SENSOR TECHNOLOGY AND SUPPLIER SELECTION VIA FUZZY AXIOMATIC DESIGN METHODOLOGY

(BULANIK AKSİYOMATİK DİZAYN YÖNTEMİ İLE SENSÖR TEKNOLOJİSİ VE TEDARİKÇİSİ SEÇİMİ)

by

Doğan Aybars İLHAN, B.S.

Thesis

Submitted in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

in

INDUSTRIAL ENGINEERING

in the

GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

of

GALATASARAY UNIVERSITY

Supervisor: Prof. Dr. Gülçin BÜYÜKÖZKAN FEYZİOĞLU

October 2016

This is to certify that the thesis entitled

SENSOR TECHNOLOGY AND SUPPLIER SELECTION VIA FUZZY AXIOMATIC DESIGN METHODOLOGY

prepared by **Doğan Aybars İLHAN** in partial fulfillment of the requirements for the degree of **Master of Science in Industrial Engineering** at the **Galatasaray University** is approved by the

Examining Committee:

Prof. Dr. Gülçin BÜYÜKÖZKAN FEYZİOĞLU (Supervisor)
Department of Industrial Engineering
Galatasaray University ------------------------

Prof. Dr. Orhan FEYZİOĞLU
Department of Industrial Engineering
Galatasaray University ------------------------

Assist. Prof. Dr. Jbid Ani ARSENYAN ÜŞENMEZ
Department of Industrial Engineering
Bahçeşehir University ------------------------

Date: ------------------------

ACKNOWLEDGEMENTS

I would like to sincerely thank my supervisor Professor Gülçin BÜYÜKÖZKAN FEYZİOĞLU from the Department of Industrial Engineering, for providing valuable advice guidance and encouragement for my thesis and throughout my graduate studies. As being my supervisor, her patience suggestions and reviews certainly made the completion of this thesis possible.

I want to express my sincere thanks to all of my professors from Galatasaray University and İstanbul Kültür University for their teaching and guidance in my academic studies.

I acknowledge the contribution and untiring help of the industrial experts. This study could not be fulfilled without their suggestions.

Finally, I would like to express my deep and sincere thanks to my dear parents Aydan and Uğur, my sister Asena, my grand family, all of my lovely friends and Gonca for their love and support.

October 2016

Doğan Aybars İLHAN

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The increasing development of sensor technology holds an important role in the logistics industry and supply chain management. Selecting the right supplier and technology among different alternatives with different characteristics is a significant decision-making problem for logistics industry companies. Multi-Criteria Decision Making (MCDM) is an effective technique that is commonly applied on evaluation and selection problems that include multiple and generally contrasting criteria. Taking into account the multi-criterial and complex nature of the sensor technology supplier and sensor technology selection, MCDM technique provides a powerful evaluation and selection framework. This study proposes a two-phase MCDM-based group decision making (GDM) framework for effectively evaluating supplier and sensor technology alternatives for logistics and supply chain companies. The first phase is for sensor technology supplier selection and the second phase is for sensor technology selection. After identifying several evaluation criteria, the relative weights are calculated by using fuzzy Analytic Hierarchy Process (AHP). Then, the fuzzy Axiomatic Design (AD) method is applied to perform the evaluation and selection from alternatives. In the literature there is no study on sensor technology and supplier selection by using fuzzy AHP and fuzzy AD with GDM methodology. A real case from logistics industry is handled to show the convenience of the proposed approach and obtained results are discussed. A comparative study with fuzzy VIseKriterijumska Optimizacija I Kompromisno Resenje, Multicriteria Optimization and Compromise Solution (VIKOR) and sensitivity analysis are also employed.

RESUME

Le développement rapide de la technologie de capteur tient une importance croissante dans la logistique et la chaîne d'approvisionnement. Choisir le bon fournisseur et la technologie parmi les alternatives différentes avec des spécifications différentes est un problème important de la prise de décision pour les entreprises de logistique. L'aide à la décision multicritère (*Multi- Criteria Decision Making, MCDM)* est un outil puissant qui est largement utilisé afin d'évaluer et de ranger des problèmes qui contiennent des critères multiples généralement contradictoires. Compte tenu des caractéristiques multidimensionnelles de la technologie des capteurs, MCDM prévoit un cadre d'évaluation efficace. Cet article propose une prise de décision collective basée sur l'aide à la décision multicritère afin que l'on évalue efficacement les options de fournisseurs et de technologies de capteur pour la logistique et les entreprises de la chaîne d'approvisionnement. À la première étape, après avoir identifié les plusieurs critères d'évaluation, les poids sont déterminés en utilisant la méthode floue de hiérarchie analytique (*Fuzzy Analytic Hierarcy Process, fuzzy AHP*). À la deuxième étape, la conception floue axiomatique (*Fuzzy Axiomatic Design, fuzzy AD*) est adoptée pour effectuer l'évaluation. Dans la littérature il n'y a aucune étude sur la technologie de capteur et la sélection des fournisseurs en utilisant floue AHP- floue AD et la méthodologie de la prise de décision collective. Une étude de cas est donnée pour démontrer le potentiel de l'approche proposée. Une étude comparative avec floue VIKOR et l'analyse de sensibilité sont employées.

ÖZET

Sensör teknolojisindeki hızlı gelişmeler lojistik ve tedarik zinciri alanları açısından önemli önemli bir yer teşkil etmektedir. Birçok farklı özelliklere sahip alternatifler arasından doğru tedarikçi ve teknoloji seçimini yapabilme lojistik şirketleri için kritik bir karar verme problemidir. Çok Kriterli Karar Verme (ÇKKV) yöntemi, genellikle birden fazla ve çelişen kriterler içeren değerlendirme ve sıralama problemleri için güçlü bir yöntemdir. Sensör teknolojisi tedarikçisi ve sensör teknolojisi seçiminin çok boyutlu özelliği göz önüne alındığında, (ÇKKV) etkili bir değerlendirme sistemi sağlar. Bu çalışmada lojistik ve tedarik zinciri firmaları için sensör teknolojisi ve tedarikçisi alternatiflerini değerlendirmek amacıyla (ÇKKV) temelli grup karar verme sistemi sunulmuştur. Öncelikle birçok değerlendirme kriterinin belirlenmesinden sonra bunların bulanık Analitik Hiyerarşi Süreci ile ağırlıkları hesaplanır. Sonrasında değerlenirme bulanık Aksiyomatik Dizayn yöntemi ile yapılır. Literatürde sensör teknolojisi ve tedarikçisinin bulanık Analitik Hiyerarşi - bulanık Aksiyomatik Dizayn, Grup Karar Verme yöntemleriyle seçimi daha önce çalışılmamıştır. Çalışmada, sunulan yaklaşım için gerçek verilere dayanan bir uygulamaya ve ardından bulanık VIKOR yöntemi ile karşılaştırma ve duyarlılık analizine yer verilmiştir.

1. INTRODUCTION

Increasing technology development in the industry gains more and more importance as it makes all operations much more efficient. Time, cost and quality are crucial for every industry segment and process (Hou & Su, 2006; Kandjani et al., 2015).

A sensor is a device that transforms a physical incident into an electrical signal (Wilson, 2005). These physical incidents could be pressure, noise, heat, light, motion or any phenomenon. The output signal is used for further processes by conversion or transmission. At the end of the processes, the output may become a display for human on a screen or became an input for another process on a network.

Sensor technology is used for a variety of applications in daily life and industry. In daily life sensor based technologies are used for different purpose. For example, in car parks to spot the empty areas, in smart phones to assist many operations and applications, in roads and traffic signs to prevent from traffic jam sensor based technologies are adopted to the systems.

Similarly, sensor technology plays an important role in operations and processes in industry. From manufacturing to distribution sensor based systems have a wide range area of usage. The main reasons behind the usage of sensor-based technology are security, effectiveness, increasing automated systems, ease of integration etc.

In the competitive industry, companies must reduce costs and risks while increasing quality and efficiency. These musts require keeping the technology up-to-date as competitors do. Sensor technology is the key element of the systems that provide before mentioned advantages. Therefore, sensor-based systems have an important place in today's technology. Companies aim to invest on the such technology that provides more benefit to them.

Sensors have a wide-range of usage area in logistics industry operations. For example, warehouse automation processes, distribution, inventory control, and tracking are some of the activities that sensors are used in. Automated systems are getting more common in the industry and sensors are the key elements of such systems. They are high technology equipment and provide more efficiency in operations, compared to the traditional methods. Data is transferred fast with minimum error. That makes operations easier and more secure (Woo et al., 2009). With emerging demand, various models with wide-range features become more available in the market. Sensors and sensor-based systems can be found for different types of purposes with acceptable costs.

There are lots of sensor technology suppliers in the market. The point is to select sensor or sensor-based system from the right supplier so that keeping track with the new technologies and being more competitive.

Companies aim to select the proper product from the right supplier among a variety of different alternatives. Although they have different selection process dynamics, sensor technology and sensor technology supplier selection are closely related with each other. Therefore, the selection of the best high technology product and supplier presents a complex problem.

Sensor technology selection and sensor technology supplier selection are two main selection problem. In this study, these two main selection problems are handled together to propose a whole decision-making framework. The two problems have their specific decision environment with different goals. Putting these two problems together and seeking for a solution covering the both makes the decision problem more complex and makes the solution more meaningful at the same time.

The complex nature of the sensor technology and the sensor technology supplier selection processes with different objectives need to be handled by many different criteria to select the best.

Appropriate techniques must be applied to the problem to overcome the complexity and risks that arise from the problem.

MCDM is an effecive technique applied for such problems that contain various and generally contrasting criteria (Polmerol & Romero, 2000). This study presents a two-phase MCDM methodology employing fuzzy logic for making an effective evaluation for supplier and sensor technology alternatives by using mainly two MCDM techniques. The first phase is related with sensor technology supplier selection and the second phase with sensor technology selection from the selected supplier. The two main techniques are fuzzy AD and fuzzy AHP.

GDM approach is utilized for the collection of all sets of data from experts. After the evaluation criteria of both supplier and sensor technology alternatives are defined by using Delphi Method (Bojadziev & Bojadziev, 1997). Fuzzy AHP (Ma et al., 2007) is used to find the relative weights of each defined sensor technology supplier selection and sensor technology selection criterion. For the evaluation and ranking of the sensor technology supplier and sensor technology alternatives in terms of the defined criteria, fuzzy AD technique is used.

A case study is also applied with proposed methodology and framework to evaluate sensor technology supplier and sensor technology that has a wide variety of application areas in the logistics industry.

One of the original contributions of this thesis is the new evaluation framework for sensor technology and sensor technology supplier selection to help the decision-makers in logistics and supply chain field. Determination of the evaluation criteria evaluation method and the application on a real case are the other contributions of the study. There is no study in the literature applying fuzzy AHP- fuzzy AD methodology on sensor technology and sensor technology supplier selection problem.

This study is organized as follows. Section 2 shows the previous studies in the recent literature. Section 3 proposes the methods and techniques used in the study. A case study is presented in Section 4 covering a sensor technology supplier and sensor technology selection problem in logistics and supply chain industry. In Section 5 fuzzy VIKOR methodology is applied to compare the results of the proposed methodology then, sensitivity analysis is employed to examine the response of the proposed method in changing situations. Finally, the study is concluded in Section 6 with some concluding remarks.

2. LITERATURE REVIEW

2.1. Technology Selection

Sensor technology is widely used in several logistics industry operations. Sensors, key elements of automated systems are high technology equipment providing efficiency in operations. Sensor technology provides fast and secure operations (Woo et al., 2009). According to the review of the literature, sensor technology selection related studies did not cover the selection for industrial use of sensor technology, instead the studies cover sensor technology development via technical specification, modeling etc. Additionally, the studies handled selection problem for specific technical cases. Some of the mentioned studies may be referred as (Charmi & Gulfi, 2013; Liu et al., 2013; Kehong et al., 2014; Mao & Jackson, 2016). However, this study aims to provide a selection framework for industrial usage of sensor technology. Sensor technology selection is considered as a type of technology selection problem. Technology is thought to be an important factor in the competitive industry. Shen et al. (2011) emphasized the importance of carefully evaluating and selecting the technology alternatives for companies and governments. According to Gregory (1995) technology management consists of identifying, selecting, acquiring, developing and preserving. Technology selection is strictly related to company's or organization's goals and industrial and technological conditions (Shehabuddeen et al., 2006).

