# INTEGRATED VIKOR WITH MULTIPLE PREFERENCE RELATIONS FOR COLLABORATIVE ROBOT SELECTION

(ENTEGRE ÇOKLU TERCİH İLİŞKİLERİ ve VİKOR YÖNTEMİYLE İŞBİRLİKSEL ROBOT SEÇİMİ)

by

**Burcu BAHADIR, 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**

June 2017

This is to certify that the thesis entitled

**INTEGRATED VIKOR WITH MULTIPLE PREFERENCE RELATIONS FOR COLLABORATIVE ROBOT SELECTION**

prepared by **Burcu BAHADIR** 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** -------------------------

Associate Prof. Dr. A. Çağrı TOLGA
**Department of Industrial Engineering**
**Galatasaray University** -------------------------

Assist.Prof. Dr. Umut ASAN
**Department of Industrial Engineering**
**İstanbul Technical University** -------------------------

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

**ACKNOWLEDGMENT**

This thesis could not be completed without the help and encouragement of many people. First of all I would like to express my gratitude to Prof. Dr. Gülçin Büyüközkan Feyzioğlu, for her support, help and guidance.

I would like to thank Halefşan Sümen for his valuable ideas.

I would like to thank to my friends Öykü and Deniz for their help and support. This M.S. study would not be fun without you.

Thank you to my best friends, Sule and Burcu, who have always been with me and supported me since high school.

I would like to thank my beloved roommate Defne, for endless support and help.

I would also like to thank my dear friend Erhan who has always helped me since the beginning of our undergraduate journey.

Finally, I want to thank to my beloved family for their endless love and support.

June, 2017.

BURCU BAHADIR

## TABLE OF CONTENT

**LIST OF SYMBOLS**

**AHP** : Analytic Hierarchy Process
**DEA** : Data Envelopment Analysis
**DM** : Decision Maker
**DoE** : Design of Experiment
**DoF** : Degrees of Freedom
**ELECTRE** : ELimination and Et Choice Translating REality
**E-VIKOR** : Extended VIKOR
**FAD** : Fuzzy Axiomatic Design
**FAHP** : Fuzzy Analtic Hierarchy Process
**FDM** : Fuzzy Delphi Method
**FTOPSIS** : Fuzzy Technique for Order Preference by Similarity to Ideal Solution
**FVIKOR** : Fuzzy Vlse Kriterijumsa Optimizacija Kompromisno Resenje
**GRA** : Grey Relational Analysis
**GTMA** : Graph theory and matrix approach
**HFPR** : Hesitant Fuzzy Preference Relations
**IF-VIKOR** : Intuitionistic fuzzy VIKOR
**ITL-TOPSIS** : Interval 2-Tuple Linguistic TOPSIS
**ITL – VIKOR** : Interval 2-Tuple Linguistic
**IVF-COPRAS** : Interval-Valued Fuzzy Multiple Criteria Complex Proportional Assessment
**IVFM-TOPSIS** : Interval-Valued Fuzzy Modified Technique for Order Preference by Similarity to Ideal Solution
**MADM** : Multi Attribute Decision Making
**MAGDM** : Multi Attribute Group Decision Making
**MCDM** : Multi Criteria Decision Making

| | |
|---|---|
| **MCGDM** | **:** Multi Criteria Group Decision Making |
| **MCost** | **:** Maintenance Cost |
| **MOORA** | **:** Multi-Objective Optimization On The Basis Of Ratio Analysis |
| **MULTIMOORA** | **:** Multi Multi-Objective Optimization On The Basis Of Ratio Analysis |
| **NGT** | **:** Nominal Group Technique |
| **OWG** | : Ordered |
| **PAM** | **:** Polygons Area Method |
| **PCost** | **:** Purchase Cost |
| **QFD** | **:** Quality Function Deployment |
| **QGID** | **:** Quantifier Guided Importance Degree |
| **RE** | **:** Repeatability |
| **ROVM** | **:** Range of Value Method |
| **SAW** | **:** Simple Additive Weighting |
| **SERVQUAL** | **:** Service Quality |
| **TOPSIS** | **:** Technique for Order Preference by Similarity to Ideal Solution |
| **TIFNS** | : Triangular intuitionistic fuzzy numbers |
| **VIKOR** | **:** Vlse Kriterijumsa Optimizacija Kompromisno Resenje |
| **WASPAS** | **:** Weighted Aggregated Sum Product Assessment |
| **WPM** | **:** Weighted Product Model |

**LIST OF FIGURES**

## LIST OF TABLES

**ABSTRACT**

The industrial revolutions that started with the use of water and steam power in production at the end of the 18th century reached the 4th stage today with the developing technology. In the fourth industrial revolution or more commonly known as industry 4.0, machines work collaboratively with each other, with products and people through the internet of objects and other technologies. One of these technologies is, of course, the robots that are indispensable for the production environment. Robots that are starting to enter the production environment with Industry 4.0 are smarter, collaborative and secure. Choosing the right robot for the company is a strategic decision when it is thought that robots are products that require high investment. In traditional decision making, decision makers are asked to use a specific scale. But in real life, due to their background or experiences, they can express their preferences as they want or even incompletely. The aim of this study is to present a model that creates a single group decision for importance weight of criteria and alternative evaluations with missing preference relations and multiple preference relations techniques and then select the best alternative by sorting the alternatives by using VIKOR method. To show the application of the proposed model, an application was made to select a collaborative robot to be used in a firm's machine tending operation. In the study, 5 collaborative robots were evaluated considering 4 main criteria and 17 sub criteria.

# ÖZET

18.yüzyılın sonlarında su ve buhar gücünün üretimde kullanılmasıyla başlayan endüstriyel devrimler, gelişen teknolojiyle birlikte günümüzde 4.evresine ulaştı. 4. endüstriyel devir ya da daha bilinen ismiyle endüstri 4.0'da nesnelerin interneti sayesinde makineler birbirleriyle, ürünlerle ve insanlarla işbirliği içinde çalışmaktadır. Birçok teknoloji sayesinde fabrikalardaki tüm sistemlerin birbiriyle iletişim içinde olması sağlanmaktadır. Bu teknolojilerden biri de tabi ki de üretimin vazgeçilmezi robotlardır. Endüstri 4.0 ile birlikte üretim ortamına girmeye başlayan robotlar daha akıllı, işbirlikçi ve güvenli robotlardır. Bu çalışmada bir firma için makine besleme görevinde kullanılacak işbirlikçi robot seçimi problemi çalışılmıştır. Firmalar için doğru robotun seçimi stratejik önem taşımaktadır. Özellikle robotların yüksek yatırım gerektiren ürünler olması doğru robot seçiminin firmalar için ne kadar önemli olduğunu göstermektedir. Klasik karar verme problemlerinde, karar vericilerden belirli bir şekilde değerlendirmelerini vermeleri istenir. Fakat karar vericiler değerlendirme yaparken kendilerinin istediği formatta değerlendirmelerini ya da o konuyla ilgili eksik bilgi verebilir. Bu çalışmanın amacı eksik tercih ilişkileri ve çoklu tercih ilişkileri teknikleriyle, kriter ağırlığı ve alternatif değerlendirmeleri için tek bir grup kararı oluşturup daha sonra VIKOR yöntemiyle alternatifleri sıralayıp en iyi alternatifin seçilmesini sağlayan modelin sunulmasıdır. Çalışmada 4 ana kriter 17 alt kriter göz önünde bulundurularak 5 işbirlikçi robot değerlendirilmiştir. Yapılan hesaplamalar sonucunda kriterlerin önem ağırlıkları ve alternatiflerin önemleri belirlenmiş daha sonra alternatifler sıralanarak en iyi alternatifin seçimi yapılmıştır.

# 1. INTRODUCTION

The first industrial revolution began in 1784 with the discovery of steam power. In this stage, the human muscle power was replaced by steam machines. The second industrial revolution sparked with the electricity was introduced to production in the $19^{th}$ century. Industry 3.0 started in the 1970s with the introduction of programmable logic circuits, the integration of electronics and computing circuits into the industry. Today, we are now heading towards a new industrial era, the 4th industrial revolution or the well-known names industry 4.0. In industry 4.0, machines and products in smart factories communicate with each other to direct production in a collaborative way. Raw materials and machines are connected with each other by Internet of Things (IoT). The vision of Industry 4.0 is to provide a highly flexible, personalized and resource-friendly mass production. With Industry 4.0, companies will be able to offer customized products to their customers and at relatively reasonable prices. It also has the advantages of providing high flexibility to be adaptable to changes for the industry, improving productivity, reducing costs, and developing new service and business models. (Selek, 2016) In Industry 4.0, all activities are connected with the help of various technologies, including cyber-physical systems, internet of things, cloud services, big data, sensors, 3D printers, augmented reality and robotics.

Robots are indispensable members of the production environment as in industry 4.0. Because they can perform repetitive, dangerous and hazardous tasks precisely also they can dramatically improve quality and productivity. (Özgürler et al., 2011)

Robot selection problem is one of the toughest and complicated decisions that companies have to make. Increasing number of alternatives together with developing technology, more complex robots make this decision harder.

Moreover, the fact that robots are high-cost products makes choosing the right robot more important for companies. Companies usually want to choose the best alternative that meets their needs with minimal cost.

When studying the literature, we can see that there are many studies about the robot selection problem. It is seen that most of the techniques used in these problems are multi-criteria decision making (MCDM) techniques. Decision makers can select the best alternative considering many criteria by using MCDM.

In decision-making problems, more than one decision maker's idea is taken. Thus, the opinions of decision makers with different experiences and ideas are evaluated together to obtain better and stronger results. Therefore, group decision making is more preferred.

