,6)	(4,5,6)	(6,7,8)

Table C.31: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 14.

BO VECTOR, C14				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	(2,3,4)	(8,9,10)	1	1
A2	(8,9,10)	1	(2,3,4)	(2,3,4)
A3	1	(2,3,4)	(6,7,8)	(6,7,8)
A4	(2,3,4)	(4,5,6)	(4,5,6)	(8,9,10)
A5	(2,3,4)	(6,7,8)	(8,9,10)	(4,5,6)
A6	(2,3,4)	(6,7,8)	(2,3,4)	(2,3,4)
OW VECTOR, C14				
A1	(2,3,4)	1	(8,9,10)	(8,9,10)
A2	1	(8,9,10)	(6,7,8)	(6,7,8)
A3	(8,9,10)	(6,7,8)	(2,3,4)	(2,3,4)
A4	(2,3,4)	(4,5,6)	(2,3,4)	1
A5	(2,3,4)	(2,3,4)	1	(4,5,6)
A6	(2,3,4)	(2,3,4)	(4,5,6)	(6,7,8)

Table C.32: TFNs of preferences for best-to-others (BO) and others-to-worst (OW) vectors with respect to criterion 15.

BO VECTOR, C15				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	1	1	(4,5,6)	(2,3,4)
A2	(2,3,4)	(2,3,4)	(2,3,4)	1
A3	(8,9,10)	(4,5,6)	(4,5,6)	(6,7,8)
A4	(4,5,6)	(2,3,4)	1	(4,5,6)
A5	(6,7,8)	(2,3,4)	(8,9,10)	(8,9,10)
A6	(2,3,4)	(8,9,10)	(2,3,4)	(4,5,6)
OW VECTOR, C15				
A1	(8,9,10)	(8,9,10)	(2,3,4)	(2,3,4)
A2	(4,5,6)	(4,5,6)	(4,5,6)	(8,9,10)
A3	1	(2,3,4)	(4,5,6)	(6,7,8)
A4	(2,3,4)	(4,5,6)	(8,9,10)	(2,3,4)
A5	(2,3,4)	(4,5,6)	1	1
A6	(6,7,8)	1	(6,7,8)	(4,5,6)

Table C.33: Crisp values of Best-to-others and others-to-worst vectors for criterion 1.

BO VECTOR, C1				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	9	1	1	3
A2	3	3	5	5
A3	5	5	9	1
A4	3	7	7	9
A5	7	9	3	7
A6	1	3	5	3
OW VECTOR, C1				
A1	1	9	9	3
A2	5	7	3	5
A3	5	5	1	9
A4	7	3	3	1
A5	3	1	5	3
A6	9	7	5	5

Table C.34: Crisp values of Best-to-others and others-to-worst vectors for criterion 2.

BO VECTOR, C2				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	1	5	7	9
A2	3	9	3	3
A3	5	1	5	1
A4	7	7	1	5
A5	9	3	9	3
A6	3	5	3	7
OW VECTOR, C2				
A1	9	3	5	1
A2	3	1	3	7
A3	5	9	3	9
A4	3	3	9	5
A5	1	7	1	3
A6	7	5	7	7

Table C.35: Crisp values of Best-to-others and others-to-worst vectors for criterion 3

BO VECTOR, C3				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	3	1	3	1
A2	7	9	9	3
A3	1	3	5	9
A4	5	5	3	5
A5	3	3	7	7
A6	9	7	1	3
OW VECTOR, C3				
A1	7	9	3	9
A2	3	1	1	5
A3	9	7	5	1
A4	5	5	7	5
A5	3	3	3	3
A6	1	3	9	7

Table C.36: Crisp values of Best-to-others and others-to-worst vectors for criterion 4.

BO VECTOR, C4				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	3	1	7	9
A2	9	3	3	3
A3	1	9	9	1
A4	5	5	5	5
A5	3	3	3	7
A6	7	7	1	3
OW VECTOR, C4				
A1	3	9	3	1
A2	1	3	7	3
A3	9	1	1	9
A4	5	5	5	5
A5	3	7	5	3
A6	3	3	9	7

Table C.37: Crisp values of Best-to-others and others-to-worst vectors for criterion 5.

BO VECTOR, C5				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	9	9	3	9
A2	3	1	7	7
A3	5	3	9	1
A4	1	5	3	5
A5	7	3	1	3
A6	3	3	5	7
OW VECTOR, C5				
A1	1	1	3	1
A2	7	9	3	3
A3	5	7	1	9
A4	9	5	5	5
A5	3	5	9	7
A6	7	5	5	3

Table C.38: Crisp values of Best-to-others and others-to-worst vectors for criterion 6.