Because in the sensor technology selection literature there is no study related to this study's purpose, some topics, that may be considered as similar and not irrelevant, such as technology selection, Radio Frequency IDentification (RFID) selection, Personal Digital Assistant (PDA) selection, mobile technology selection, smart technology selection, intelligent technology selection, digital technology selection and robot selection are also reviewed. Some of the related studies are given in Table 2.1a and Table 2.1.b

Table 2.1a: Technology selection related studies

AUTHOR & DATE	APPLICATION AREA	METHODS	FUZZY APPROACH	GDM	STUDY
Chatterjee et al. (2010)	Robot selection	AHP, VIKOR, ELECTRE		X	Illustrative
Kumar & Gorg (2010)	Robot selection	DBA			Illustrative
Devi (2011)	Robot selection	VIKOR	X	X	Illustrative
Koulouriotis & Ketipi (2011)	Robot selection	Digraph	X		Illustrative
Shen et al. (2011)	Technology selection	Delphi, DEMATEL, ANP	X	X	Case Study
Vahdani et al. (2011)	Robot selection	Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	X	X	Illustrative
Buyukozkan et al. (2012)	PDA selection	AD, AHP	X	X	Case study
Tao et al. (2012)	Robot selection	DEA, AFS, AHP, TOPSIS	X		Illustrative
İç et al. (2013)	Robot selection	AHP	X		Case Study
Chuu (2014)	RFID selection	Maximum entropy ordered weighted averaging	X	X	Illustrative

Table 2.1b: Technology selection related studies

AUTHOR & DATE	APPLICATION AREA	METHODS	FUZZY APPROACH	GDM	STUDY
Igoulalene & Benyoucef (2014)	Robot selection for supply chain	TOPSIS	X	X	Illustrative
Liu et al. (2014)	Technology selection	MULTIMO ORA	X	X	Case Study
Rashid et al. (2014)	Robot selection	TOPSIS	X	X	Illustrative
Vats et al. (2014)	Technology selection	VIKOR	X		Case study
Budak & Üstündağ (2015)	RTLS selection	AHP	X		Case study

According to the studies in the literature, in the vast majority of the reviewed studies, MCDM technique or techniques were used to solve selection problem. Studies emphasized the complexity of such technology selection problems. Furthermore, studies suggested that these type of complex problems must be handled by multiple criteria. Fuzzy approach and GDM were also employed many of these studies

It can be concluded that integrated fuzzy MCDM techniques with GDM approach were used in recent studies. AHP TOPSIS and VIKOR were commonly used whereas application of fuzzy AD was relatively few.

2.2. Technology Supplier Selection

Supplier selection, may also be cited as vendor selection Chen & Huang (2007), is assumed in industry to be one of the vital factor for a successful supply chain and in the related literature there are many studies on supplier selection since the past several decades (Weber at al., 1991; De Boer et al., 2001; Ho et al., 2010; Chai et al., 2013).

Supplier selection is a process including identification evaluation and meeting the company's needs (Saen, 2007). Considering the complex nature of selecting the right vendor, De Boer et al. (2001), proposed a 4 – step framework covering all steps of the selection process. These steps are defining the problem, criteria formulation, evaluation, and selection.

Although in traditional point of view purchasing decisions are mainly focused on cost criterion supplier selection considered as MCDM problem (Soukup, 1987; Weber et al., 1991; Seydel, 2006). In the literature, supplier selection criteria are identified by a group of experts' opinions as a result supplier selection is considered as multi-criteria GDM problem (Chen et al., 2006).

As supplier selection literature has countless studies for further studies readers are referred Weber et al. (1991) that analyzed 74 studies presented between 1966-1991, Sönmez (2006) that gathered 145 articles presented between 1985-2005, Ho et al. [14] which gives the 78 studies published between 2000-2008 and Chai et al. (2013) which analyzed 123 articles presented between 2008-2012.

Chai et al. (2013) made a systematic review of vendor selection techniques. According to the study, between 2008 and 2012 mainly three types of decision-making techniques are applied for this type of problems. These are MCDM techniques Mathematical Programming (MP) techniques and Artificial Intelligence (AI) techniques. MCDM is the most used technique followed by MP and AI techniques respectively. AHP is ranked as the most applied technique for such problems. Additionally, fuzzy hybrid approaches are used in the 60 percent of the studies.

As sensor technology supplier selection related studies do not exist in the literature, considering the results of the above-mentioned study, MCDM techniques used for supplier selection problems are reviewed. Some of the reviewed papers are shown in Table 2.2a and Table 2.2b.

Table 2.2a: Supplier selection problems and MCDM techniques

AUTHOR & DATE	METHODS	FUZZY APPROACH	GDM	STUDY
Bhattacharya et al. (2010)	AHP, QFD		X	Case study
Chamodrakas et al. (2010)	AHP, Modified fuzzy preference programming method	X		Illustrative
Lin et al. (2010)	ANP, Interpretive structural modeling			Case study
Sanayei et al. (2010)	VIKOR	X	X	Case study
Dalalah et al. (2011)	DEMATEL, TOPSIS	X		Case study
Deng & Chan (2011)	TOPSIS	X		Illustrative
Liao & Kao (2011)	TOPSIS, Multi-choice goal programming	X		Case study
Lin et al. (2011)	ANP, TOPSIS, Linear programming			Case study
Shemshadi et al. (2011)	VIKOR	X	X	Case study
Vinodh et al. (2011)	ANP	X		Case study
Zeydan et al. (2011)	AHP, TOPSIS, Data envelopment analysis	X		Case study
Büyüközkan & Çifçi (2012)	ANP, TOPSIS, DEMATEL	X		Case study
Hsu et al. (2012)	DEMATEL, ANP, VIKOR			Illustrative
Lin (2012)	ANP, Multi-objective linear programming	X		Illustrative
Yu et al. (2012)	AHP	X		Case study
Zouggari & Benyoucef (2012)	AHP, TOPSIS	X	X	Illustrative
Roshandel et al. (2013)	TOPSIS	X		Case study

Table 2.2b: Supplier selection problems and MCDM techniques

AUTHOR & DATE	METHODS	FUZZY APPROACH	GDM	STUDY
Kahraman et al. (2014)	AHP	X		Illustrative
Beikkhakhian et al. (2015)	TOPSIS, AHP	X		
Junior & Carpinetti, (2016)	SCOR, TOPSIS	X		Case study
You et al. (2016)	VIKOR	X	X	Case study

Studies show that MCDM techniques were used for several kinds of supplier selection problem from supplier selection for automotive or electronics industry to green supplier selection. Considering this, for also sensor technology supplier selection problem, MCDM may propose an effective solution. Furthermore, studies show that fuzzy and GDM approaches were used with integrated MCDM methods for supplier selection problems.

According to the recent studies MCDM techniques are effective tools for technology selection and supplier selection problems. The reasons why MCDM is widely used for such problems are:

- Problems have complex nature.
- Many different criteria are involved in problems.
- MCDM techniques are relatively simple to apply comparing other methods and techniques.
- MCDM techniques are easily hybridized with different techniques for more effective solutions.

Additionally, GDM approach is also useful for such selection problems as well as fuzzy approaches.

In this study, an integrated fuzzy MCDM methodology is applied with GDM approach. The methodology consists of mainly fuzzy AHP and fuzzy AD techniques and Delphi methodology for better GDM approach.

2.3. Literature Survey for Integrated Fuzzy AHP- Fuzzy AD Methodology

The Axiomatic Design (AD) methodology (Suh, 1990), an MCDM technique, is used for design a process, organization, system, product, software etc. (Suh 2001; Kandjani et al.,2015). Also, AD provides an opportunity to measure how functional requirements (FRs) can be met by system capabilities. AD basically has two axioms; independence axiom and information axiom, respectively. The second axiom enables the selection of the alternative that has the minimum Information Content (IC). Information axiom is widely used for complex selection problems. Fuzzy logic is preferred when judgment and opinions are subjective, blurred and not certain (Zadeh, 1975).

AD and fuzzy AD methodologies have been proposed in previous studies for the different type of problems. Table 2.3a, Table 2.3b and Table 2.3c show some fuzzy AD applications in the literature. Cebi and Kahraman (2010a), proposed a fuzzy AD method by using both independence and information axioms for passenger car indicator design. Ferrer et al. (2010), developed a design for a manufacturing model by using the independence axiom of AD. Lee et al. (2011) designed a chemical product by applying the first axiom of AD. Vinodh (2011), studied agile production system design applying the independence axiom of AD. Similarly, Hong and Park (2014) proposed a modular product design by applying the first axiom of AD. A system interface design for structuring ship design project approval mechanism towards installation of operator was developed by Cebi et al. (2010). Khandekar and Chakraborty (2016), used for non-traditional machining process selection. Cebi and Kahraman (2010a), developed a group decision support system for the information axiom and applied a method for selection of optimal location for health emergency service in İstanbul. Arsenyan and Büyüközkan (2016), used fuzzy AD, Fuzzy House of Quality and Fuzzy Rule-based Systems for technology planning in product development. Kır and Yazgan (2016), applied fuzzy AD, Tabu search algorithm and Genetic algorithm for scheduling problem.

AD and fuzzy AD methodologies have been used in recent studies for supplier and product evaluation and selection problems in the literature. To name some of them, the following studies can be cited. Cicek and Celik (2010), developed a fuzzy AD model selection interface and applied it to different material selection problem concepts. Büyüközkan (2012), proposed an AD based fuzzy MCDM approach for green supplier evaluation. Weng & Jeng (2012), proposed a method for equipment selection for agile manufacturing unit, using both the first and second axioms. Büyüközkan et al. (2012), developed a two-phase fuzzy MCDM method for personal digital assistant selection problem. Atalay & Eraslan (2014), studied the evaluation of electronic devices for customer use. Fuzzy TOPSIS fuzzy AHP and fuzzy AD were compared in the study. Bilisik et al. (2014), applied an integrated fuzzy AHP and fuzzy AD method for location selection for public transportation systems. Recently, Bahadır and Satoğlu (2014), proposed an AD approach for robot arm selection problem while Kannan et al. (2014), applied fuzzy AD method for green supplier selection problem. Kulak et al. (2015), proposed fuzzy AD considering risks for medical imaging system selection. Khandekar & Chakraborty (2015), used the method for selection of material handling equipment.

AHP is one of the commonly used technique for selection processes. In recent studies AHP and triangular fuzzy set integrated methods are applied for supplier selection (Opricovic, 1998). Chan et al. (2008), Bottani & Rizzi (2008), applied the fuzzy AHP technique and linguistic pairwise comparisons for supplier evaluation. Kilincci & Onal (2011), used a fuzzy AHP decision model. Yucenur et al. (2011) introduced integrated fuzzy AHP-Analytic Network Process (ANP) approach, triangular fuzzy numbers are used in pairwise comparison matrices. Zeydan et al. (2011), integrated multiple techniques, including fuzzy AHP, TOPSIS, and Data Envelopment Analysis (DEA). Similarly, Wang et al. (2009), applied fuzzy AHP integrated with TOPSIS, and Lee et al. (2009), with multiple goal programming.

Following these researches, by considering the supplier and product selection problem's complex nature, an integrated fuzzy AHP- fuzzy AD methodology is proposed in this study for effective supplier and sensor technology selection process. A case study covering the selection of the most appropriate supplier and sensor technology among alternatives for a logistics company is also given to validate the effectiveness of the methodology.

Table 2.3a: Fuzzy AD applications

AUTHOR & DATE	APPLICATION AREA	METHODS	GDM	STUDY
Cebi et al. (2010)	System interface design	Theoretical development Application of fuzzy AD	x	Illustrative
Cebi & Kahraman (2010a)	Decision Support Systems design	Theoretical development Application of fuzzy AD	x	Case study
Cebi & Kahraman (2010b)		Theoretical development	x	Illustrative
Cebi & Kahraman (2010c)	Product design	Application of fuzzy AD- fuzzy AHP	x	Case study
Celik (2010)	Operation enhancement	Application of fuzzy AD- AHP	x	Case study
Cicek & Celik (2010)	Material Selection	Theoretical development Application of fuzzy AD		Case study
He et al. (2010)	Product design	Application of fuzzy AD- TOPSIS		Case study
Buyukozkan et al. (2012)	Product selection	Application of fuzzy AD- fuzzy AHP	x	Case study
Buyukozkan (2012)	Supplier evaluation	Application of fuzzy AD- fuzzy AHP	x	Case study

Table 2.3b: Fuzzy AD applications

AUTHOR & DATE	APPLICATION AREA	METHODS	GDM	STUDY
Li (2012)		Theoretical development Application of fuzzy AD	x	Illustrative
Weng & Jenq (2012)	Product evaluation	Application of fuzzy AD		Illustrative
Li (2013)		Theoretical dev. Fuzzy Intuitionistic fuzzy AD	x	Illustrative
Maldonado et al. (2013)	Ergonomic evaluation for Advanced Manufacturing Technology	Theoretical dev. Application of fuzzy AD	x	Illustrative
Atalay & Eraslan, (2014)	Product evaluation	Application of fuzzy AD	x	Illustrative
Bilişik et al. (2014)	Location selection	Integrated methods Application of fuzzy AD- fuzzy AHP	x	Case Study
Kannan et al. (2014)	Supplier selection	Application of fuzzy AD	x	Case Study
Khandekar & Chakraborty (2015)	Product selection	Application of fuzzy AD		Illustrative
Kulak et al. (2015)	Product selection	Application of fuzzy AD with risks	x	Case Study
Arsenyan & Büyüközkan (2016)	Technology planning in product development	Application of fuzzy AD-Fuzzy House of Quality-Fuzzy Rule-based Systems	x	Case Study
Khandekar & Chakraborty (2016)	Process selection	Application of fuzzy AD		Illustrative

Table 2.3c: Fuzzy AD applications

AUTHOR & DATE	APPLICATION AREA	METHODS	GDM	STUDY
Kır & Yazgan (2016)	Scheduling	Application of fuzzy AD-Tabu search algorithm-Genetic algorithm		Case Study

3. PROPOSED METHODOLOGY

3.1. Main Stages of the Proposed Methodology

MCDM techniques are used in a large variety of fields. MCDM is one of the highly used techniques for evaluation and ranking problems. Studies show that the MCDM technique is a well-suited and accurate methodology to solve multi-criteria problems such as the evaluation and selection (Hwang & Yoon, 1981). That is why MCDM proposes an effective and powerful framework for such problems. Decision makers make use of this technique directly to get a solution for complex problems. Considering the type of the problem, fuzzy MCDM techniques are used in this study to provide more objective and unbiased conclusions.