In the literature, most of the studies are concerned with the selection of industrial robots. This study is also about industrial robots selection problem. However, it is separated from other works because the robots used in this study are collaborative robots which became a part of our lives with industry 4.0.

In GDM, the evaluations given by decision makers can show diversity according to their past experiences. They can give their evaluations in many different ways like numerically, linguistically etc. (Büyüközkan & Cifçi, 2013) Also, as we all know, sometimes decision makers can give incomplete information due to lack of information or any other reason.

The aim of the study is to apply the VIKOR methodology to collaborative robot selection problem using GDM approach with multiple preference formats and incomplete information.

This study is organized as follows. In Section 2, literature reviews about robot selection problems, multiple preference relations, incomplete preference relations and VIKOR techniques are given.

In Section 3, the proposed methodology is presented and all steps of this methodology are explained step by step. In Section 4, an application of the proposed methodology over collaborative robot selection problem is presented. Then, in section 5 all results obtained from analysis were explained. The final chapter concludes the study and mentions what can be done in further studies.

# 2. LITERATURE REVIEW

In this section, studies in the literature about the robot selection problem and the techniques used in the proposed model are summarized.

## 2.1 Literature Review about Robot Selection Problem

The robot is a machine that can detect, plan and act in the shortest possible way. Robots have become an indispensable technology of the industry due to their ability to work in situations where they cannot do business, to do dangerous and vital work, to increase productivity, to provide faster and more mass production, and to reduce the error rate to almost zero. With the increasing number of robots with the development of technology, human power has begun to take the place of robots. However, with the developing technology has become more difficult for firms. It is vital for the company to make the right strategic decision for robots that require high investment due to their high cost. In the literature, it appears that many authors offer systematic approaches to cope with the robot selection problem. It is seen that the studies about this problem went back to the 1980s. Imany & Schlesinger (1989) proposed a goal programming approach to determine the best robot alternative that satisfies the objective criteria of the study. They illustrated an example which evaluates 27 robot alternatives. Kapoor & Tak (2005) proposed FAHP methodology for solving the robot selection problem and illustrate an illustrative example to show the applicability of the proposed methodology. Karsak & Ahiska (2005) developed a practical common weight MCDM methodology with an improved discriminating power for robot selection. To illustrate the applicability of the method, they presented a case study in which 12 robot alternatives were evaluated. As it seen in literature review, there have been many studies about robot selection problem. However, it seems that there is not any study that was studied collaborative robot selection problem. Previous studies summarized in Table 2.1.

Table 2.1a : Several studies about robot selection problem

| Authors | The aim of the study is | Methodology | Area | Type |
|---|---|---|---|---|
| (Karsak, 2005) | To introduce a practical common-weight MCDM model to determine the best industrial robot among several alternatives. | Practical common-weight MCDM | Manufacturing | Illustrative Example |
| (Bhattacharya et al., 2005) | To propose integrated approach which combines QFD and AHP, for solving the robot selection problem | AHP, QFD | Manufacturing process in Pharmaceutical Company | Real World Example |
| (Rao & Padmanabhan, 2006) | To suggest a selection procedure based on digraph and matrix methods to determine the best robot alternative from set of alternatives | Digraph and matrix methods | - | Illustrative Example |
| (Kahraman et al., 2007) | To propose a model based on fuzzy hierarchical topsis for evaluating industrial robotic systems. | Fuzzy Hierarchical TOPSIS | Automative Company | Real World Example |
| ( Karsak & Ahiska, 2008b) | To present an improvement of their previous study(Karsak & Ahiska 2005) about technology selection | Common-weight MCDM | - | Illustrative Examples |
| (Karsak, 2008a) | To propose a novel approach based on QFD and fuzzy regression for for robot selection problem | QFD, Fuzzy Regression | - | Illustrative Example |
| (Kumar & Garg, 2010) | To propose a deterministic quantitative model based on distance-based approach for robot selection problem. | Distance Based Approach | - | Illustrative Example |
| (Chatterjee et al., 2010) | To define the best robot alternative using VIKOR and ELECTRE methods and compare the results that are obtained from these methods. | VIKOR, ELECTRE | pick-n place operation | Real World Examples |
| (Vahdani et al., 2011) | To propose a fuzzy modified TOPSIS model to select the best alternative while considering both qualitative and quantitative attributes. | Fuzzy modified TOPSIS | Material handling tasks and rapid prototyping process | Illustrative Examples |
| (Singh & Rao, 2011) | to propose a new integrated method and apply to 3 different problem examples in industrial environment to present the potential of this method | Graph theory and matrix approach (GTMA), AHP | Jointed-arm robot selection | Illustrative Example |

Table 2.1b : Several studies about robot selection problem

| | | | | |
|---|---|---|---|---|
| (Chakraborty, 2011) | to solve 6 different problems in manufacturing environment including the robot selection problem with the MOORA method and to demonstrate the usability of this method. | MOORA | Pick-n-place operation | Illustrative Example |
| (Özgürler et al., 2011) | To deal with a robot selection problem for material handling task in a manufacturing system with two MCDM methods. | AHP TOPSIS | Metal cutting workshop at tractor factory | Real World Example |
| (Koulouriotis & Ketipi, 2011) | To propose a fuzzy digraph method for robot selection and evaluation problems. | Fuzzy Digraph | Material handling task | Illustrative Example |
| (Kentli & Kar, 2011) | To propose a simple model for solving industrial robot selection problem | Satisfaction Function, Distance Measure | -- | Illustrative Example |
| (Devi, 2011) | To extend VIKOR in intuitionistic fuzzy environment to solve decision making problems and apply this method in robot selection problem | IF-VIKOR | Material handling task | Illustrative Example |
| (Athawale & Chakraborty, 2011) | To compare the ranking performance of ten MCDM methods while solving the robot selection problem for pick-n-place operation | SAW, WPM, AHP, TOPSIS, GTMA, VIKOR, ELECTRE II, PROMETHEE II, GRA,ROVM | Pick-n place operation | Illustrative Example |
| (Rao et al., 2011) | To propose a MADM model for a robot selection problem while considering both objective and subjective attributes | MADM method | Pick-n place operation | Real world examples |
| (Karsak et al., 2012) | To develop a regression-based decision making approach for robot selection problem | Fuzzy Linear Regression | - | Illustrative Example |
| (Chaghooshi et al., 2012) | To propose a new method based on fuzzy Shannon's Entropy and fuzzy TOPSIS for robot selection problem. | Fuzzy Shannon's Entropy, FTOPSIS, | - | Illustrative Example |

Table 2.1c : Several studies about robot selection problem

| | | | | |
|---|---|---|---|---|
| (Momeni et al., 2012) | to present a new integrated method for technology selection and demonstrate the numerical example to show the application of the proposed methodology. | FAHP, Interval TOPSIS | - | Illustrative Example |
| (Mazumder, 2009) | To present application of ELECTRE methods in several decision making problems including robot selection problem | ELECTRE | Manufacturing | Illustrative Example |
| (Bahadir & Satoglu, 2012) | To propose a robot arm selection methodology based on axiomatic design principles. | Axiomatic Design | Pick-n-place operation | Illustrative Example |
| (İç, 2012) | To study the applicability of the integrated methodology to solve four computer-integrated manufacturing technology selection including industrial robot selection problem. | TOPSIS DoE | Manufacturing | Illustrative Example |
| (Amin & Emrouznejad, 2012) | to select the most convenient robot alternative in advanced manufacturing technology in the presence of both cardinal and ordinal data | DEA | - | Illustrative Example |
| (Vahdani et al., 2013) | To propose an new IVFS-TOPSIS method which can handle the subjective and objective information in real life and present a numerical application for a robot selection problem to prove validity of this method | IVFS-TOPSIS | Material handling | Illustrative Example |
| (Mondal & Chakraborty, 2013) | To determine the feasible robots using four models of DEA. | Data Envelopment Analysis (DEA) | Pick-n-place operations | Illustrative Examples |
| (Vahdani et al., 2014) | To propose a decision making method based on IVF-COPRAS to solve robot selection problem | IVF-COPRAS | Material handling tasks | Illustrative Example |

Table 2.1d Several studies about robot selection problem

| | | | | |
|---|---|---|---|---|
| (Rashid et al., 2014) | To propose a method to get aggregated opinions from decision makers where their opinions represented by generalized internal-valued trapezoidal fuzzy numbers | TOPSIS, generalized internal-valued trapezoidal fuzzy numbers | Material handling tasks | Illustrative Example |
| (Omoniwa, 2014) | To use GRA for robot selection problems and confirm the validity of this method. | GRA | Manufacturing environment | Illustrative Examples |
| (Shahrabi, 2014) | To show the applicability of the integrated methods and select the best robot alternative from numerous alternative with 2 MADM methods. | FAHP FTOPSIS | Metal cutting at truck factory | Real World Example |
| ( Liu et al., 2014) | To propose ITL-TOPSIS to handle uncertainty and incomplete information in robot selection problem. | ITL-TOPSIS | Material handling tasks at | Illustrative Example |
| (Koulouriotis & Ketipi, 2014) | to present the literature review about methods which were used to deal with solving robot selection problems. | -- | -- | Literature Review |
| (Bairagi et al., 2014) | To present the applicability of 3 fuzzy MCDM methods in robot selection problems. | FAHP, FTOPSIS, FVIKOR, COPRAS-G | Pick-n-place operation in foundry shop | Real World Example |
| ( Azimi et al., 2014) | To present the PAM method for a robot selection problem and applicability of this method by giving examples. | PAM, SAW,WPM, TOPSIS, VIKOR | Manufacturing | Illustrative Example |
| (Adakane & Narkhede, 2014) | To select the best robot alternative for powder coating operation using 3 different MCDM methods. | AHP, TOPSIS, PROMETHEE | Powder Coating Operation | Real World Example |