BO VECTOR, C6				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	3	1	1	3
A2	5	3	3	7
A3	3	5	5	5
A4	1	3	9	3
A5	9	3	7	1
A6	7	9	3	9
OW VECTOR, C6				
A1	3	9	9	7
A2	3	5	5	3
A3	3	3	3	5
A4	9	7	1	5
A5	1	7	3	9
A6	3	1	5	1

Table C.39: Crisp values of Best-to-others and others-to-worst vectors for criterion 7.

BO VECTOR, C7				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	1	3	9	3
A2	9	3	3	7
A3	3	1	1	1
A4	5	5	7	3
A5	3	7	5	5
A6	3	9	3	9
OW VECTOR, C7				
A1	9	5	1	3
A2	1	5	7	3
A3	7	9	9	9
A4	5	3	3	7
A5	3	3	5	5
A6	5	1	3	1

Table C.40: Crisp values of Best-to-others and others-to-worst vectors for criterion 8.

BO VECTOR, C8				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	9	1	1	1
A2	3	3	3	9
A3	1	5	5	3
A4	3	9	3	5
A5	7	3	7	3
A6	3	7	9	7
OW VECTOR, C8				
A1	1	9	9	9
A2	5	5	7	1
A3	9	5	5	7
A4	5	1	3	5
A5	3	7	5	7
A6	3	3	1	3

Table C.41: Crisp values of Best-to-others and others-to-worst vectors for criterion 9.

BO VECTOR, C9				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	3	3	3	3
A2	9	9	9	5
A3	5	5	5	9
A4	1	1	3	3
A5	7	7	5	7
A6	3	3	1	1
OW VECTOR, C9				
A1	5	3	7	7
A2	1	1	1	5
A3	3	5	5	1
A4	9	9	7	3
A5	3	3	3	7
A6	7	7	9	9

Table C.42: Crisp values of Best-to-others and others-to-worst vectors for criterion 10.

BO VECTOR, C10				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	3	7	1	3
A2	5	3	9	7
A3	1	1	3	1
A4	7	3	5	3
A5	9	5	7	5
A6	3	9	3	9
OW VECTOR, C10				
A1	5	3	9	7
A2	3	7	1	3
A3	9	9	7	9
A4	3	5	5	5
A5	1	3	3	3
A6	3	1	7	1

Table C.43: Crisp values of Best-to-others and others-to-worst vectors for criterion 11.

BO VECTOR, C11				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	3	1	1	1
A2	7	3	9	3
A3	9	5	7	5
A4	5	3	5	9
A5	3	3	3	7
A6	1	9	5	3
OW VECTOR, C11				
A1	3	9	9	9
A2	3	7	1	3
A3	1	5	5	5
A4	5	5	5	1
A5	7	7	3	3
A6	9	1	5	7

Table C.44: Crisp values of Best-to-others and others-to-worst vectors for criterion 12.

BO VECTOR, C12				
ALTERNATIVES	DM1	DM 2	DM 3	DM 4
A1	1	1	9	7
A2	9	3	7	3
A3	3	5	3	1
A4	5	3	5	9
A5	7	3	3	3
A6	3	9	1	5
OW VECTOR, C12				
A1	9	9	1	3
A2	1	7	3	7
A3	3	5	5	9
A4	5	7	3	1
A5	3	3	3	7
A6	7	1	9	5

Table C.45: Crisp values of Best-to-others and others-to-worst vectors for criterion 13.

BO VECTOR, C13				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	1	9	1	3
A2	3	3	5	1
A3	9	3	9	9
A4	3	1	3	7
A5	3	5	7	5
A6	3	5	5	3
OW VECTOR, C13				
A1	9	1	9	7
A2	5	7	3	9
A3	1	7	1	1
A4	7	9	7	3
A5	3	5	3	5
A6	3	5	5	7

Table C.46: Crisp values of Best-to-others and others-to-worst vectors for criterion 14.

BO VECTOR, C14				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	3	9	1	1
A2	9	1	3	3
A3	1	3	7	7
A4	3	5	5	9
A5	3	7	9	5
A6	3	7	3	3
OW VECTOR, C14				
A1	3	1	9	9
A2	1	9	7	7
A3	9	7	3	3
A4	3	5	3	1
A5	3	3	1	5
A6	3	3	5	7

Table C.47: Crisp values of Best-to-others and others-to-worst vectors for criterion 15.

BO VECTOR, C15				
ALTERNATIVES	DM 1	DM 2	DM 3	DM 4
A1	1	1	5	3
A2	3	3	3	1
A3	9	5	5	7
A4	5	3	1	5
A5	7	3	9	9
A6	3	9	3	5
OW VECTOR, C15				
A1	9	9	3	3
A2	5	5	5	9
A3	1	3	5	7
A4	3	5	9	3
A5	3	5	1	1
A6	7	1	7	5