In this study, a two-phase methodology is used by applying integrated fuzzy AHP- fuzzy AD method. Phases are related to the supplier and sensor technology respectively. Figure 3.1 shows the stages of the proposed methodology. In phase one sensor technology supplier is determined. After that, sensor technologies from the selected supplier are evaluated. All necessary information, data and opinions provided by three experts, two from logistics and one from sensor technology company, by consensus applying Delphi Methodology. Delphi methodology, developed by Rand Corporation, is commonly used technique for gathering experts' opinions (Lee et al., 2001). Delphi method improves the quality of GDM (Shen et al., 2011).

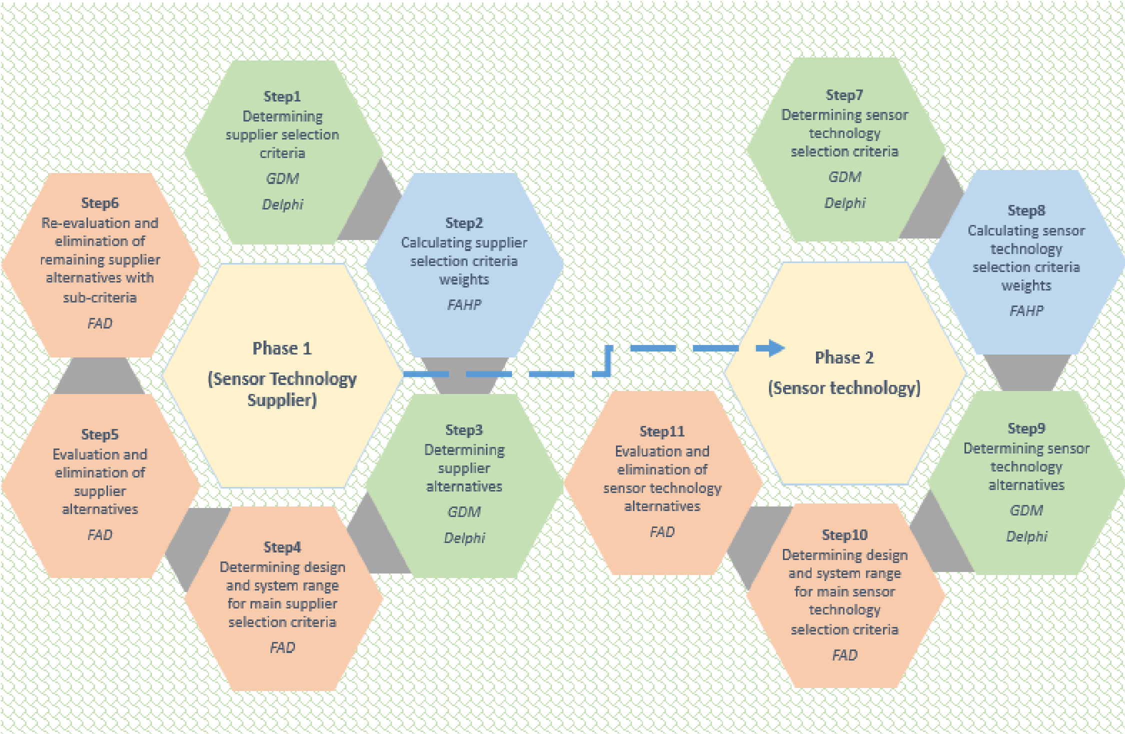


Figure 3.1: Phases and steps of the proposed methodology

In the phase one, group of expert's opinions is gathered and aggregated by consensus using Delphi Methodology to specify selection criteria for supplier evaluations. Criteria are defined and divided into groups. AHP (Saaty, 1980) is one of the most used technique to calculate the relative weights of the criteria. In this thesis fuzzy AHP (Ma et al., 2007) is used, because this technique gives better results for such complex problems to be more objective and accurate, to calculate the defined criteria weights. Finally, supplier alternatives are also determined.

In the next step of the phase one, experts determine the system and design ranges by using linguistic scale. Then, these linguistic terms are fuzzified and aggregated for fuzzy AD methodology. After the thresholds are specified, the elimination is made according to the rule that says, if the alternative cannot meet the specified thresholds the alternatives take infinite IC, and so, are eliminated. Then, in the following step of the first phase, same processes are repeated with the remaining alternatives by considering the sub-criteria and related ranges. Finally, ranking of the supplier alternatives is made according to the value of ICs from lowest to highest to select the best alternative as a supplier.

The second phase is related to the sensor technology alternatives from the previously selected supplier. Experts' opinions are gathered to specify selection criteria for product evaluations. Criteria are defined and alternatives are determined. System and design ranges are specified. Figure 3.2 shows the representation of the two ranges and the area between this two ranges in a fuzzy environment with triangular fuzzy numbers. Then the data is aggregated to perform the fuzzy AD technique. Afterward, sensor technology alternatives are ranked. Then, the best sensor technology alternative is selected.

3.2. Main Techniques Used in the Proposed Methodology

3.2.1. Fuzzy Analytic Hierarchy Process

This fuzzy AHP methodology is adopted from (Ayağ, 2005). By using triangular fuzzy numbers, via pair-wise comparison, the fuzzy judgment matrix $\tilde{A}$ is constructed as given below:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix} \tag{3.1}$$

where $\tilde{a}_{ij}^{\alpha} = 1$, if i is equal to j, and $\tilde{a}_{ij}^{\alpha} = \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$ or $\tilde{2}^{-1}, \tilde{4}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}$ if i is not equal to j. In the next step, the fuzzy eigenvalues are solved. A fuzzy eigenvalue, $\tilde{\lambda}$, is a fuzzy number solution to:

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x} \tag{3.2}$$

where $\tilde{\lambda}_{max}$ is the largest eigenvalue of Ã and $\tilde{x}$ is a non-zero n×1 fuzzy vector containing fuzzy number $\tilde{x}_i$. To perform fuzzy multiplications and additions by using the interval arithmetic and α-cut, the Equation 3.2 is equivalent to:

$$[a_{i1l}^{\alpha}x_{1l}^{\alpha}, a_{i1u}^{\alpha}x_{1u}^{\alpha}] \oplus \ldots \oplus [a_{inl}^{\alpha}x_{nl}^{\alpha}, a_{inu}^{\alpha}x_{nu}^{\alpha}] = [\lambda x_{inl}^{\alpha}, \lambda x_{iu}^{\alpha}] \tag{3.3}$$

where,

$$\tilde{A} = [\tilde{a}_{ij}^{x}], \tilde{x}^{t} = (\tilde{x}_1, \ldots., \tilde{x}_n),\ \tilde{a}_{ij}^{\alpha} = [a_{ijl}^{\alpha}, a_{iju}^{\alpha}],\ \ \tilde{x}_{ij}^{\alpha} = [x_{il}^{\alpha}, xj_{1u}^{\alpha}], \tilde{\lambda}^{\alpha} = [\lambda_{l}^{\alpha}, \lambda_{u}^{\alpha}] \tag{3.4}$$

for $0 < a \leq 1$ and all i, j, where i = 1, 2, . . . , n, j = 1, 2 . . . , n.
The a-cut is known to incorporate the experts or decision makers confidence over preferences. The degree of satisfaction for the judgment matrix Ã is estimated by the index of optimism μ. A larger value of the index μ indicates a higher degree of optimism. The index of optimism is a linear convex combination defined as (Lee, 1999):

$$\tilde{a}_{ij}^{\alpha} = \mu a_{ijl}^{\alpha} + (1-\mu)a_{ijl}^{\alpha}, \quad \forall \alpha \in [0,1] \tag{3.5}$$

When a is fixed, the following matrix can be obtained after setting the index of optimism, μ, in order to estimate the degree of satisfaction:

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11}^{\alpha} & \tilde{a}_{12}^{\alpha} & \cdots & \tilde{a}_{1n}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & \tilde{a}_{22}^{\alpha} & \cdots & \tilde{a}_{2n}^{\alpha} \\ \vdots & & & \vdots \\ \tilde{a}_{n1}^{\alpha} & \tilde{a}_{n2}^{\alpha} & \cdots & \tilde{a}_{nn}^{\alpha} \end{bmatrix} \tag{3.6}$$

The eigenvector is calculated by fixing the μ value and identifying the maximal eigenvalue. The Consistency Ratio (CR) is calculated, dividing Consistency Index (CI) by Random Consistency Index (RI), to measure the consistency of the pairwise comparisons as:

$$CR = CI/RI \qquad \text{where} \qquad CI = \frac{\lambda_{max} - n}{n-1} \tag{3.7}$$

CR should be less than 0.10 in order to be considered as acceptable. In the last step, the priority weight of each alternative is obtained by multiplying the matrix of evaluation ratings by the vector of attribute weights and summing overall attributes.

3.2.2. Fuzzy Axiomatic Design

AD is a systematic method introduced by Suh and is used for a variety of design process. Also, AD provides the opportunity to measure how functional requirements (FRs) can be met by system capabilities. AD basically has two axioms; independence axiom and information axiom respectively. The first one is the independence axiom. This axiom states that the independence of the functional requirements (FRs) should be maintained. The second axiom is the information axiom. This one says that the design that takes the minimum IC among the designs satisfying FRs is the best design. Thus, the second axiom presents the selection of alternatives that has the minimum IC. The information axiom is widely used for complex selection problems. Fuzzy AD is preferred when judgment and opinions are subjective, blurred and not certain. Therefore, the fuzzy AD methodology is proposed in this study for sensor technology and supplier selection problem by considering the problem’s complex nature.

Related formulations for the technique are shown in Equations (3.8) -(3.9) -(3.10) -(3.11) -(3.12) -(3.13) -(3.14) -(3.15).

$$I_i = \log_2(\frac{1}{p_i}) \tag{3.8}$$

I_i represents the IC of a design with a probability of success p_i for a given FR_i. The probability is given by the design and system ranges. Probability of success is formulated by:

$$p_i = \int_l^u p(FR_i)dFR_i \tag{3.9}$$

l is the lower and u is the upper limits of the design range, where p is the probability density function of a given FR_i.

P_i equals to the common area A_c. Therefore, I_i can be expressed as;

$$I_i = \log_2(\frac{1}{A_C}) \tag{3.10}$$

If the probability density function is uniform;

$$p_i = \frac{common\ range}{system\ range} \tag{3.11}$$

Thus, the IC can be expressed as;

$$I_i = \log_2(\frac{system\ range}{common\ range}) \tag{3.12}$$

IC in a fuzzy environment is;

$$I_i = \{ \infty \text{ , } no\ intersection, \log_2 \left(\frac{area\ of\ system\ range}{common\ area} \right),\ otherwise, \tag{3.13}$$

Total Weighted Information Content (WIC) for the main criteria is calculated by;

$$I = \sum_{i=1}^{n} w_i I_i \tag{3.14}$$

where n is the number of main criteria.