Table 2.1e : Several studies about robot selection problem

| | | | | |
|---|---|---|---|---|
| (Igoulalene & Benyoucef, 2014) | To develop a new approach which is dedicated to strategic selection problem for supply chain coordination. | Consensus-based TOPSIS | Manufacturing | Illustrative Example |
| (Khandekar & Chakraborty, 2015) | To investigate the applicability of the Fuzzy Axiomatic Design (FAD) method to solve the robot selection problem. | Fuzzy Axiomatic Design | Assembly operation | Real World Example |
| (Chakraborty et al., 2014) | to validate the applicability and usefulness of WASPAS method as a decision-making tool using five industrial selection problems like robot selection. | WASPAS | - | Illustrative Example |
| (Parameshwaran et al., 2015) | To propose a new integrated model to decide the best robot alternative for robotic course . | FDM, FAHP, Fuzzy Modified TOPSIS, FVIKOR, Brown-Gibson Model | Education | Real World Example |
| (Sen et al., 2015) | To propose the extended TODIM approach under grey environment. | Grey-TODIM | - | Illustrative Example |
| ( Zhang et al., 2015) | to present an approach that measures the group consensus in MADM problem when multiple preference informations are used when evaluating alternatives. | Multiple Preference | - | Illustrative Example |
| (Xue et al., 2016) | To present a hesitant 2-tuple linguistic QUALIFLEX model to select the most suitable robot alternative with incomplete weight information. | QUALIFLEX, hesitant 2-tuple linguistic term sets | Material Handling task | Real World Example |
| (Ghorabaee, 2016) | To propose a MCGDM model that use VIKOR method with interval type-2 fuzzy numbers for robot selection | VIKOR, Interval type-2 fuzzy numbers | Automotive Industry | Real World Example |

Table 2.1f: Several studies about robot selection problem

| | | | | |
|---|---|---|---|---|
| (Mirfakhradin et al., 2016) | to apply the integrated method for robot selection problem which is one of the technology selection problems | AHP,<br>TOPSIS | - | Real World Example |
| (Sen et al., 2016) | to select the best robot alternative with the extended Promethee method by considering subjective and objective criteria | Extended PROMETHEE | - | Illustrative Example |
| (Karande et al., 2016) | to compare and investigate the robustness and sensitivity of 6 different MCDM methods using 2 real-world robot selection problems. | WSM, WPM,WASPAS,MOORA, MULTIMOORA | Pick-n-place operation | Real World Examples |
| (Sen et al., 2017) | To extend the crisp-TODIM methodology with linguistic variables and suggest to fuzzy TODIM approach for robot selection problem. | F-TODIM | - | Illustrative Examples |

## 2.2 Literature Review about Multiple Preference Relations

Decision makers' can give their assessments in different ways during decision-making process. Their assessments can vary according to the decision makers' educational or cultural background, their experiences or even their current mental status and time. While the decision makers' choices can vary so much, compelling them to make a single assessment can reduce the effectiveness of the decision-making process. Multiple preference relation techniques are used to cope with this situation. Once the decision makers have evaluated the factors in the desired format, evaluations are unified by using these techniques and a common decision is reached.

Multiple preference techniques are divided into two categories according to whether the evaluations are complete or incomplete. The multi-preference or complete preference relations technique is used if all evaluations about criteria or alternatives are complete.
The incomplete preference relations technique is used if there are missing information in the decision makers' evaluations

### 2.2.1 Literature Review about Complete Preference Formats

In MCDM problems, experts' preference information is used in decision making process. However, the experts' ideas vary in form and depth. (Zhang et al., 2015) In practice, generally same representation format used to model GDM problems and form in preferences. But as we mentioned before, people can give information about their personal preferences in many different ways, depending on their different cultural and education background and value systems. In this case, when we force decision makers to give their preferences in one way (like in classic MCDM methods), will cause to reduce the accuracy and strength of the decision. The multi-preference technique is used to prevent this and to make a common group decision when more than one type of preference is used. The main aim of the multi preference technique is to be able to achieve a common decision by unifying the different types of preferences received from decision makers.

In literature, there are many different preference formats those are used to express the DMs' opinions. Decision makers can give their evaluations in the following formats:

- Ordered vector: The criteria / alternatives are ranked from good to bad.
- Importance degree vector: The criteria / alternatives are weighted by importance.
- Linguistic importance vector: Linguistic assessments (very good, very bad, etc.) are given about the criteria / alternatives.
- Multiplicative preference relations: Evaluations on criteria / alternatives are given in the form of a pair wise matrix, which is also familiar from the AHP.
- Selected subset: Criteria/alternatives that seem more important/ better among the others can be selected.
- They can express that some criteria/alternatives are more important or better from other criteria/alternatives without degree explicitly.

There are some benefits of the multi preference relations. The advantages are as following, (Zhang et al., 2004)

- Provide flexibility to DMs with applying different forms of judgments
- Helps to reach to a higher satisfaction level on the decision making process
- Helps to getting the decision outcome with high satisfaction level.

Even though, the multiple preference relations has advantages, it also has disadvantage. These approaches are inadequate for studies that have lack information.

Based on the literature, the previous studies with multi preference relations are summarized in Table 2.2.

Table 2.2a : Several studies about multi-preference formats

| Authors | The aim of the study is | Methodology | Area | Type |
|---|---|---|---|---|
| (Jiang et al., 2013) | To develop consensus models as for intuitionistic multiplicative preference relations that have different properties in GDM procedures | GDM with intuitionistic multiplicative preference relations | School Evaluation | Illustrative Example |
| (Li et al., 2012) | To propose the QFD technique by determining the customer requirements with an integrated approach of the GDM. | GDM, multi-format preference analyses in QFD | Design improvement in an electric corporation | Real World Example |
| (Wang, 2012) | present a nonlinear programming approach to describe the relative importance weights of customer needs | QFD, Multiple preference, Nonlinear programming | Pencil Example | Illustrative Example |
| (Xia & Xu, 2013) | To introduce the intuitionistic multiplicative preference relation based on the interval-valued multiplicative preference relation | GDM, Intuitionistic multiplicative preference relation | Internet Service Selection | Illustrative Example. |
| (Büyüközkan & Çifçi, 2013) | to present a novel approach of group decision making and implement the QFD technique in sustainable supply chain | QFD, incomplete preference, multiple preference | Turkish logistic sector | Real World Example |
| (Dong & Zhang, 2014) | To examine the multi person decision making problem with different preference representation constructions | MPDM, preference orderings, utility functions, multiplicative preference relations and fuzzy preference relations | | Illustrative Example |
| (Jiang & Xu, 2014) | To establish a transformation mechanism and to develop ordered weighted operators for aggregating intuitionistic multiplicative information | Intuitionistic multiplicative preference relations | | Illustrative Example. |

Table 2.2b : Several studies about multi-preference formats

| | | | | |
|---|---|---|---|---|
| (Zhou et al., 2014) | To develop a new operator to define the optimum weights of experts in GDM | GDM with multiplicative linguistic preference relation | Supplier selection | Illustrative Example |
| (Ureña et al., 2014) | To make a review and analyze the methods about estimation of missing preferences in GDM process. | GDM, multiplicative preference relations and incomplete preference relations | | Literature Review |
| (Xia & Chen, 2014) | To examine the consistency of interval multiplicative preference relations in group decision making | GDM, Interval multiplicative preference relations | | Illustrative Example. |
| (Chu & Lin, 2003) | Evaluation of Supply chain RFID technologies | Fuzzy Linguistic | | Case Study |
| (Büyüközkan & Çifçi, 2015a) | To implement the integrated QFD methodology and two GDM approaches | Fuzzy GDM in QFD with multiple preference formats and incomplete preference relations | Portable Entertainment and Game Systems | Real World Example |
| (Büyüközkan & Güleryüz, 2015c) | To use extended QFD methodology in CPD for IT planning with two different GDM approaches | Fuzzy GDM in QFD with multiple preference formats and incomplete preference relations | Turkish Software Company | Illustrative Example |
| (Jiang et al., 2015) | To propose a model for GDM with incomplete IMPR | GDM, Intuitionistic multiplicative preference relation, incomplete | | Illustrative Example |
| ( Zhang et al., 2015) | To propose an approach to measure the group consensus in MADM with 7 different decision makers' preference information on alternatives. | Multiple attribute decision-making with multiple preference formats | Robot selection | Real World Example |

Table 2.2c : Several studies about multi-preference formats

| | | | | |
|---|---|---|---|---|
| ( Zhang et al., 2015) | To examine the fuzzy MAGDM and to develop a novel GDM approach considering regret aversion of the decision makers. | Fuzzy MAGDM with multi-dimensional preference relations and incomplete weight information | Investment decision | Illustrative Example. |
| (Cid-López et al., 2015) | Improvement in customer service time table in ICT sector | Fuzzy linguistic | | Real World Example |
| (Rianthong et al., 2016) | To develop a stochastic programming model to design the optimal sequence of hotels | Multi criteria decision making with multi-dimensional preferences | | Real World Example |
| (Zulueta et al., 2016) | Environmental Impact Significance Assessment | Fuzzy Linguistic | | Case Study |
| (Zhang, 2016a) | To present a novel preference relation to develop several independent and correlative interval valued intuitionistic multiplicative aggregation operators | GDM, interval-valued intuitionistic multiplicative preference relations | | Illustrative Example |

### 2.2.2 Literature Review about Incomplete Preference Format

As we mentioned in the previous section, experts express their preferences with different preference representation formats. However, sometimes it can be difficult to gather all preference relations. It is common that experts might not have a precise or adequate level of knowledge of part of the problem, as a result of this situation; experts might not provide all the information which is required for the decision-making process. (Urena et. al., 2015) Incomplete preferences should not be ignored in the evaluation process. Because these preferences are another types of linguistic preference relations where DMs' have not enough information.