Similarly, the WIC for sub-criteria for criterion i is expressed as;

$$I_i = \sum_{j=1}^{m} w_{ij} I_{ij} \tag{3.15}$$

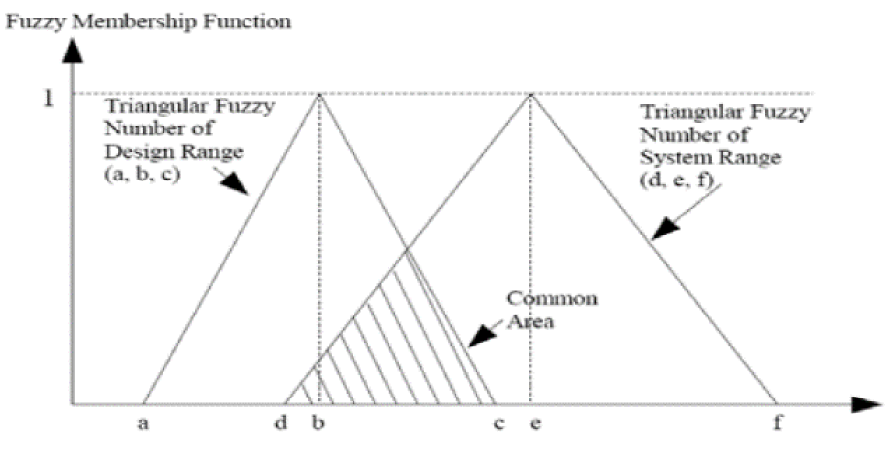


Figure 3.2: Fuzzy environment with triangular numbers

4. CASE STUDY: APPLICATION TO LOGISTICS INDUSTRY

With technological improvements, sensors are widely used in different areas for a variety of processes. Sensors provide high efficiency and therefore competitiveness to companies. Technological developments have a positive impact on reducing the cost of sensors. This leads companies to invest in the sensor technology. Consequently, sensor technology selection becomes an important issue for companies which plan to invest in this technology. On the other hand, another important issue, selecting the right supplier, arises from the previous reason. Companies want to select the best sensor technology and supplier. Therefore, supplier and sensor technology selection problems gain more importance. The case is studied to show the implementation of the methodology to a real problem.

In this part, the proposed methodology is applied to the logistics industry. The real case covers the supplier and sensor technology selection problem. Track and trace systems are highly used in the logistics industry for a variety of operations. The consideration of the operation diversity selection of the most suitable track and trace system with its supplier is the aim of this real case.

In this study GDM approach is applied with three experts, two from logistics and one from sensor technology company, by consensus using Delphi methodology. All data and information required for the study are gathered. Firstly, sensor technology supplier and then sensor technology is selected from the alternatives. Related criteria are identified by experts and help of the studies in the literature. Criteria weights are calculated by using fuzzy AHP technique. Evaluation and selection are made by using fuzzy AD technique.

4.1. Phase 1: Supplier Evaluation

Step 1: Determining the supplier selection criteria

At first criteria are identified with the consultation of experts and consideration of the literature. The selected criteria for supplier evaluation process are explained in detail as follows;

In this study five main criteria, supplier's product characteristics (Tam & Tummala, 2001; Lin et al., 2008), supplier's product functionality (Chen et al., 2009; Jeong et al., 2009; Sanayei et al., 2010), cost (Tam & Tummala, 2001; Bei et al., 2006; Sanayei et al., 2010), after sales services (Tam & Tummala, 2001; Bei et al., 2006; Büyüközkan et al., 2012), brand reliability (Tam & Tummala, 2001; Bei et al., 2006; Lin et al., 2008) are used and divided into their sub-criteria.

Supplier's product characteristics implies the measurable or tangible attributes of a product, whereas supplier's product functionality includes intangible specifications of a product. Cost covers price or other expenses. After sales services are related to the service standards of a company after its product is purchased. Brand reliability gives information about companies' reputation and expertise for its all operations.

Supplier's product characteristics has three sub-criteria. These are "physical characteristics", "technical characteristics" and "safety standards".

Physical characteristics include shape, size, and weight of the product. Technical characteristics may vary according to the type and purpose of use of the product. Safety standards gain more and more importance for companies because of the regulations and to achieve more efficient working environment.

Supplier's product functionality is divided into four sub-criteria. These are "ease of use", "function diversity", "adaptability" and "flexibility".

Ease of use may be considered as the term "user-friendly". This allows workers to learn how to use the equipment easily and reduce training time and costs. Function diversity gives the opportunity to make various similar tasks with one equipment and provides high efficiency in working environment. Adaptability of an equipment to the current process or machinery may save time and additional costs. Flexibility plays an important role for the effectiveness of a process when small changes are required for the existing system.

Cost related sub-criteria are “product price” and “operating cost”.

Product price and operating cost are always taken into consideration while making short or long term investment plans.

After sales service has “technical support”, “vendor reputation” and “capacity” sub-criteria.

Technical support must be perfect in order to maintain continuity of the process otherwise process efficiency reduces. Vendor reputation gives an idea about how well its service level is. The capacity of after sales service is needed to be at a sufficient level to provide wide range support to the customer needs.

Brand reliability is expanded into “market share”, “brand reputation”, “technical knowledge”, “product range”, “sectoral expertise” and “product availability” sub-criteria.

Market share and brand reputation are the two key factor affecting the reliability. Technical knowledge must be high enough to overcome difficulties in any level of the operations. If product range and sectoral expertise of a brand are high the brand may find best-fitted solutions to customers' need. Product availability reduces time and cost when a part change or maintenance is required.

Step 2: Calculating the supplier selection criteria weights

The weights of the criteria are calculated by using fuzzy AHP. First, experts are asked to evaluate the criteria according to the linguistic scale given in Table 4.1 with corresponding fuzzy numbers. Delphi method is also employed while gathering the information.

Table 4.1: Linguistic scale and corresponding fuzzy numbers

Term	Abbreviation	Membership
Equal	E	(1.00, 1.00, 2)
Moderate	M	(2.00, 3.00, 4.00)
Strong	S	(4.00, 5.00, 6.00)
Very Strong	VS	(6.00, 7.00, 8.00)
Absolute	A	(8.00, 9.00, 10.00)

The relative importance of the supplier selection criteria is gathered. Table 4.2 shows the linguistic pairwise comparison matrix. Then the linguistic terms are replaced with the corresponding fuzzy numbers to be able to apply fuzzy approach.

Table 4.2: Linguistic pairwise comparison matrix for supplier selection criteria

	C1	C2	C3	C4	C5
C1	1.000				
C2	VS	1.000	M	M	M
C3	S		1.000	E	E
C4	S			1.000	E
C5	S				1.000

In the next step, α-cuts fuzzy comparison matrix is calculated by taking α = 0.5 as shown in Table 4.3a and Table 4.3b.

Table 4.3a: α-cuts fuzzy comparison matrix for supplier selection criteria (α = 0.5)

	C1	C2	C3	C4	C5
C1	1.000	[1/8,1/6]	[1/6,1/4]	[1/6,1/4]	[1/6,1/4]
C2	[6,8]	1.000	[2,4]	[2,4]	[2,4]
C3	[4,6]	[1/4,1/2]	1.000	[1,2]	[1,2]

Table 4.3b: α-cuts fuzzy comparison matrix for supplier selection criteria (α = 0.5)

	C1	C2	C3	C4	C5
C4	[4,6]	[1/4,1/2]	[1/2,1]	1.000	[1,2]
C5	[4,6]	[1/4,1/2]	[1/2,1]	[1/2,1]	1.000

Table 4.4 shows the comparison matrix of the main supplier selection criteria obtained from the previous table.

Table 4.4: Comparison matrix for main supplier selection criteria

	C1	C2	C3	C4	C5
C1	1.000	0.146	0.208	0.208	0.208
C2	7.000	1.000	3.000	3.000	3.000
C3	5.000	0.375	1.000	1.500	1.500
C4	5.000	0.375	0.750	1.000	1.500
C5	5.000	0.375	0.750	0.750	1.000

Then the values are normalized to get the normalized matrix. Priority vector is calculated and weights of the criteria are obtained. Normalized matrix and calculated priority vector are given in Table 4.5.

Table 4.5: Normalized matrix for main supplier selection criteria

	C1	C2	C3	C4	C5	Weight
C1	0.044	0.064	0.037	0.032	0.029	0.04
C2	0.305	0.441	0.526	0.465	0.416	0.43
C3	0.217	0.165	0.175	0.232	0.208	0.20
C4	0.217	0.165	0.131	0.155	0.208	0.18
C5	0.217	0.165	0.131	0.116	0.139	0.15

To evaluate the consistency of the results additional analysis is required. Important factors are given in Table 4.6. As CR is less than 0.1 results are considered as consistent.

Table 4.6: Important factors for main supplier selection criteria

Lambda Max	5.269
CI	0.067
CR	0.060

Afterward, the weights of the sub-criteria are calculated one by one with the same method. Table 4.7 and Table 4.8 show the pairwise comparison matrix, priority vector and important factors for C1.

Table 4.7: Comparison matrix for supplier selection C1

C1	C11	C12	C13	Weight
C11	1.000	0.146	0.750	0.11
C12	7.000	1.000	5.000	0.74
C13	1.500	0.208	1.000	0.15

Table 4.8: Important factors for supplier selection C1

Lambda Max	3.061
CI	0.031
CR	0.053

Table 4.9 and Table 4.10 show the pairwise comparison matrix, priority vector and important factors for C2.

Table 4.9: Comparison matrix for supplier selection C2

C2	C21	C22	C23	C24	Weight
C21	1.000	1.500	3.000	5.000	0.44
C22	0.750	1.000	3.000	3.000	0.33
C23	0.375	0.375	1.000	1.500	0.14
C24	0.208	0.375	0.750	1.000	0.10

Table 4.10: Important factors for supplier selection C2

Lambda Max	4.183
CI	0.061
CR	0.068

Table 4.11 and Table 4.12 show the pairwise comparison matrix, priority vector and important factors for C3.

Table 4.11: Comparison matrix for supplier selection C3

C3	C31	C32	Weight
C31	1.000	0.375	0.26
C32	3.000	1.000	0.74

Table 4.12: Important factors for supplier selection C3

Lambda Max	2.061
CI	0.061
CR	N/A

Table 4.13 and Table 4.14 show the pairwise comparison matrix, priority vector and important factors for C1.

Table 4.13: Comparison matrix for supplier selection C4

C4	C41	C42	C43	Weight
C41	1.000	5.000	5.000	0.70
C42	0.208	1.000	1.500	0.17
C43	0.208	0.750	1.000	0.13

Table 4.14: Important factors for supplier selection C4

Lambda Max	3.081
CI	0.040
CR	0.070

Table 4.15a, Table 4.15b and Table 4.16 show the pairwise comparison matrix, priority vector and important factors for C5.

Table 4.15a: Comparison matrix for supplier selection C5

C5	C51	C52	C53	C54	C55	C56	Weight
C51	1.000	0.375	0.375	0.750	0.375	0.375	0.07
C52	3.000	1.000	1.500	3.000	1.500	1.500	0.25
C53	3.000	0.750	1.000	3.000	1.500	1.500	0.23

Table 4.15b: Comparison matrix for supplier selection C5

C5	C51	C52	C53	C54	C55	C56	Weight
C54	1.500	0.375	0.375	1.000	1.500	1.500	0.14
C55	3.000	0.750	0.750	0.750	1.000	1.500	0.16
C56	3.000	0.750	0.750	0.750	0.750	1.000	0.15

Table 4.16: Important factors for supplier selection C5

Lambda Max	6.551
CI	0.110
CR	0.089

After calculations the most important main criteria is supplier's product functionality (C2) with the weight of 0.43 followed by cost (C3) with the weight of 0.20, after sales services (C4) with the weight of 0.18, brand reliability (C5) with the weight of 0.15, and supplier's product characteristic (C1) has the minimum relative weight 0.04.

Table 4.17a and Table 4.17b give the overall supplier selection main and sub-criteria and relative weights.

Table 4.17a: Main and sub-criteria and calculated weights for supplier evaluation

Main Criteria	Weights	Sub-criteria	Weights
Supplier's product functionality (C2)	0.43	Ease of use (C21)	0.44
		Function diversity (C22)	0.33
		Adaptability (C23)	0.14
		Flexibility (C24)	0.10

Table 4.17b: Main and sub-criteria and calculated weights for supplier evaluation

Main Criteria	Weights	Sub-criteria	Weights
Cost (C3)	0.20	Operating cost (C31)	0.26
		Product price (C32)	0.74
After sales services (C4)	0.18	Technical support (C41)	0.70
		Vendor reputation (C42)	0.17
		Capacity (C43)	0.13
Brand reliability (C5)	0.15	Market share (C51)	0.07
		Brand reputation (C52)	0.25
		Technical knowledge (C53)	0.23
		Product range (C54)	0.14
		Sectoral expertise (C55)	0.16
		Product availability (C56)	0.15
Supplier's product characteristics (C1)	0.04	Physical characteristics (C11)	0.11
		Technical characteristics (C12)	0.74
		Safety standards (C13)	0.15

Step 3: Determining the supplier alternatives

Supplier alternatives for sensor technology are identified. Four well-known sensor technology suppliers namely SICK (www.sick.com), Cognex (www.cognex.com), Leuze (www.leuze.com) and Data Logic (www.datalogic.com) are selected as alternatives S1, S2, S3, and S4.

Step 4: Determining the system and design ranges for supplier selection

Fuzzy AD technique is employed for evaluation and selection of the supplier alternatives. Firstly, design and system ranges are determined by using 11-scaled linguistic terms. Table 4.18 shows the scale and corresponding abbreviation (Büyüközkan et al., 2012). Figure 4.1 and Figure 4.2 indicate the membership functions for system and design ranges respectively.

Table 4.18: Scale for Linguistic Terms

Term	Abbreviation	Term	Abbreviation
None	N	At least none	LN
Very low	VL	At least very low	LVL
Low	L	At least low	LL
Fairly low	FL	At least fairly low	LFL
More or less low	ML	At least more or less low	LML
Medium	M	At least medium	LM
More or less good	MG	At least more or less good	LMG
Fairly good	FG	At least fairly good	LFG
Good	G	At least good	LG
Very good	VG	At least very good	LVG
Excellent	E	At least excellent	LE

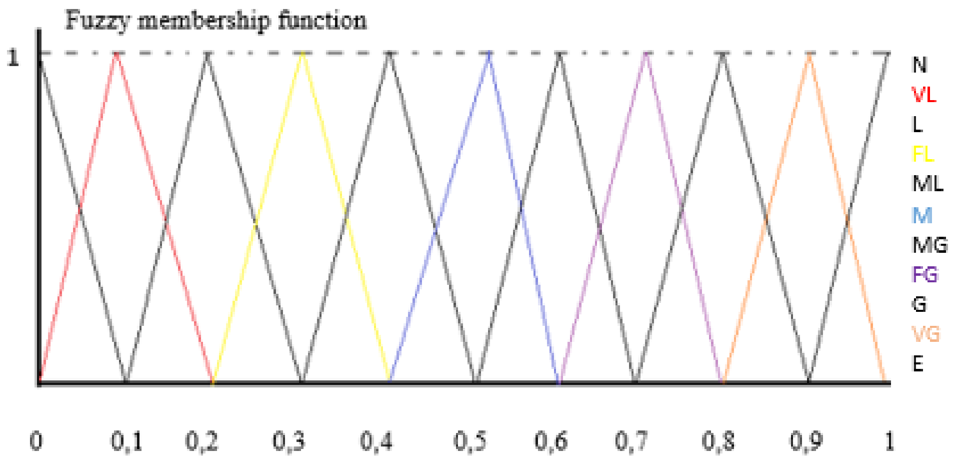


Figure 4.1: Membership functions for system range

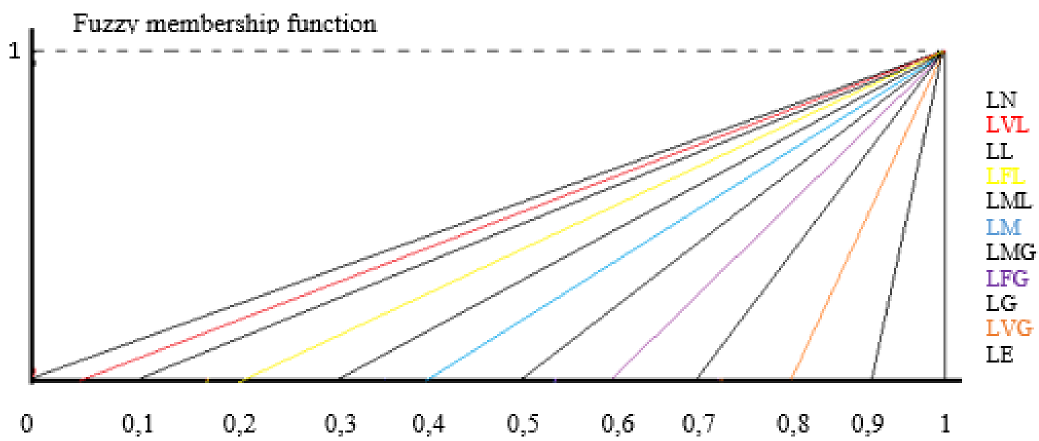


Figure 4.2: Membership functions for design range

Step 5: Evaluation and elimination of the supplier alternatives

Experts' evaluations on alternatives for system range and defined minimum requirements of the criteria for design range are shown in Table 4.19 and aggregated fuzzy values are shown in Table 4.20. Alternatives are evaluated by the experts by linguistic terms. Design ranges also, considered as the minimum requirement for the system, are specified by the consensus of the experts.

Table 4.19: Linguistic values of supplier alternatives

	Design range	S1	S2	S3	S4
C1	LFG	VG	FG	G	FG
C2	LMG	VG	MG	G	FG
C3	LFG	G	FG	G	G
C4	LMG	VG	MG	FG	ML
C5	LMG	VG	ML	MG	ML

Table 4.20: Fuzzified values of supplier alternatives

	Design range	S1	S2	S3	S4
C1	0.60, 1.00, 1.00	0.80, 0.90, 1.00	0.60, 0.70, 0.80	0.70, 0.80, 0.90	0.60, 0.70, 0.80
C2	0.50, 1.00, 1.00	0.80, 0.90, 1.00	0.50, 0.60, 0.70	0.70, 0.80, 0.90	0.60, 0.70, 0.80
C3	0.60, 1.00, 1.00	0.70, 0.80, 0.90	0.60, 0.70, 0.80	0.70, 0.80, 0.90	0.70, 0.80, 0.90
C4	0.50, 1.00, 1.00	0.80, 0.90, 1.00	0.50, 0.60, 0.70	0.60, 0.70, 0.80	0.30, 0.40, 0.50
C5	0.50, 1.00, 1.00	0.80, 0.90, 1.00	0.30, 0.40, 0.50	0.50, 0.60, 0.70	0.30, 0.40, 0.50

ICs are calculated for each supplier and criterion. Table 4.21 shows the calculated ICs.

Table 4.21: Calculated IC for supplier alternatives

	S1	S2	S3	S4
IC1	0.995	1.322	0.135	1.322
IC2	0.061	1.584	0.263	0.678
IC3	0.135	1.322	0.135	0.135
IC4	0.061	1.584	0.678	∞
IC5	0.061	∞	1.584	∞
ITOT	1.313	∞	2.795	∞

Then WICs are calculated by considering the corresponding criteria weights. Table 4.22 WICs for all supplier alternatives.

Table 4.22: WIC for supplier alternatives

	S1	S2	S3	S4
WIC1	0.041	0.054	0.006	0.054
WIC2	0.026	0.681	0.113	0.292
WIC3	0.027	0.264	0.027	0.027
WIC4	0.011	0.278	0.119	∞
WIC5	0.009	∞	0.244	∞
WIC TOTAL	0.114	∞	0.508	∞
Ranking	1		2	

After calculations, supplier alternatives Cognex (S2) and Data Logic (S4) are eliminated because they have infinite IC. These two supplier alternative are not able to meet minimum requirements for one or more criteria.

Step 6: Re-evaluation and elimination of the remaining supplier alternatives

Remaining supplier alternatives S1 and S3 are re-evaluated by using the same method with sub-criteria. Table 4.23 gives the linguistic evaluation of supplier alternatives for each criterion. Linguistic terms are then converted into the corresponding fuzzy numbers.

Table 4.23: Linguistic evaluation of remaining supplier alternatives

	Design range	S1	S3
C11	LFG	VG	G
C12	LFG	VG	G
C13	LFG	VG	G
C21	LFG	VG	G
C22	LFG	VG	G
C23	LFG	G	FG
C24	LG	VG	G
C31	LFG	VG	G
C32	LFG	FG	G
C41	LMG	VG	FG
C42	LMG	VG	FG
C43	LMG	VG	MG
C51	LM	G	MG
C52	LFG	VG	FG
C53	LM	VG	M
C54	LG	G	G
C55	LFL	VG	FL
C56	LG	VG	G

ICs for remaining suppliers are calculated considering the sub-criteria. ICs are given on Table 4.24.

Table 4.24: Calculated IC for remaining supplier alternatives

	S1	S3
IC11	0.099	0.447
IC12	0.099	0.447
IC13	0.099	0.447
IC21	0.099	0.447
IC22	0.099	0.447
IC23	0.447	1.322
IC24	0.193	1
IC31	0.099	0.447
IC32	1.322	0.447
IC41	0.061	0.678
IC42	0.061	0.678
IC43	0.061	1.585
IC51	0.175	0.881
IC52	0.099	1.322
IC53	0.042	1.807
IC54	1	1
IC55	0.023	2.170
IC56	0.193	1

After calculation of the ICs, WICs of the remaining supplier alternatives are also calculated considering the weights of the corresponding sub-criteria and main criteria. Calculated WICs are shown in Table 4.25.

After calculations, SICK (S1) has the minimum WIC and therefore considered as the best supplier alternative followed by Leuze (S3).

Table 4.25: WIC for remaining supplier alternatives

	S1	S3
WIC11	0.000	0.002
WIC12	0.003	0.014
WIC13	0.001	0.003
WIC21	0.019	0.084
WIC22	0.014	0.063
WIC23	0.026	0.078
WIC24	0.008	0.043
WIC31	0.005	0.023
WIC32	0.195	0.066
WIC41	0.008	0.084
WIC42	0.002	0.020
WIC43	0.001	0.036
WIC51	0.002	0.010
WIC52	0.004	0.052
WIC53	0.001	0.063
WIC54	0.021	0.021
WIC55	0.001	0.055
WIC56	0.004	0.023
WITOTAL	0.315	0.737
Ranking	1	2

Founded in 1946, SICK now has more than 50 subsidiaries and equity investments as well as numerous agencies around the globe. In the fiscal year 2015, SICK had more than 7,400 employees worldwide and achieved Group sales of just under EUR 1.3 billion. In different areas SICK is one of the biggest sensor technology provider.

4.2. Phase 2: Sensor Technology Evaluation

In the second phase, same steps of the methodology is applied for the sensor technology evaluation with the alternatives froö the firm SICK.

Step 7: Determining the sensor technology selection criteria

Criteria are identified with the consultation of experts and consideration of the literature. The selected criteria for sensor technology evaluation are sensor’s price (Lee, 2009; Liu & Wang, 2009; Sanayei et al., 2010), that must be within the affordable limits, sensor’s functionality (Lee, 2009; Qi et al., 2009; Sanayei et al., 2010), that gives opportunity to use the product for more than one purposes, adaptability for future provides easy adaptation for future developments and different processes, processing speed (Işıklar & Büyüközkan, 2007; Lee et al., 2007; Lin et al., 2008), and the technological level, latest and up to date or not, as they are the key factors affecting the sensor technology selection processes.

Step 8: Calculating the sensor technology selection criteria weights

The weights of the criteria are calculated by using fuzzy AHP. First, experts are asked to evaluate the criteria according to the linguistic scale previously given in Table 4.1 with corresponding fuzzy numbers. Delphi method is also employed while information gathering process. The relative importance of the sensor technology selection criteria is gathered. Table 4.26 shows the linguistic pairwise comparison matrix. Then the linguistic terms are replaced with the corresponding fuzzy numbers to be able to apply fuzzy approach.

Table 4.26: Linguistic pairwise comparison matrix sensor technology selection criteria

	C1	C2	C3	C4	C5
C1	1.000			S	S
C2	M	1.000	E	VS	VS
C3	E		1.000	S	S
C4				1.000	
C5				E	1.000

In the next step, α-cuts fuzzy comparison matrix is calculated by taking $\alpha = 0.5$ as shown in Table 4.27.

Table 4.27 : α-cuts fuzzy comparison matrix for sensor technology selection criteria ($\alpha = 0.5$)

	C1	C2	C3	C4	C5
C1	1.000	[1/4,1/2]	[1/2,1]	[4,6]	[4,6]
C2	[2,4]	1.000	[1,2]	[6,8]	[6,8]
C3	[1,2]	[1/2,1]	1.000	[4,6]	[4,6]
C4	[1/6,1/4]	[1/8,1/6]	[1/6,1/4]	1.000	[1/2,1]
C5	[1/6,1/4]	[1/8,1/6]	[1/6,1/4]	[1,2]	1.000

Table 4.28 shows the comparison matrix of the main sensor technology selection criteria obtained from the previous table.

Table 4.28: Comparison matrix for sensor technology selection criteria

	C1	C2	C3	C4	C5
C1	1.000	0.375	0.750	5.000	5.000
C2	3.000	1.000	1.500	7.000	7.000
C3	1.500	0.750	1.000	5.000	5.000
C4	0.208	0.146	0.208	1.000	0.750
C5	0.208	0.146	0.208	1.500	1.000

Then the values are normalized to get the normalized matrix. Priority vector is calculated and weights of the criteria are obtained. Normalized matrix and calculated priority vector are given in Table 4.29.

Table 4.29: Normalized matrix for sensor technology selection criteria

	C1	C2	C3	C4	C5	Weight
C1	0.17	0.16	0.20	0.26	0.27	0.21
C2	0.51	0.41	0.41	0.36	0.37	0.41
C3	0.25	0.31	0.27	0.26	0.27	0.27
C4	0.04	0.06	0.06	0.05	0.04	0.05
C5	0.04	0.06	0.06	0.08	0.05	0.06

To evaluate the consistency of the results additional analysis is required. Important factors are given in Table 4.30. As CR is less than 0.1 results are considered as consistent.