The main purpose of the incomplete preference relation technique is to obtain the decision makers' importance relation matric by completing the missing information based on the information given by the decision maker as it seen in Figure 2.1.

| | C1 | C2 | C3 |
|---|---|---|---|
| C1 | - | ? | √ |
| C2 | ? | - | √ |
| C3 | √ | √ | - |

→

| | C1 | C2 | C3 |
|---|---|---|---|
| C1 | - | √ | √ |
| C2 | √ | - | √ |
| C3 | √ | √ | - |

Figure 2.1 Incomplete preference relation

There are some benefits of the incomplete preference relations. The advantages are as following, (Büyüközkan & Çifçi, 2015a)

- Managing evaluation limitations effectively.
- Improving quality and strength of the evaluation

Based on the literature, the previous studies with incomplete preference relations are summarized in Table 2.3.

Table 2.3a: Several studies about incomplete preference formats

| Authors | The aim of the study | Methodology | Area | Type |
|---|---|---|---|---|
| (Dopazo & Ruiz-Tagle, 2011) | To find the missing informations by using incomplete pairwise comparison matrices | GDM, Incomplete information, Logarithmic goal programming | - | Illustrative example |
| (Xu et al., 2011) | to prove that the proposed study is more reasonable than Xu and Chen's additive consistent inc. fuzzy preference | GDM, Incomplete reciprocal relations, Additive transitivity consistency | - | Illustrative Example |
| (Buyukozkan & Cifci, 2012) | To propose a QFD methodology extended by GDM approach and determine the design requirements on collaborative software process | QFD, GDM, Incomplete Preference Relations | Software development | Real-world example |
| (Gong et al., 2012) | To present optimal priority methods on the IFPR and IIPR | GDM, Least square method, Incomplete intuitionistic fuzzy and interval preference relation | - | Illustrative Example |
| (Lee, 2012) | To develop a new group decision making method with incomplete fuzzy preference relations based on the additive consistency and the order consistency, | GDM, Incomplete fuzzy preference relations, Additive and order consistency | - | Illustrative Example |
| (Wang & Li, 2012) | To propose a linear programming technique for multidimensional analysis of preference method | MAGDM, incomplete pairwise comparison preference, linear programming | Recommending undergraduate students | Illustrative Example |

Table 2.3b: Several studies about incomplete preference formats

| | | | | |
|---|---|---|---|---|
| (Xu, 2012) | To develop a consensus reaching process of group decision making, by making use of the multiplicative transitivity properties | GDM, incomplete preference relation | Financial Merger Strategies | Illustrative Example |
| (Zhang et al. 2012) | To propose a linear optimization model to solve some problems on individual consistency construction, consensus model and management of incomplete fuzzy preference relations | Linear optimization models, GDM, fuzzy preference relations | - | Illustrative Example |
| (Büyüközkan & Cịfçi, 2013) | to present a novel approach of group decision making and implement the QFD technique in sustainable supply chain | QFD, incomplete preference, multiple preference | Turkish logistic sector | Real World Example |
| (Chen et al., 2013) | To present a novel methodology by using fuzzy preference relations to develop the Lee's method | GDM, incomplete fuzzy preference relations, additive and order consistency | - | Illustrative Example |
| (Nahm et al., 2013) | To propose new methods for customer preferences and satisfaction ratings, | QFD, incomplete customer preferences, new rating method | Product Improvement in Car Design | Illustrative Example |
| (Xu & Wang, 2013a) | To present the eigenvector method to priority for an incomplete fuzzy preference relation | Incomplete fuzzy preference relation, Eigenvector method | - | Illustrative Example |
| (Xu et al., 2013b) | To present a logarithmic least squares method to rank alternatives in group decision making with incomplete fuzzy preference relations | GDM, incomplete fuzzy preference, Logarithmic least squares method | - | Illustrative Example |
| (Yang & Wang, 2013) | To present a linguistic decision aiding technique called multi-criteria semantic dominance based on incomplete preference information. | Linguistic modeling, incomplete preferences | Recruit decision | Illustrative Example |

Table 2.3c: Several studies about incomplete preference formats

| | | | | |
|---|---|---|---|---|
| (Huang et al., 2014) | To propose a new decision-making method based on the AHP and DS theory | AHP, incomplete preferences, Dempster–Shafer evidence theory | | Illustrative Examples |
| (Liu & Zhang, 2014) | to propose a new algorithm, to solve the GDM problem with incomplete interval fuzzy preference relations. | Incomplete interval fuzzy preference relations, Topsis, GDM, consistency, goal programming | Partnership selection in formation of virtual enterprises | Real World Example |
| (Ureña et al., 2014) | To make a review about the methods and processes which are developed to estimating missing preferences in GDM process . | GDM, incomplete preference relations, consistency | | Literature Review |
| (Vetschera et al., 2014) | To present a comprehensive computational study on the effects of providing different forms of incomplete preference information in group decision models | Incomplete preference information, additive group decision models | | Illustrative Example |
| (Xu & Cai, 2014) | To develop a more rational estimation procedure for incomplete IV-IPR procedure and develop an approach to GDM with incomplete IV-IPRs. | GDM, Incomplete Interval-Valued Intuitionistic Preference Relations | Evaluation of exchange doctoral students | Illustrative Example |
| (Xu et al., 2014) | To propose methods for constructing additive consistent IFPRs based on acceptable incomplete IFPRs. | Incomplete interval fuzzy preference relation, Additive consistent, GDM | Supplier Selection | Real World Example |
| (Zhang & Guo, 2014) | To develop a method on GDM problems with heterogeneous incomplete uncertain preference relations to present a bi-objective optimization model. | GDM, incomplete uncertain preference relations | - | Illustrative Example |

Table 2.3d : Several studies about incomplete preference formats

| | | | | |
|---|---|---|---|---|
| (Zhang & Xu, 2014) | to present an interval programming with using the main structure of LINMAP to solve the MAGDM problems. | MAGDM, Incomplete preference, Hesitant fuzzy set, Interval programming | Energy Project Selection | Illustrative Example |
| (Zhu & Xu, 2014) | To reduce the four steps of GDM problems into two steps by developing a new fuzzy linear programming method. | GDM, fuzzy preference relations, fuzzy linear programming method | - | Illustrative example |
| (Büyüközkan & Çifçi, 2015a) | To implement the integrated QFD methodology and two GDM approaches. | Fuzzy GDM in QFD with multiple preference formats and incomplete preference relations | Portable Entertainment & Game Systems | Illustrative Example |
| (Büyüközkan & Güleryüz, 2015c) | To use extended QFD methodology in CPD for IT planning with two different GDM approaches | Fuzzy GDM, QFD, multiple and incomplete preference | Turkish software company | Real World Example |
| (Dong et al., 2015) | To develop two integrated approaches for MCGDM problems. | Incomplete information, triangular fuzzy power geometric operator, GDM | Investment Decision | Illustrative Example |
| (Jiang et al., 2015) | To propose a model for GDM with incomplete IMPR and its consistency property by presenting two approaches | GDM, Intuitionistic multiplicative preference relation, incomplete intuitionistic multiplicative preference relation | Communication | Illustrative example |
| (Meng & Chen, 2015) | To develop a new algorithm for the GDM with incomplete fuzzy preference information | GDM, AHP, incomplete fuzzy preference relations | | Illustrative Examples |
| (Park, 2015) | To examine the characteristics of potential games concerning Nash equilibria and defining Nash equilibrium for games with incomplete preferences. | Incomplete preference relations, Nash equilibrium | - | Illustrative Example |

Table 2.3e : Several studies about incomplete preference formats

| | | | | |
|---|---|---|---|---|
| (Ureña et al., 2015) | To prove the mathematical equivalence between the set of reciprocal intuitionistic fuzzy preference relations and the set of asymmetric fuzzy preference relations | GDM, incomplete reciprocal intuitionistic preference relations | | Illustrative example |
| (Wang & Chen, 2015a) | To develop a SA-based permutation method for MCDA problems under incomplete preference information within the environment of interval type -2 fuzzy sets. | Incomplete preference information, annealing-based permutation method | | Illustrative example |
| (Wu et al., 2015) | To propose a new trust based consensus model for social network in a 2-tuple linguistic context under incomplete information | Incomplete linguistic information, GDM | | Illustrative Example |
| (Xu et al., 2015a) | To propose a new method, for the priority vector derivation from incomplete reciprocal preference relations | Incomplete reciprocal preference relation, GDM, Least deviation method | - | Illustrative Example |
| (Yan & Ma, 2015) | To refer the two types of uncertainties underlying QFD, which are fuzzy preference relation and fuzzy majority, for developing a new GDM method. | GDM, fuzzy preference relations, uncertain QFD | manufacturing and Chinese restaurants | Illustrative Examples |
| (Zhang et al., 2015) | To develop two estimation procedures to determine the missing information in an expert's incomplete hesitant fuzzy preference relation | GDM, Incomplete hesitant fuzzy preference | Investment decision | Real World Example |
| (Xu et al., 2015c) | To propose a method for constructing interval additive consistent fuzzy preference relations | AHP, incomplete interval fuzzy preference, additive transitivity | Supplier selection | Illustrative Example and Case Study |
| (Xu et al., 2015b) | To propose chi-square method to handle decision problems with IRPR and obtain a priority vector for GDM problems | Chi-square method, Incomplete reciprocal preference relations | - | Illustrative Example |