Table 4.30: Important factors for sensor technology selection criteria

Lambda Max	5.209
CI	0.052
CR	0.047

After calculations the most important main criteria is sensor's functionality (C2) with the weight of 0.41 followed by adaptability for future (C3) with the weight of 0.27, sensor's price (C1) with the weight of 0.21, technological level (C5) with the weight of 0.06, and processing speed (C4) has the minimum relative weight 0.05.

Table 4.31 gives the overall sensor technology selection criteria and relative weights.

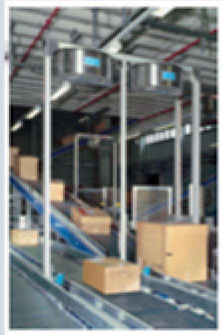
Table 4.31: Criteria and calculated weights for sensor technology evaluation

Criteria	Weights
Sensor's functionality (C2)	0.41
Adaptability for future (C3)	0.27
Sensor's price (C1)	0.21
Technological level (C5)	0.06
Processing speed (C4)	0.05

Step 9: Determining the sensor technology alternatives

Sensor technology alternatives, from the selected supplier alternative SICK, are identified with detailed analysis of firm's product catalogue and consultation of individual experts as OPS400 (ST1) DWS510 (ST2) RFMS Pro (ST3) and RF GS Pro (ST4). Figure 4.3 Figure 4.4 Figure 4.5 and Figure 4.6 show the sensor technology alternatives ST1 ST2 ST3 and ST4 and their details respectively.

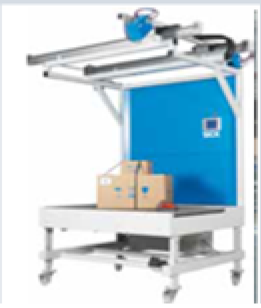
ST1
(OPS400)



- Compact housing
- Plug-and-play (optimized CLV Setup)
- Integrated tracking for minimum object distances
- Scanning /decoder frequency max. 1,200 Hz
- Real-time autofocus function
- Variants: standard, high or low density
- No supplementary components necessary for detection of object distances
- Reliable code recognition in real time through SMART technology
- Flash-PROM for Firmware

Figure 4.3: Details of the sensor technology alternative ST1

ST2
(DWS510)



- Dimensioning, weighing and identification data with the push of a button
- Complete solution with integrated frame and roller conveyor
- Commissioning within a few minutes
- Legal-for-trade approved (according to OIML, MID and NAWI)
- Automated invoicing of freight charges using legal-for-trade weight and volume data (revenue recovery)
- Several freely programmable host interfaces can be used to generate additional data for sorting parcels

Figure 4.4: Details of the sensor technology alternative ST2

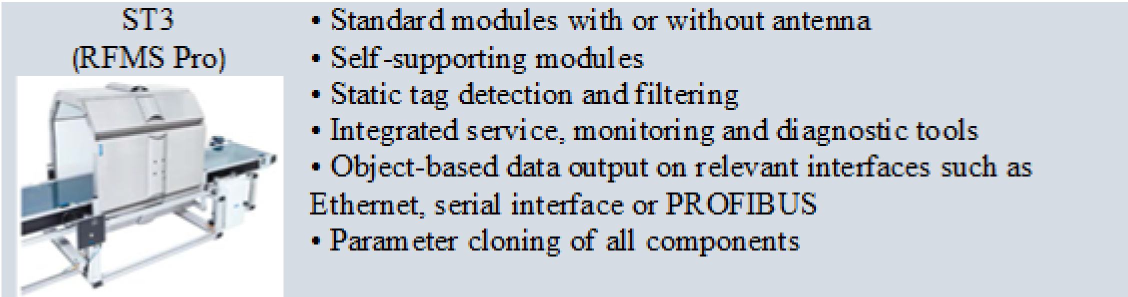


Figure 4.5: Details of the sensor technology alternative ST3

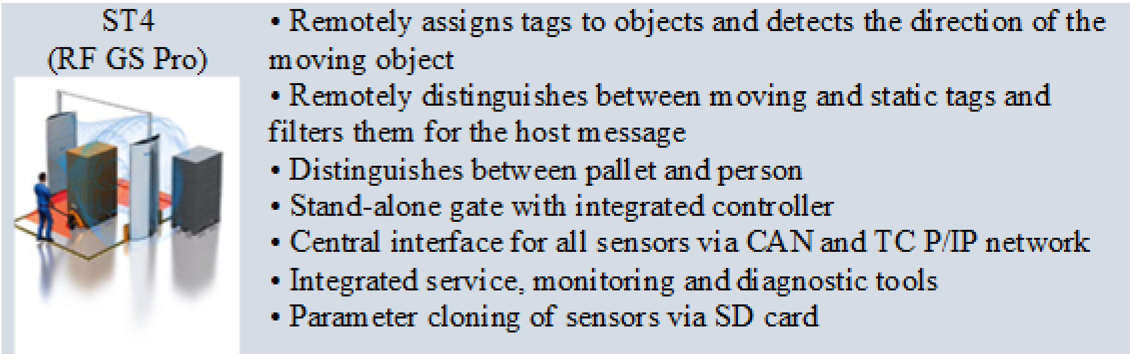


Figure 4.6: Details of the sensor technology alternative ST4

Step 10: Determining the system and design ranges for sensor technology selection

Afterward, fuzzy AD is employed to evaluate and select the appropriate sensor technology. Design ranges are specified and performances of the supplier alternatives are defined as shown in Table 4.32.

Table 4.32: Linguistic values of sensor technology alternatives

	Design range	ST1	ST2	ST3	ST4
C1	LMG	G	L	FG	G
C2	LG	G	G	VG	VG
C3	LFG	FG	G	VG	VG
C4	LMG	FG	VG	G	ML
C5	LMG	FG	VG	VG	E

Step 11: Evaluation of the sensor technology alternatives based on the criteria

Then ICs of the sensor technology alternatives are calculated. Table 4.33 shows the calculated ICs for each alternative and criterion.

Table 4.33: Calculated IC for sensor technology alternatives

	ST1	ST2	ST3	ST4
IC1	0.263	∞	0.678	0.263
IC2	1	1	0.193	0.193
IC3	1.322	0.447	0.099	0.099
IC4	0.678	0.061	0.263	∞
IC5	0.678	0.061	0.061	0

After calculation of the ICs, their WICs are also calculated. Table 4.34 gives the WICs and total WICs of the sensor technology alternatives.

Table 4.34: WIC for sensor technology alternatives

	ST1	ST2	ST3	ST4
WIC1	0.055	∞	0.143	0.055
WIC2	0.412	0.412	0.080	0.080
WIC3	0.360	0.122	0.027	0.027
WIC4	0.033	0.003	0.013	∞
WIC5	0.038	0.003	0.003	0.000
WITOT	0.899	∞	0.266	∞
Ranking	2		1	

Results show that DWS510 (ST2) and RF GS Pro (ST4) are eliminated because they have infinite IC. RFMS Pro (ST3) is selected as the best sensor technology since it has minimum IC followed by OPS400 (ST1).

Results were shared with and discussed by experts. Experts commented the results of the proposed approach as reasonable.

5. OBTAINED RESULTS

5.1. Validation of the Proposed Approach

In order to evaluate the effectiveness of the proposed fuzzy AHP- fuzzy AD approach, a comparative study is presented in this part. Then sensitivity analysis is made to make accurate conclusions.

The comparative study covers comparison of fuzzy AD results with other MCDM technique Fuzzy VIKOR and sensitivity analysis performed on sensor technology selection FRs.

5.1.1. Comparison with fuzzy VIKOR methodology

Fuzzy VIKOR is used to make comparison on the proposed methodology's results. VIKOR, developed by Buckley (1985a), Buckley (1985b), is a method basically focused on selecting and ranking alternatives with conflicting criteria according to the closeness to the ideal alternative results obtained.

To be consistent VIKOR is adapted to fuzzy environment and applied as second technique in this study since VIKOR has been widely applied in different studies such as Rao (2008), Sanayei et al. (2010), Wu et al. (2010), Kuo and Liang, (2011), San Cristobal, (2011), Ilangkumaran and Kumanan (2012), Anojkumar et al. (2014).

Table 5.1 and Table 5.2 give the fuzzy AD and fuzzy VIKOR results on supplier and sensor technology alternatives respectively with rankings.

Table 5.1: Comparative performance indices for supplier evaluation

Alternatives	WIC (Fuzzy AD)	Alternatives	Q (Fuzzy VIKOR)
S1	0.114	S1	0.889
S3	0.508	S3	0.926
S2	∞	S4	0.963
S4	∞	S2	1.000

Table 5.2: Comparative performance indices for sensor technology evaluation

Alternatives	WIC (Fuzzy AD)	Alternatives	Q (Fuzzy VIKOR)
ST3	0.266	ST4	0.000
ST1	0.899	ST3	0.226
ST2	∞	ST2	0.976
ST4	∞	ST1	1.000

Results suggest that evaluation of the alternatives by the two methods are different. Although S1 is the best supplier for both methods ranking of the sensor technology alternatives are dramatically changed. Worst ranked alternative in fuzzy AD ST4 becomes the best according to the fuzzy VIKOR results followed by ST3 ST2 and ST1.

Fuzzy VIKOR seeks the closeness to the ideal alternative without considering the requirement whereas fuzzy AD considers the defined requirements. This may be the main cause for the difference between these two methods' results.

5.1.2. Sensitivity analysis

Sensitivity analysis is applied to examine how proposed methodology responds when making some changes. Sensitivity analysis is conducted on functional requirement (FR4) with different values to see the change. While changing the value of only FR4 the rest is not changed. The outcome is shown in Table 5.3.

Table 5.3: Sensitivity analysis with different FR4 values

Alternatives	WITOT	WITOT	WITOT	WITOT	WITOT
FR4	(0.50,1.00, 1.00)	(0.45,1.00, 1.00)	(0.40,1.00, 1.00)	(0.35,1.00, 1.00)	(0.30,1.00, 1.00)
ST1	0.899	0.889	0.884	0.881	0.878
ST2	∞	∞	∞	∞	∞
ST3	0.266	0.266	0.265	0.263	0.262
ST4	∞	0.438	0.343	0.290	0.253

When FR4 (minimum requirement for C4) decreases step by step WICs for all alternatives decreases as well except for ST2. The value of ST2 remains the same because the eliminating criterion of ST2 is C1, not C4.

The value of ST1 and ST3 decrease slowly. However, the value of ST4 decreased fast from infinity to 0.438 first, then to 0.253 which is lower, better, than the value of ST3 which is 0.262. Because the eliminating criterion for ST4 is C4 (processing speed) in fuzzy AD. Figure 5.1 shows WIC change of each sensor technology alternative according to the different FR values. Proposed methodology very quickly responds small changes in the system.

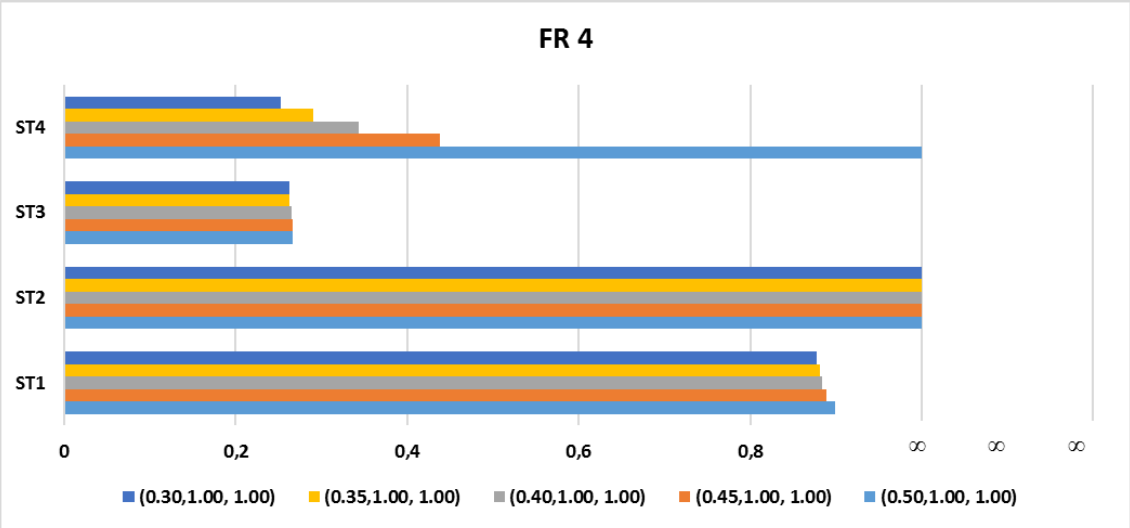


Figure 5.1: WIC of alternatives with different FR 4 values

The analysis also shows that when FR4 decreases similarity between the results of the two methodologies, fuzzy AD, and fuzzy VIKOR, increases. The reason behind the increase in similarity can be explained by the characteristics, considering the requirements while evaluating the alternatives, of fuzzy AD. Fuzzy VIKOR, however, evaluates the alternatives based on their relative performances each other not considering any defined requirements.