Table 2.3f : Several studies about incomplete preference formats

| | | | | |
|---|---|---|---|---|
| (Wang & Chen, 2015) | To propose an interval type-2 fuzzy permutation method for addressing multiple criteria decision-making problems under incomplete preference information. | Interval type-2 fuzzy permutation method | -- | Illustrative Example |
| (Wang & Xu, 2016) | To focus on the incomplete linguistic preference relations and to discuss the consistency and the fulfill algorithms of incomplete linguistic preference relations | Incomplete linguistic preference relation, Consistency | Chinese Energy Channels | Real World Example |
| (Zhang & Guo, 2016b) | To examine the fusion of heterogeneous incomplete hesitant preference relations beneath the GDM settings | GDM, heterogeneous incomplete hesitant preference relations | Supplier selection, | Illustrative Examples |
| (Khalid & Beg, 2016) | To propose a method for estimating missing preferences while incorporate incomplete interval valued fuzzy preference and multiplicative fuzzy preference relations in decision making process. | Incomplete interval valued fuzzy preference relations, multiplicative fuzzy preference relations | -- | Illustrative Examples |
| (Xu et al., 2016) | To present incomplete HFPRs for group decision making process | Incomplete hesitant fuzzy preference relations, Goal programming | Strategy initiatives | Illustrative Examples |
| (Wang & Li, 2016) | To propose a model based on two-stage quadratic program for estimating missing values. | Incomplete IPR, Quadratic program, | ERP selection | Illustrative Examples |
| (Zhang et al., 2016) | To propose a hybrid consensus model for GDM problems with incomplete RPRs. | Incomplete preference multiplicative transitivity | - | Illustrative Example |

## 2.3 Literature Review about VIKOR Method

The VIKOR (VlseKriterijumsa Optimizacija Kompromisno Resenje) method was developed by Opricovic in 1988 for multiple criteria optimization of complex systems. The VIKOR method, which focuses on ranking and selecting from a set of alternatives, provides compromise solutions for problems with conflicting criteria (Opricovic & Tzeng, 2004). Compromise solution is a feasible solution, which is the closest to the ideal solution, and compromise means an agreement established by mutual concessions made between the alternatives. The multi criteria merit for compromise ranking is developed from the Lp-metric used in compromise programming method. Development of the VIKOR method is started with the following form of $L_p$-metric: (Yu, 1973)

$$L_{pj} = \left\{\sum_{i=1}^{n}\left[w_i \times \frac{(f_i^* - f_{ij})}{f_i^* - f_i^-}\right]^p\right\}^{\frac{1}{p}} \tag{2.1}$$

There are many studies in the literature about VIKOR method. The application areas in which VIKOR was used can be categorized as follows; design, mechanical engineering and manufacturing, business management, logistics and supply chain management, environmental management, information technology, policy social and education, energy management, financial management, transportation engineering. (Gul et al., 2016)

Table 2.4a: Several studies about VIKOR method

| Authors | The aim of the study is | Methodology | Area | Type |
|---|---|---|---|---|
| (Chou & Cheng, 2012) | To develop hybrid model for evaluation of the websites. | FANP, FVIKOR | E-commerce | Real World Example |
| (Datta et al., 2012) | To select the best green supplier | VIKOR, Interval-valued fuzzy sets | Supplier selection | Real World Example |
| (Kuo & Liang, 2012) | To propose a new performance evaluation model for handle fuzzy MCDM problems. | VIKOR, interval-valued fuzzy sets | Performance Evaluation | Real World Example |
| (Liu & Wu, 2012) | To propose a hybrid model to personel selection problem. | VIKOR, multi-granularity, two-semantics, entrophy | Human resources | Illustrative Example |
| (Dai et al., 2012) | To build a decision-making model to select the optimal renewable energy planning | VIKOR | Energy management | Real World Example |
| (Yalcin et al., 2012) | To develop a new financial performance evaluation model based on the accounting-based and value-based financial performance measures. | VIKOR FAHP TOPSIS | Financial performance evaluation | Real World Example |
| (Yücenur & Demirel, 2012) | To analyze Turkish insurance companies for a foreign investors | Trapezoidal fuzzy number VIKOR | Insurance Sector | Real World Example |
| (Wang & Tzeng, 2012) | to propose the brand marketing to enhance brand values of products and use MCDM model to identify the most important factor of the brand marketing | DANP, VIKOR | Marketing | Real World Example |
| (Jeya Girubha & Vinodhi 2012) | To select the best material for an automotive component. | Fuzzy VIKOR | Automotive Industry | Real World Example |
| (Hsu et al., 2012) | to determine the best vendor for conducting the recycled material. | VIKOR , DANP | Vendor selection | Real World Example |
| (Liu et al., 2012) | To suggest an optimal tourism policy improvement plan. | Dematel, DANP, VIKOR | Tourism | Real World Example |

Table 2.4b: Several studies about VIKOR method

| | | | | |
|---|---|---|---|---|
| (Ju & Wang, 2013) | To select the most suitable emergency alternative | VIKOR , 2-tuple linguistic | Emergency alternative selection | |
| (H.-C. Liu et al., 2013a) | To propose an integrated IOWA VIKOR method | VIKOR, IOWA | Material Selection | Illustrative Example |
| (H. C. Liu et al., 2013b) | To present 2-tupel linguistic VIKOR method for a material selection problem under uncertain and incomplete information | 2 tuple linguistics, VIKOR | Material selection | Illustrative Example |
| (C.-H. Liu et al., 2013c) | To propose a hybrid model for the transportaion system to improve the tourisim in Taiwan | VIKOR, DANP, DEMATEL | Transportation | Real World Example |
| (Sakthivel et al., 2013) | To select the best biodiesel blend for IC engines | VIKOR, FAHP, TOPSIS | Machine tool selection | Real World Example |
| (Tan & Chen, 2013) | To develop a DM approach to solve MCGDM problem where preferences of DMs represented by interval-valued intuitionistic fuzzy set | VIKOR Choquet Integral GDM, intuitionistic fuzzy set | | Illustrative Example |
| (Wan et al., 2013) | To propose an extended VIKOR method for solving MAGDM problems with TIFNs and to illustrate the application of this approach analyze the department manager selection problem | VIKOR – TIFNS | Human resources | Illustrative Example |
| (Zhang & Wei, 2013) | To develop extended VIKOR method and TOPSIS method with hesitant fuzzy sets and apply these methods to the project selection problem to show the applicability | E-VIKOR TOPSIS Hesitant fuzzy set | Strategy initiativies | Illustrative Example |
| (Zhao et al., 2013) | To propose an extended VIKOR method to handle with a GMCDM problems. | VIKOR, MCGDM, Entropy, Interval-valued intuitionistic fuzzy sets | - | - |

Table 2.4c: Several studies about VIKOR method

| | | | | |
|---|---|---|---|---|
| (Chiu et al., 2013) | To propose a new hybrid MADM model to improve e-store business. | DANP, VIKOR | E-Store Commerce | |
| (Liao & Xu, 2013) | To extend the VIKOR method with hesitant preference information. | Hesitant Fuzzy Set, VIKOR | Service quality in airline industry | Illustrative example |
| (Rezaie et al., 2014) | To suggest a model based on FAHP and VIKOR for evaluating the financial performance of Iranian cement firms. | FAHP-VIKOR | Financial performance evaluation | Real World Example |
| (Hsu et al., 2014) | To suggest a model based on ANP and VIKOR to evaluate suppliers according to their carbon performance. | ANP-VIKOR | Green supply chain | Real World Example |
| (Wang et al., 2014) | To present a hybrid MCDM model combining 3 methods for evaluating and improving six sigma projects | VIKOR, DEMATEL ANP | Project selection | Illustrative Example |
| (Anvari et al., 2014) | To propose a modified VIKOR method for the lean tool selection problem in manufacturing systems. | VIKOR | Manufacturing Systems | Illustrative Example |
| (Hsu, 2014) | To suggest a hybrid model to deal with investment decision making process. | VIKOR, GRA, Grey clustering, grey entropy weighting method | Investment Decision | Real World Example |
| (Aydına & Kahraman, 2014) | to propose a MCDM model for bus selection for public transport. | FAHP, Fuzzy VIKOR | Transportation | Real World Example |
| (Chang & Lin, 2014) | To apply VIKOR method to evaluate the design of the water quality monitoring network in the Taipei Water Resource Domain | VIKOR | Water Resource Management | Real World Example |
| (Celik et al., 2014) | To evaluate the customer satisfaction level for the rail transit network in Istanbul | SERVQUAL, VIKOR, Interval type-2 fuzzy sets | Transportation | Real World Example |

Table 2.4d: Several studies about VIKOR method

| | | | | |
|---|---|---|---|---|
| (Anojkumar et al., 2014) | To show the application of different MCDM methods for solving the material selection problem for pipes in sugar industry and to compare the ranking performance of methods | FAHP-TOPSIS, VIKOR, ELECTRE,PROMETHEE | Sugar industry | Real World Example |
| (H.-C. Liu et al., 2014b) | To solve site selection problem for the municipal solid waste management with extended VIKOR methodology. | VIKOR, Fuzzy linguistic | Waste Management | Real World Example |
| (H. C. Liu et al., 2014a) | To propose a new method for selecting the best disposal site for municipal solid waste. | Interval 2-tuple, VIKOR | Waste management | Real World Example |
| (Tadić et al., 2014) | To propose a new hybrid MCDM model for selecting the most suitable city logistics concept | Fuzzy Dematel, Fuzzy VIKOR, FANP | City Logistics | Real World Example |
| (Chang, 2014) | To propose an approach based on the fuzzy sets theory and VIKOR method to evaluate the hospital service quality with systematic approach. | Fuzzy VIKOR | Hospital Service Quality | Real World Example |
| (Kim et al., 2015) | To propose a framework for the prioritize the plans in strategic environmental assessment with incomplete information | VIKOR | Construction | Real World Example |
| (Liu et al., 2015) | To propose a VIKOR method which was combined with interval 2-tuple linguistic variables, for personnel selection problem | Interval 2-Tuple Linguistic VIKOR | Human resources, health industry | Real World Example |
| (Chang et al., 2015) | To develop an appropriate business model | FAHP, VIKOR, TOPSIS, GRA | E-commerce | Real World Example |
| (Tosun & Akyüz, 2015) | To develop a TODIM approach for supplier selection problem | Topsis, VIKOR, triangular fuzzy number | Furniture Manufacturing Company | Real World Example |
| (You et al., 2015) | To propose extended VIKOR with interval 2-tuple linguistic information for group multi-criteria supplier selection | ITL - VIKOR | Supplier selection | Real World Example |

Table 2.4e: Several studies about VIKOR method

| | | | | |
|---|---|---|---|---|
| (Zhu et al., 2015) | To propose an approach to manipulate the vagueness and subjectivity to enhance the objectivity in design concept evaluation. | AHP, VIKOR, Rough number | Manufacturing Tools | Illustrative Example |
| (Sharma et al., 2015) | to rank India's potential energy alternatives with the proposed method and determine the best energy alternative for the future. | Interval VIKOR and TOPSIS, cross entropy | Energy resources | Real World Example |
| (Büyüközkan & Görener, 2015b) | To suggest an integrated MCDM approach to select the most convenient product development partner | AHP-VIKOR | Product Development | Real World Example |
| (Yazdani & Payam, 2015) | To propose a systematic approach for selecting the most appropriate material for microelectromechanical systems electrostatic actuators. | VIKOR, Ashby, TOPSIS | Material Selection | Real World Example |
| (Rostamzadeh et al., 2015) | Using VIKOR to solve the green MCDM problems. | Fuzzy VIKOR | Green Supply Chain Management | Real World Example |
| (Awasthi & Kannan, 2016) | To propose an fuzzy NGT and VIKOR based model to solve the oroblem or evualation of green supplier development | Fuzzy VIKOR, NGT | Green Supply Chain Management | Real World Example |
| (Babashamsi et al., 2016) | To propose an integrating models for the prioritization of pavement maintenance alternatives. | FAHP, VIKOR | | Real World Example |
| (Tavana et al., 2016) | To propose an Extended VIKOR method to solve the MCDM problems | VIKOR, subjective judgments, stochastic data, FAHP, DEMATEL | - | Illustrative Example |
| (Wu et al., 2016) | To develop a MCGDM technique to solve the CNC machine tool selection | VIKOR, Fuzzy linguistic (Triangular fuzzy number) | Manufacturing Tools | Case Study |
| (Çelikbilek & Tüysüz, 2016) | To present a grey MCDM model which integrates 3 methods to evaluate the renewable energy sources. | Grey Dematel, Grey ANP, Grey VIKOR | Renewable Energy | Real World Example |

As a result of the literature reviews, the following situations arise:

- There is not any study about  collaborative robot selection
- As a method, there are studies those use VIKOR - incomplete preference, VIKOR - multi preference, or using multi - preference in robot selection, but there is not any study that all of them used together.

# 3. PROPOSED METHODOLOGY

## 3.1 Collaborative Robot Selection

Industrial robot technology in the world is entering a new era. A transition process is continuing from the first generation industrial robots, which have the least interaction with humans of the robotic cells, to the new generation industrial robots that are in passive / active collaboration with humans. Collaborative robots also known as cobots or co-robots developed under Industry 4.0 play an important role in the flexible production system by working in the division of labor in the same environment with the operator. The interaction of collaborative robots with operators and other robot automation systems through the Internet of Things (IoT) constitutes the basic structure of the production system in intelligent factories of the future. The next generation collaborative robot approach, developed with the fourth industrial revolution, aims to provide flexibility, functionality and efficiency in production. Collaborative robots, together with industry 4.0, have become one of today's hot topics. Even ABI reported that collaborative robots are the fastest growing segment of industrial robots and that by 2020, they will reach 1 billion dollar (Bay, 2015). Differences between the classic industrial robots and the collaborative robots are shown in Table 4.1.(Escalé, 2015)

Table 3.1: Differences between classical industrial robots and collaborative robots (Escalé, 2015)

| Classical Industrial Robots | Collaborative Robots |
|---|---|
| Blind and not aware what’s around | Be aware of what's around and they can understand people |
| Dangerous | Safe |
| Task must be restructured for that solution | Task done just as a human does it |
| Needs components and integration | Fully integrated and self-contained |
| Needs experts to programming | Any people can train |
| Expensive | Less expensive |

### 3.1.1 Collaborative Robot Alternatives

In the study, robots produced by the 5 firms that stand out in the fields of collaborative robots have been evaluated.

- **KUKA – LBR iiwa (A1):** KUKA robotics, a pioneer in the field of robotics, was founded in 1898 in Germany Johann Josef Keller and Jakob Knappich. In 1973, they became the pioneers in robotics history by introducing the world's first industrial robot FAMULUS. Since then, the company has continued to be a pioneer in the robotics industry. In 2013, KUKA announces a new generation of robots. They introduce the KUKA LBR iiwa, world's first industrial robot (collaborative robot) with integrated sensors in each axis.

- **Rethink Robotics – Baxter (A2):** Rethink robotics is co-founded by Rodney Brooks and Ann Whittaker in Boston, USA in 2008. In 2012 they presented their well-known collaborative robots the Baxter. After Baxter, in 2015 they developed the Sawyer which is a smaller and more flexible than Baxter to perform smaller and more detailed tasks. Rethink robotic is considered to be one of the leading companies in the field of collaborative robots.

- **Universal Robotics – UR5 (A3):** Universal robots were founded in 2005 in Denmark to make robot technology accessible for everyone. The Universal robot company has three main collaborative robots. These are UR3, UR5 and UR10.

- **Staubli – TX2-60L (A4):** Staubli is a mechatronics company and stands out in the textile machinery, connectors and robotics products. Even though the Staubli was founded in 1892 in Switzerland. They produces SCARA, 6 axis robots for industrial automation. In 2015, Staubli presented the new collaborative robot family named TX2.

- **F&P Personal Robotics – Prob-2R (A5):** F & P robotics formerly known as Neuronics Früh & Partner, has been developing and producing robots since 1996.

The firm was founded by Dr. Hansruedi Früh in Switzerland. The company presented a new robot family named P-Rob in 2014.

- The P-Rob 1R robot has been shown at the conference in Hong Kong. Later on many improvements were made on the P-Rob 1R, and in 2015 a new generation P-Rob 2R robot was presented.

### 3.1.2 Evaluation Criteria

Based on expert opinions, previous studies and surveys, four main criteria and their sub-criteria are identified. The main and sub criteria are shown in Table 3.3.

**Technical Criteria**

- **Payload:** Payload is the weight that the robot needs to be handled. (Khandekar & Chakraborty, 2015)
- **Degrees of Freedom:** The amount of values in a system possible of variation. A robotic joint is equal to one degree of freedom. (Rao et al., 2011)
- **Reach:** The distance that the robots' can reach (Khandekar & Chakraborty, 2015)
- **Speed:** How fast the robot can position the end of its arm (Khandekar & Chakraborty, 2015)
- **Repeatability:** How well the robot will return to a programmed position. ( Sen et al., 2016)

**Economic Criteria**

- **Purchase Cost:** The price that first time the investor pays for the purchase(Karande et al., 2016)
- **Maintenance Cost:** The costs associated with keeping machine in good condition by regularly checking it and repairing when it necessary.(İç, 2012)
- **Operation Cost:** The expenses which are related to the operation of a devices.
- **Energy Consumption:** The amount of energy or power used by robot

**Technological Criteria:**

- **Ease of Programming:** Ease of programming indicates whether the robot programming is simple or complex. Can robot can be programmed easily or they need an expert for robot programming to use collaborative robot.
- **User Interface:** Or man – machine interface is a software application that gives information to user about the process or control instructions.
- **Sensors:** A device that responds to physical stimuli (Cobots Guide, 2016)

**Functionality:**

- **Multi Task:** Different application areas where the robot can be used like material handling, machine tending, assembly, pick n place operation etc.
- **Base Location:** Where will the robot be mounted? This criterion represents the surface alternatives on which the robots will be mounted. Robots can be mounted on different surfaces such as floor, ceiling wall. (Cobots Guide, 2016)
- **IP Class**: IP stands for Ingress Protection or International Protection and this figure will give you a general idea of the level of protection your robot meets according to this standard. IP standards consist of two digits. First digit represents the level of protection against solid objects and second digit represents the level of protection against water ingress. (Khandekar & Chakraborty, 2015)
- **Safety:** Safety criterion is taken as the evaluation criterion for decision-making process because collaborative robots should be work safely and collaboratively with humans in in a working environment. (Sen et al., 2016)
- **Warranty & Support:** Indicates the warranty and support provided by the supplier

### 3.2 Computational Steps of Multiple Preference Relations with VIKOR

Figure 3.1 and Figure 3.2 show the steps of the proposed methodology. Before the explanation of steps, some notations are given to understand the proposed methodology.

Decision makers are categorized into $K$ groups and each group member is denoted as $\{p^{kl} : k = 1, \ldots, K; l = 1, \ldots, L_k\}$ where $L_k$ is the size of the group $k$. Step by step description of the proposed approach is as follows:

**Step 1 - Identifying criteria and alternatives:** The aim of this step is to define the criteria which affect the decision making process and the alternatives with the help of surveys, literature reviews, or expert views.