Fuzzy AD is more appropriate and outperforms when defining some requirements is required. Fuzzy VIKOR can be applied where only comparison is needed without any defined requirement.

5.2. Managerial and Theoretical Implications

Technology planning or technological investment is considered as a vital decision-making processes for companies. More specificly, sensor technology selction from the best supplier alternative requires high attention. To our knowledge, there is no study about sensor technology selection and sensor technology supplier selection for logistics industry in the literature. This study offers an insight into both sensor technology supplier and sensor technology selection problems. The proposed methodology was applied in a case study for a logistics company's needs. The reason behind developing the methodology is to assist decision-maker for such problems. The methodology may be applied any other real case about sensor technology selection sensor technology supplier selection or different selection problem in logistics industry when needed. The strong side of the study is that data was gathered by using GDM approach from both literature and the experts from logistics and sensor technology industry.

This study may be a motivation for studying on sensor technology as a topic and fuzzy AHP- fuzzy AD as an integrated methodology. The two methods have independency rule that may be one of the important factors providing a quite well match for the two methods. The integrated methodology provides an effective framework for selection problems.

6. CONCLUSION

With the rapid technological developments, high technology equipment became one of the most important parts of wide range processes. As high technology products provide high efficiency in terms of time quality and cost investment on technology gained importance. Companies aim to select most suitable technology for their processes and conditions.

Furthermore, supplier selection is also a critical step for companies. In industry, various suppliers with lots of product groups are exist. Supplier selection plays an important role in varying aspects from cost to product quality and after sales services etc.

Therefore, sensor technology and supplier selection is a type of complex problem affecting the future of an investment.

In this study, sensor technology and supplier selection problem is handled considering the complex nature of the problems. MCDM techniques are commonly used to solve such problems. Recent studies show that fuzzy integrated approaches give better conclusions.

A fuzzy multi-criteria GDM framework was proposed for the supplier and sensor technology evaluation problem. In addition, a case study was done for supplier and sensor technology selection. Related criteria were gathered from literature and experts by using Delphi methodology. Fuzzy AHP technique was employed to determine the criteria weights. Study showed that functionality plays an important role for both sensor technology and sensor technology supplier selection decisions.

Several recent applications of fuzzy AD proved that the technique is an appropriate tool for decision-making problems. Therefore, fuzzy AD was used in this study to eliminate the alternatives that are not able to satisfy the basic requirements afterward rank the remaining alternatives according to their performance values and select the best.

A real industrial case was used to illustrate the proposed methology. Firstly, the most appropriate supplier is selected. Then sensor technology alternatives from the selected supplier were evaluated with the same methodology and the most suitable alternative was selected.

The results of fuzzy AHP- fuzzy AD application were compared to the results of a commonly used other MCDM method namely fuzzy VIKOR. It could be concluded from the comparative study that there was a difference in terms of the results of the two methods.

Sensitivity analysis was conducted and outcomes of the sensitivity analysis revealed that fuzzy VIKOR technique evaluated the alternatives without considering the system requirements. However, proposed methodology considered the system requirement and eliminated the alternatives which could not meet the minimum requirements.

The main contribution of the study is that the proposed methodology is a two-phase GDM approach using fuzzy AD methodology integrating various fuzzy MCDM methods. Other industrial applications of fuzzy AD cover different areas. However, they do not cover technology evaluation such as sensor technology and track and trace systems with supplier evaluation. To our knowledge, there is no work for such problems. Furthermore, another contribution of this study was to establish criteria and methodology for evaluating sensor technology based track and trace systems and suppliers. Implementation of the case study in logistics sector proved the potential of the proposed methodology.

For future studies, proposed approach may be applied different sector and product group. To improve computational time a user-friendly software may be developed and adopted to study. Other integrated fuzzy methodologies may be developed and applied for such evaluation and selection problems.

REFERENCES

Anojkumar, L., Ilangkumaran, M., Sasirekha, V. (2014). Comparative analysis of MCDM methods for pipe material selection in sugar industry., Expert Systems with Applications : 41 (6) : 2964–2980.

Arsenyan, J., Büyüközkan, G. (2016). An integrated fuzzy approach for information technology planning in collaborative product development., International Journal of Production Research : 54 :11 : 3149-3169.

Atalay, K. D., Eraslan, E. (2014). Multi-Criteria Usability Evaluation of Electronic Devices in a Fuzzy Environment., Human Factors and Ergonomics in Manufacturing & Service Industries : 24 (3) : 336–347.

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

Bahadir, M. C., Satoglu, S. I. (2014). A novel robot arm selection methodology based on axiomatic design principles., International. Journal of Advance Manufacturing Technologies : 71 (9–12) : 2043–2057.

Bei, W., Wang, S., Hu, J. (2006). An analysis of supplier selection in manufacturing supply chain management., Service Systems and Service Management : 2 : 439–444.

Beikkhakhian, Y., Javanmardi, M., Karbasian, M., Khayambashi, B. (2015). The application of ISM model in evaluating agile suppliers selection criteria and ranking suppliers using fuzzy TOPSIS-AHP methods., Expert Systems with Applications : 42 : 6224–6236.

Bhattacharya, A., Geraghty, J., Young, P. (2010). Supplier selection paradigm: An integrated hierarchical QFD methodology under multiple-criteria environment., Applied Soft Computing : 10 : 1013–1027.

Bilişik, Ö. N., Demirtaş, N., Tuzkaya, U. R., Baraçlı, H. (2014). Garage Location Selection for Public Transportation System in Istanbul: An Integrated Fuzzy AHP and Fuzzy Axiomatic Design Based Approach., Journal of Applied Mathematics : vol. 2014.

Bojadziev, G., Bojadziev, M. (1997). Fuzzy Logic for Business, Finance, and Management., Advances in Fuzzy Systems : vol. 12.

Bottani, E., Rizzi, A. (2008). An adapted multi-criteria approach to suppliers and products selection-an application oriented to lead-time reduction., International Journal of Production Economics :111(2) : 763–781.

Buckley, J. J. (1985a). Fuzzy Hierarchical Analysis., Fuzzy Sets and Systems : 17 (3) : 233-247.

Buckley, J. J. (1985b). Ranking Alternatives using Fuzzy Numbers., Fuzzy Sets and Systems : 15 (1) : 21-31.

Budak, A., Ustundag, A. (2015). Fuzzy decision making model for selection of real time location systems., Applied Soft Computing : 36 : 177–184.

Buyukozkan, G., Cifci, G. (2012). A novel hybrid MCDM approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS to evaluate green suppliers., Expert Systems with Applications : 39 : 3000–3011.

Büyüközkan, G. (2012). An Integrated Fuzzy Multi-criteria Group Decision-making Approach for Green Supplier Evaluation., International Journal of Production Research : 50 (11) : 2892–2909.

Büyüközkan, G., Arsenyan, J., Ruan, D. (2012). Logistics Tool Selection with Two-Phase Fuzzy Multi-Criteria Decision Making: A Case Study for Personal Digital Assistant Selection., Expert Systems with Applications : 39 : 142–153.

Cebi, S., Celik, M., Kahraman, C. (2010). Structuring ship design project approval mechanism towards installation of operator-system interfaces via fuzzy axiomatic design principles., Information Sciences : 180 (6) : 886-895.

Cebi, S., Kahraman, C. (2010b). Extension of axiomatic design principles under fuzzy environment., Expert Systems with Applications :37(3) : 2682–2689.

Cebi, S., Kahraman, C. (2010c). Indicator design for passenger car using fuzzy axiomatic design principles., Expert Systems with Applications :37(9) : 6470–6481.

Cebi, S., Kahraman, C. (2010a). Indicator design for passenger car using fuzzy axiomatic design principles., Expert Systems with Applications : 37 (9) : 6470-6481.

Celik, M. (2010). Enhancement of occupational health and safety requirements in chemical tanker operations: The case of cargo explosion., Safety Science : 48 : 195–203.

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

Chamodrakas, I., Batis, D., Martakos, D. (2010). Supplier selection in electronic marketplaces using satisficing and fuzzy AHP., Expert Systems with Applications : 37 : 490–498.

Chan, F. T. S., Kumar, N., Tiwari, M. K., Lau, H. C. W., Choy, K. L. (2008). Global supplier selection: A fuzzy-AHP approach., International Journal of Production Research :46(14) : 3825–3857.

Charmi, A., Gulfi, P. (2013). Sensor selection via compressed sensing., Automatica : 49 : 3304–3314.

Chatterjee, P., Athawale, V. M., Chakraborty, S. (2010). Selection of industrial robots using compromise ranking and outranking methods., Robotics and Computer-Integrated manufacturing : 26 : 483–489.

Chen, C. T., Lin, C. T., Huang, S. F. (2006). A fuzzy approach for supplier evaluation and selection in supply chain management., International Journal of Production Economics : 102 (2) : pp. 289–301.

Chen, J., Yen, D., Chen, K. (2009). The acceptance and diffusion of the innovative smart phone use: A case study of a delivery service company in logistics. Information & Management : 46 : 241–248.

Chen, Y. M., Huang, P. N. (2007). Bi-negotiation integrated AHP in supplier selection. Benchmarking., An International Journal 14 (5), p. 575–593.

Chuu, S. J. (2014). An investment evaluation of supply chain RFID technologies: A group decision-making model with multiple information sources., Knowledge-Based Systems : 66 : 210–220.

Cicek, K., Celik, M. (2010). Multiple attribute decision-making solution to material selection problem based on modified fuzzy axiomatic design-model selection interface algorithm., Materials & Design : 31 (4) : 2129-2133.

Dalalah, D., Hayajneh, M., Batieha, F. (2011). A fuzzy multi-criteria decision making model for supplier selection., Expert Systems with Applications : 38 : 8384–8391.

De Boer, L., Labro, E., Morlacchi, P. (2001). A review of methods supporting supplier selection., European Journal of Purchasing and Supply Management : 7 (2) : pp. 75–89.

Deng, Y., Chan, F. T. S. (2011). A new fuzzy dempster MCDM method and its application in supplier selection., Expert Systems with Applications : 38 : 9854–9861.

Devi, K. (2011). Extension of VIKOR method in intuitionistic fuzzy environment for robot selection., Expert Systems with Applications : 38 : 14163–14168.

Ferrer, I. J., Rios, J., Ciurana, M., Garcia-Romeu, L. (2010). Methodology for Capturing and Formalizing DFM Knowledge., Robotics and Computer Integrated Manufacturing : 26 : 420–429.

Gregory, M. J. (1995). Technology management: A process approach., Proceedings of the Institution of Mechanical Engineers : 209(5) : 347–355.

He, Y., Tang, X., Chang, W. (2010). Technical Decomposition Approach of Critical to Quality Characteristics for Product Design for Six Sigma., Quality and Reliability Engineering International : 26 : 325—339.

Ho, W., Xu, X., 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.

Hong, E. P., Park, G. J. (2014). Modular design method based on simultaneous consideration of physical and functional relationships in the conceptual design stage., Journal of Mechanical Science and Technology : 28 (1) : 223-235.

Hou, J., Su, D. (2006). Integration of Web Services technology with business models within the total product design process for supplier selection., Computers in Industry : 57 : 797–808.

Hsu, C. H., Wang, F. K., Tzeng, G. H. (2012). The best vendor selection for conducting the recycled material based on a hybrid MCDM model combining DANP with VIKOR., Resources, Conservation and Recycling : 66 : 95– 111.

Hwang, C., Yoon, K. (1981). Multiple attribute decision making: Methods and applications., New York: Springer-Verlag.

Igoulalene, I., Benyoucef, L. (2014). Consensus-based Fuzzy TOPSIS Approach for Supply Chain Coordination: Application to Robot Selection Problem., 19th World Congress The International Federation of Automatic Control Cape Town, South Africa.

Ilangkumaran, M., Kumanan, S. (2012). Application of Hybrid VIKOR model in selection of maintenance strategy., International Journal of Information Systems and Supply Chain Management : 5(2) : 59–81.

Işıklar, G., Buyukozkan, G. (2007). Using a multi-criteria decision making approach to evaluate mobile phone alternatives., Computer Standards & Interfaces : 29 : 265–274.

İç, Y. T., Yurdakul, M., Dengiz, B. (2013). Development of a decision support system for robot selection., Robotics and Computer-Integrated Manufacturing : 29 : 142–157.