**Step 2 – Unifying DMs evaluations:** In this step, each individual evaluation is gathered from the experts to define the group opinion. The purpose of this step is to make DMs evaluations uniform. Decision makers' preferences may differ from each other, so that decision makers can give preferences in different formats as follows.( Büyüközkan & Çifçi, 2015a; Büyüközkan & Güleryüz, 2015c) :

• DMs can give their importance value as an *ordered vector* ($o(1), \ldots, o(N)$). In this vector $o(i)$ represent the importance ranking of criteria $i$. If the most important criterion is i than o(i) = 1, if it is the least important one then o(i) = N . This order vector can be converted into a relative importance relation as it follows,

$$p_{ij} = 9^{u_i - u_j} \text{ for all } 1 \leq i \neq j \leq N \qquad \text{where } u_i = (N - o(i))/(N - 1). \tag{3.1}$$

• DMs can give an *importance degree vector* ($u_1, \ldots, u_N$) where $u_i \in [0,1]$ $i = 1, \ldots, N$. If the importance degree $u_i$ is close to 1 that means the criterion i is more important than other criteria. This importance degree vector can be converted into relative importance as it follows,

$$p_{ij} = u_i/u_j \qquad \text{for all } 1 \leq i \neq j \leq N. \tag{3.2}$$

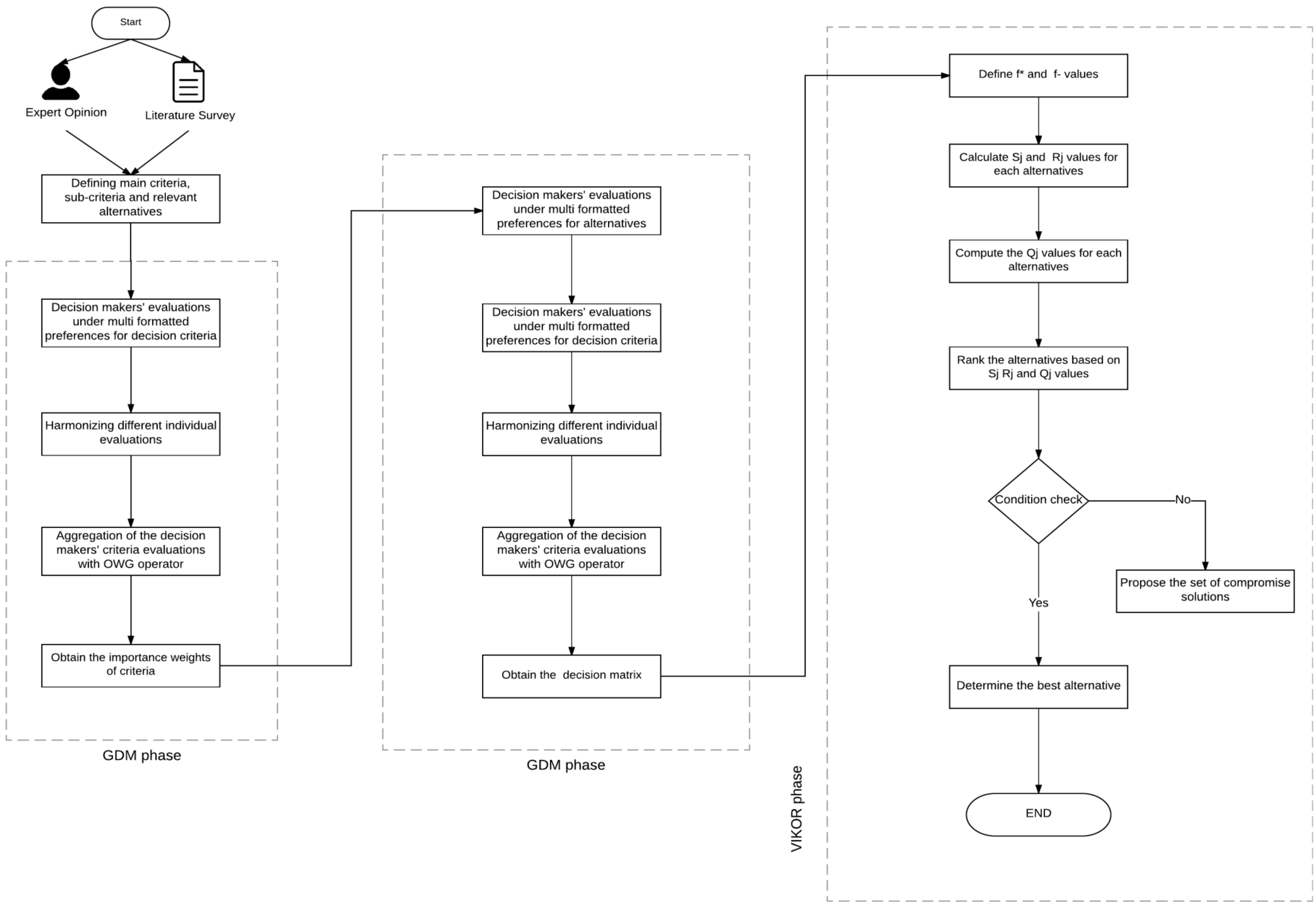


Figure 3.1 Computational steps of integrated fuzzy VIKOR with multi preferences

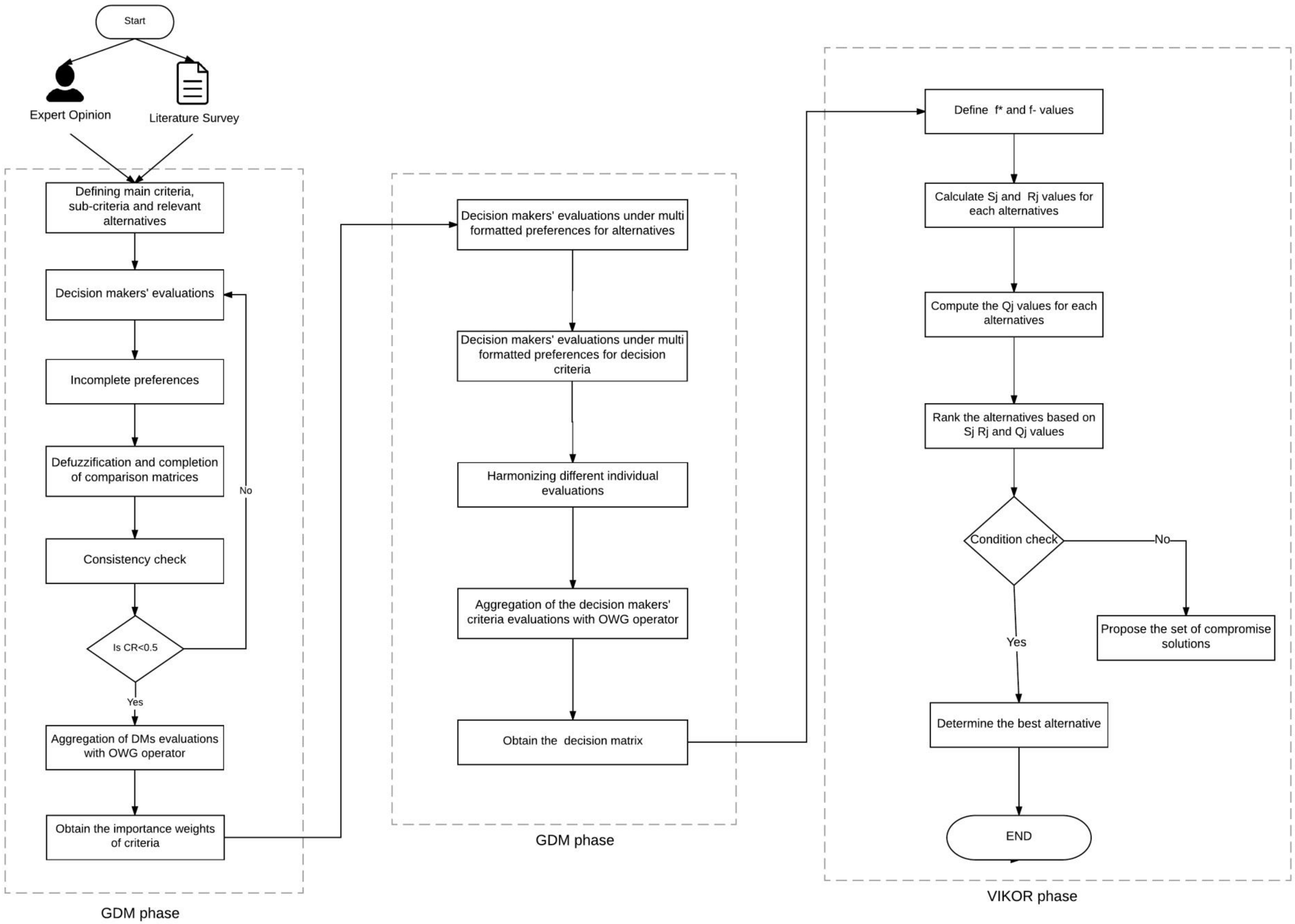


Figure 3.2 Computational steps of integrated VIKOR with incomplete preference

•DMs can give a *linguistic importance vector* $(s_1, \ldots, s_N)$ where $s_i$, i = 1, …, N can be one of "Not Important (NI), Some Important (SI), Moderately Important (MI), Important (I) and Very Important (VI)." Given that a fuzzy triangular number can be noted as $(a_i, b_i, c_i)$ where $b_i$ is the most encountered value. The membership functions of linguistic terms used in this study are as follows NI = (0.00, 0.00, 0.25), SI = (0.00, 0.25, 0.50), MI = (0.25, 0.50, 0.75), I = (0.50, 0.75, 1.00) and VI = (0.75, 1.00, 1.00). Linguistic term vector can be converted into a relative importance relation as it follows,

$$p_{ij} = 9^{b_i - b_j} \quad \text{for all } 1 \leq i \neq j \leq N. \tag{3.3}$$

• DMs can give a *pair-wise comparison matrix*, where each term represent the relative importance of one criterion against others. Pairwise matrices can be obtained using the ratio scale presented by Saaty. The matrix is multiplicatively reciprocal $x_{ij}$ = a and $x_{ji}$= 1/a for all a ∈ {1, …, 9}(Büyüközkan & Çifçi, 2015a).