Jeong, N., Yoo, Y., Heo, T. Y. (2009). Moderating effect of personal innovativeness on mobile-RFID services: Based on Warshaw's purchase intention model., Technological Forecasting and Social Change : 76 : 154–164.

Junior, F. R. L., Carpinetti, L. C. R. (2016). Combining SCORs model and fuzzy TOPSIS for supplier evaluation and management., International Journal of Production Economics : 174 : 128–141.

Kahraman, C., Oztayşi, B., Sarı, İ. U., Turanoğlu E. (2014). Fuzzy analytic hierarchy process with interval type-2 fuzzy sets., Knowledge-Based Systems : 59 : 48–57.

Kandjani, H., Tavana, M., Bernus, P., Wen, L., Mohtarami, A. (2015). Using extended Axiomatic Design theory to reduce complexities in Global Software Development projects., Computers in Industry : 67 : 86–96.

Kannan, D., Govindan, K., Sivakumar, R. (2014). Fuzzy axiomatic design approach based green supplier selection: a case study from Singapore., Journal of Cleaner Production : 1-15.

Kehong, L., Xiaodong, T., Guanjun, L., Chenxu, Z. (2014). Sensor selection of helicopter transmission systems based on physical model and sensitivity analysis., Chinese Journal of Aeronautics : 27(3) : 643–654.

Khandekar, A. V., Chakraborty, S. (2015). Selection of Material Handling Equipment Using Fuzzy Axiomatic Design Principles., Informatica : 26 (2) : 259–282.

Khandekar, A. V., Chakraborty, S. (2016). Application of fuzzy axiomatic design principles for selection of non-traditional machining processes., International Journal of Advance Manufacturing Technologies : 83 : 529–543.

Kır, S., Yazgan, H. R. (2016). A sequence dependent single machine scheduling problem with fuzzy axiomatic design for the penalty costs., Computers & Industrial Engineering : 92 : 95–104.

Kilincci, O., Onal, S. A. (2011). Fuzzy AHP approach for supplier selection in a washing machine company., Expert Systems with Applications :38(8) : 9656–9664.

Koulouriotis, D. E., Ketipi, M. K. (2011). A fuzzy digraph method for robot evaluation and selection., Expert Systems with Applications : 38 : 11901–11910.

Kulak, O., Goren, H. G., Supciller, A. A. (2015). A new multi criteria decision making approach for medical imaging systems considering risk factors., Applied Soft Computing : 35 : 931–941.

Kumar, R., Garg, R.K. (2010). Optimal selection of robots by using distance-based approach method., Robotics and Computer-Integrated Manufacturing : 26 : 500–506.

Kuo, M. S, Liang, G. S. (2011). Combining VIKOR with GRA techniques to evaluate service quality of airports under fuzzy environment., Expert Systems with Applications : 38 : 1304–1312.

Lee, A. H. I. (2009). A fuzzy supplier selection model with the consideration of benefits, opportunities, costs and risks., Expert Systems with Applications :36 : 2879–2893.

Lee, A. H. I., Kang, H., Chang, C. (2009). Fuzzy multiple goal programming applied to TFT-LCD supplier selection by downstream manufacturers., Expert Systems with Applications : 36(3) : 6318–6325.

Lee, A. R. (1999). Application of Modified Fuzzy AHP Method to Analyze Bolting Sequence of Structural Joints., UMI Dissertation Services.

Lee, C. C., Cheng, H., Cheng, H. H. (2007). An empirical study of mobile commerce in insurance industry: Task-technology fit and individual differences., Decision Support Systems : 43 : 95–110.

Lee, J. W., Kim, S. H. (2001). An integrated approach for interdependent information system project selection., International Journal of Project Management : 19(2) : 111–118.

Lee, K. S., Jeon, B., Cha, S.W. (2011). A study on optimizing the mechanical properties of glass fiber-reinforced polypropylene for automotive parts., Polym-Plast Technology Engineering : 50 : 95–101.

Li, M. (2013). Extension of Axiomatic Design Principles for Multicriteria Decision Making Problems in Intuitionistic Fuzzy Environment. Mathematical Problems in Engineering :Volume 2013 : 813471.

Liao, C. N., Kao, H. P. (2011). An integrated fuzzy TOPSIS and MCGP approach to supplier selection in supply chain management., Expert Systems with Applications : 38 : 10803–10811.

Lin, C. T., Chen, C. B., Ting, Y. C. (2011). An ERP model for supplier selection in electronics industry., Expert Systems with Applications : 38 : 1760–1765.

Lin, M., Wang, C., Chen, M., Chang, C. (2008). Using AHP and TOPSIS approaches in customer-driven product design process., Computers in Industry : 59 : 17–31.

Lin, R. H. (2012). An integrated model for supplier selection under a fuzzy situation., International Journal of Production Economics :138 : 55–61.

Lin, Y. T., Lin, C. L., Yu, H. C., Tzeng, G. H. (2010). A novel hybrid MCDM approach for outsourcing vendor selection: A case study for a semiconductor company in Taiwan., Expert Systems with Applications : 37 : 4796–4804.

Liu, H. C., You, J. X., Lu, C., Shan, M. M. (2014). Application of interval 2-tuple linguistic MULTIMOORA method for health-care waste treatment technology evaluation and selection., Waste management : 34 : 2355–2364.

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

Liu, Z., Wanga, J., Xueb, Y. (2013). PCRLB-based sensor selection for maneuvering target tracking in range-based sensor networks., Future Generation Computer Systems : 29 : 1751–1757.

Ma, M. Y., Chen, C. Y., Wu, F. G. (2007). A design decision-making support model for customized product color combination., Computers in Industry : 58 : 504–518.

Maldonado, A., García, J. L., Alvarado, A., Balderrama, O. C. (2013). A hierarchical fuzzy axiomatic design methodology for ergonomic compatibility evaluation of advanced manufacturing technology., International Journal of Advance Manufacturing Technology : 66 : 171–186.

Mang, L. (2012). Extension of Axiomatic Design Method for Fuzzy Linguistic Multiple Criteria Group Decision Making with Incomplete Weight Information., Mathematical Problems in Engineering :Volume 2012 : 634326.

Mao, L., Jackson, L. (2016). Selection of optimal sensors for predicting performance of polymer electrolyte membrane fuel cell., Journal of Power Sources : 328 : 151-160.

Opricovic, S. (1998). Multi-criteria optimization of civil engineering systems., Faculty of Civil Engineering.

Pomerol, J.C., Barba-Romero, S. (2000). Multicriterion Decision in Management: Principles and Practice., Kluwer Academic Publishers, Norwell.

Qi, J., Li, L., Li, Y., Shu, H. (2009). An extension of technology acceptance model: Analysis of the adoption of mobile data services in China., Systems Research and Behavioral Science : 26 : 391–507.

Rao, R. V. (2008). A decision making methodology for material selection using an improved compromise ranking method., Materials and Design : 29(10) : 1949–1954.

Rashid, T., Beg, I., Husnine, S. M. (2014). Robot selection by using generalized interval-valued fuzzy numbers with TOPSIS., Applied Soft Computing : 21 : 462–468.

Roshandel, J., Nargesi, S. S. M., Shirkouhi, L. H. (2013). Evaluating and selecting the supplier in detergent production industry using hierarchical fuzzy TOPSIS., Applied Mathematical Modelling : 37 : 10170–10181.

Saaty, T. (1980). The analytic hierarchy process. New York: McGraw Hill.

Saen, R. F. (2007). A new mathematical approach for supplier selection: Accounting for non-homogeneity is important., Applied Mathematics and Computation : 185 (1) : pp. 84–95.

San Cristobal, J. R. (2011). Multi-criteria decision-making in the selection of a renewable energy project in Spain: The VIKOR method., Renewable Energy : 36 : 498–502.

Sanayei, A., Mousavi, S. F., Yazdankhah, A. (2010). Group decision making process for supplier selection with VIKOR under fuzzy environment., Expert Systems with Applications : 37(1) : 24–30.

Seydel, J. (2006). Data envelopment analysis for decision support., Industrial Management and Data Systems : 106 (1) : pp. 81–95.

Shehabuddeen, N., Probert, D., Phaal, R. (2006). From theory to practice: Challenges in operationalising a technology selection framework., Technovation : 26(3) : 324–407.

Shemshadi, A., Shirazi, H., Toreihi, M., Tarokh, M. J. (2011). A fuzzy VIKOR method for supplier selection based on entropy measure for objective weighting., Expert Systems with Applications : 38 : 12160–12167.

Shen, Y. C., Lin, G. T. R., Tzeng, G. H. (2011). Combined DEMATEL techniques with novel MCDM for the organic light emitting diode technology selection., Expert Systems with Applications : 38 (2011) 1468–1481.

Shen, Y., Lin, G. T. R., Tzeng, G. (2011). Combined DEMATEL techniques with novel MCDM for the organic light emitting diode technology selection., Expert Systems with Applications : 38 : 1468–1481.

Sonmez, M. (2006). A Review and Critique of Supplier Selection Process and Practices., Business School Occasional Papers Series.

Soukup, W. R. (1987). Supplier Selection Strategies., Journal of Purchasing and Materials Management : Summer : pp. 7-12.

Suh, N. (2001). Axiomatic design – advances applications. New York: Oxford University Press.

Suh, N.P. (1990). The principles of design. New York: Oxford University Press.

Tam, M., Tummala V. (2001). An application of the AHP in vendor selection of a telecommunications system., Omega : 29 : 171–182.

Tao, L., Chen, Y., Liu, X., Wang, X. (2012). An integrated multiple criteria decision making model applying axiomatic fuzzy set theory., Applied Mathematical Modelling : 36 : 5046–5058.

Vahdani, B., Mousavi, S. M., Moghaddam, R. T. (2011). Group decision making based on novel fuzzy modified TOPSIS method., Applied Mathematical Modelling : 35 : 4257–4269.

Vats, S., Vats, G., Vaish, R., Kumar, V. (2014). Selection ofoptimal electronic toll collection system for India: A subjective-fuzzy decision making approach., Applied Soft Computing : 21 : 444–452.

Vinodh, S. (2011). Axiomatic modelling of agile production system design., International Journal of Production Research : 49 (11) : 3251-3269.

Wang, J., Cheng, C., Huang, K. (2009). Fuzzy hierarchical TOPSIS for supplier selection., Applied Soft Computing Journal : 9(1) : 377–386.

Weber, C. A., Current, J. R., Benton, W. C. (1991). Vendor selection criteria and methods., European Journal of Operational Research : 50 (1) : pp. 2–18.

Weng, F. T., Jenq, S. M. (2012). Application integrating axiomatic design and agile manufacturing unit in product evaluation., International Journal of Advance Manufacturing Technologies : 63 : 181–189

Wilson, J. S. (2005). Sensor Technology Handbook., Elsevier, Newnes.

Woo, S. H., Choi, J. Y., Kwak, C., Kim, C. O. (2009). An active product state tracking architecture in logistics sensor networks., Computers in Industry : 60 : 149–160.

Wu, H. Y., Chen, J. K., Chen, I. S. (2010). Innovation capital indicator assessment of Taiwanese Universities: A hybrid fuzzy model application., Expert Systems with Applications :37(2) : 1635–1642.

You, X. Y., You, J. X., Liu, H. C., Zhen, L. (2016). Group multi-criteria supplier selection using an extended VIKOR method with interval 2-tuple linguistic information., Expert Systems with Applications : 42 : 1906–1916.

Yu, M. C., Goh, M., Lin, H. C. (2012). Fuzzy multi-objective vendor selection under lean procurement., European Journal of Operational Research : 219 : 305–311.

Yucenur, G. N., Vayvay, Ö., Demirel, N. Ç. (2011). Supplier selection problem in global supply chains by AHP and ANP approaches under fuzzy environment., International Journal of Advanced Manufacturing Technology :56(5–8) : 823– 833.

Zadeh, L. (1975). The concept of a linguistic variable and its applications to approximate reasoning., Information Sciences :(2) : 301–357.

Zeydan, M., Çolpan, C., Çobanoglu, C. (2011). A combined methodology for supplier selection and performance evaluation., Expert Systems with Applications : 38(3) : 2741–2751.

Zouggari, A., Benyoucef, L. (2012). Simulation based fuzzy TOPSIS approach for group multi-criteria supplier selection problem., Engineering Applications of Artificial Intelligence :25 : 507–519.

BIOGRAPHICAL SKETCH

Doğan Aybars İLHAN, the candidate of M.S. degree in Industrial Engineering Department in Galatasaray University, was born on April 23, 1990, in Tokat. He graduated from Tokat Anatolian High School in 2008. In the following year, he started his bachelor education in Industrial Engineering in İstanbul Kültür University with a full scholarship. For one semester, he studied in Jönköping University in Sweden as an exchange student of the Erasmus Program. In 2014, he completed his education with the second highest GPA and graduated from İstanbul Kültür University. He has two papers presented at international congresses. He works at itelligence Turkey as project manager.