• DMs can state the importance of criteria without degree explicitly. In this case, if the criteria i is more important than the criteria j $x_{ij}$ = 9 and $x_{ji}$ = 1/9, if anything is not mentioned than $x_{ij}$ = 1.

•DMs can give an *incomplete pair-wise comparison matrix*, where some terms can be missing. First, the decision makers use the comparison scales in Table 3.1 to construct the fuzzy binary-wise comparison matrix. Table 3.1 represents the relative strength of each criterion as in following matrix. (Büyüközkan & Güleryüz, 2015c).

$$\tilde{P} = \begin{bmatrix} \tilde{p}_{11} & \tilde{p}_{12} & \cdots & \tilde{p}_{1n} \\ \tilde{p}_{21} & \tilde{p}_{22} & \cdots & \tilde{p}_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ . & . & \cdots & . \\ \tilde{p}_{n1} & \tilde{p}_{n2} & \cdots & \tilde{p}_{nn} \end{bmatrix}$$

Here, $\tilde{p}_{ij} = (p^l_{ij}, p^m_{ij}, p^u_{ij})$ represent the importance of the criterion i over the criterion j.

Table 3.2 : Corresponding linguistic terms for evaluation

| **Linguistic terms with abbreviations** | **Fuzzy Scales** |
|---|---|
| No influence (No) | (0, 0, 0.1) |
| Very low influence (VL) | (0, 0.1, 0.3) |
| Low influence (L) | (0.1, 0.3, 0.5) |
| Medium influence (M) | (0.3 , 0.5, 0.7) |
| High influence (H) | (0.5, 0.7, 0.9) |
| Very high influence (VH) | (0.7, 0.9, 1) |
| Extreme influence (E) | (0.9, 1, 1) |

➢ *Completion of the missing values*

In this step, each interdependent component in the fuzzy pair comparison matrix is defuzzified using Eq. (3.4) (Büyüközkan & Güleryüz, 2015).

$$F(\tilde{p}_{ij}) = \frac{1}{2}\int_0^1 (\inf_{x\in\Re} \tilde{p}_{ij}^{a} + sup_{x\in\Re} \tilde{p}_{ij}^{a})\, da \qquad (3.4)$$

Then, the missing values can be computed. At this step, the approach which is developed by Herrera, is used for the computation of missing values in an expert's incomplete preference relation is done using only the preference values provided by that particular expert. By doing this, it is assured that the reconstruction of the incomplete fuzzy preference relation is compatible with the rest of the information provided by that expert. (Chiclana et al., 2009)

The main purpose of this approach is to maintain or maximize the expert's global consistency, which is modeled and measured via Tanino's "additive transitivity" property. (Chiclana et al., 2009)

$$p_{ij} = p_{iy} + p_{yj} - 0.5, \forall i,j,y \in \{1, 2, \dots, n\} \qquad (3.5)$$

Eq. (3.29) can be used to calculate an estimated value of a preference degree using other preference degrees in a fuzzy preference relation. Indeed, the preference value $p_{ij}$ ($i \neq j$) can be computed in three different ways.

• From $p_{ij} = p_{iy} + p_{yj} - 0.5$, we obtain the estimate

$$cp_{ij}^{y1} = p_{iy} + p_{yj} - 0.5 \tag{3.6}$$

• From $p_{yj} = p_{yi} + p_{ij} - 0.5$, we obtain the estimate

$$cp_{ij}^{y2} = p_{yj} - p_{yi} + 0.5 \tag{3.7}$$

• From $p_{iy} = p_{ij} + p_{jy} - 0.5$, we obtain the estimate

$$cp_{ij}^{y3} = p_{iy} - p_{jy} + 0.5 \tag{3.8}$$

The preference value of one criterion over itself is always assumed to be equal to 0.5.

➢ *Checking the consistency level*

Because of the complexity of most decision-making problems, experts' preferences may not satisfy formal properties that fuzzy preference relations are required to verify. (Herrera-Viedma et al., 2007) The following equations are used to calculate the consistency level.

$$H_{ij}^{1} = \{y \neq i, j \mid (i, y), (y, j) \in \mathrm{EV}\} \tag{3.9}$$

$$H_{ij}^{2} = \{y \neq i, j \mid (y, i), (y, j) \in \mathrm{EV}\} \tag{3.10}$$

$$H_{ij}^{3} = \{y \neq i, j \mid (i, y), (j, y) \in \mathrm{EV}\} \tag{3.11}$$

In these sets, EV represent the set of pairs of alternatives for which the expert provides preference values, and $H_{ij}^1$ are the sets of intermediate alternative $a_y$ ($y \neq i, j$) that can be used to estimate the preference value $P_{ij}$($i \neq j$) using (25)-(27), respectively. (Herrera-Viedma et al., 2007) The consistency level $CL_{ij}$, associated with a preference value $p_{ij}$ ($i \neq j$) ϵ EV,

$$CL_{ij} = (1 - a_{ij}).(1 - \mathcal{E}p_{ij}) + a_{ij}.\frac{CP_i + CP_j}{2} \quad \text{where } a_{ij} \in [0,1] \tag{3.12}$$

is defined as a linear combination of the average of the completeness values associated with the two alternatives involved in that preference degree $CP_i$ and $CP_j$,

$$CP_i = \frac{card\ (EV)}{2(n-1)} \tag{3.13}$$

Card (EV) represents the number of preference values that known. Its associated error $\varepsilon p_{ij}$, can be calculated as in Eq. (3.14).

$$\varepsilon p_{ij} = \frac{2}{3}.\frac{\mathcal{E}p^1{}_{ij} + \mathcal{E}p^2{}_{ij} + \mathcal{E}p^3{}_{ij}}{K} \tag{3.14}$$

where,

$$\varepsilon P_{ij}^1 = \begin{cases} \dfrac{\sum_{j \in H_{ij}^l} \left| cp_{ij}^{kl} - p_{ij} \right|}{card\left(H_{ij}^l\right)}, if\left(card\left(H_{ij}^l\right) \neq 0\right); l \epsilon \{1,2,3\} \\ 0 \quad , otherwise \end{cases} \tag{3.15}$$

and

$$K = \begin{cases} 3, if\ \left(card\ \left(H_{ij}^1\right) \neq 0\right) \wedge \left(card\ \left(H_{ij}^2\right) \neq 0\right) \wedge \left(card\ \left(H_{ij}^2\right) \neq 0\right) \\ 2, f\ \left(card\ \left(H_{ij}^a\right) \neq 0\right) \wedge \left(card\ \left(H_{ij}^b\right) \neq 0\right) \wedge \left(card\ \left(H_{ij}^c\right) \neq 0\right) \\ \qquad a, b, c\ \epsilon\ \{1,2,3\} \\ 1, \quad otherwise \end{cases} \tag{3.16}$$

$\alpha_{ij}$ is a parameter to control the influence of completeness in the evaluation of the consistency levels.

$$a_{ij} = 1 - \frac{card(EV_i)+card(EV_j)-card(EV_i \cap EV_j)}{4(n-1)-2} \quad (3.17)$$

When the $CL_{ij}$ is higher than 0.5 than it can be say that $p_{ij}$ is consistent. In case $p_{ij}$ is inconsistent, 2 cases arise according to $\varepsilon p_{ij}$ value. If $\varepsilon p_{ij} = 0$ then preferences should be increased otherwise DMs' should revise their evaluations.

**Step 3 – Aggregation of the evaluations**

During this step, the evaluations given by decision makers in terms of criteria and alternatives are aggregated using the OWG operator to determine the group opinion. (Büyüközkan & Görener, 2015b). The ordered weighted (OWG) operator is described as :

$$\Phi^G\left\{\left(p_{ij}^{k1}, p_{ij}^{k2}, \dots, p_{ij}^{kL_k}\right)\right\} = \prod_{l=1}^{L_k} \left(p_{ij}^{-kl}\right)^{w_l} \quad (3.18)$$

where, $W = (w_l, \dots, w_{L_k})$ is an exponential weighting vector, such that $w_l \in [0,1]$ and $\sum_l w_l = 1$, and each $p_{ij}^{-kl}$ is the $l$th largest valued element in the set $p_{ij}^{k1}, p_{ij}^{k2}, \dots, p_{ij}^{kL_k}$ . (Chiclana et al. 2001)

OWG operator is introduced by Chiclana et al. (2001) used with fuzzy majority in DM processes with ratio-scale assessments. The OWG operator reflects the fuzzy majority if we calculate its weighting vector *W by* means of a fuzzy linguistic quantifier (Buyukozkan & Cifci, 2012). Traditionally, the majority is defined as a threshold number of the individuals. In this study, fuzzy majority which is a soft majority concept is expressed by a fuzzy linguistic quantifier. Proportional quantifiers, such as "*most"* is represented as subsets of interval [0,1]. Then for any $r \in [0,1]$, $Q(r)$ indicates the degree to which the proportion $r$ is compatible with the meaning of the quantifier it represents. For a non-decreasing relative quantifier, $Q$, the weights are obtained as:

$$W_l = Q(k/K) - (Q(k-1)/K) \text{ , } k = 1,\ldots,K \tag{3.19}$$

Where $Q(t)$ is defined as:

$$Q(y) = \begin{cases} 0, & if \quad t < s \\ \frac{t-s}{v-s}, & if \quad s \le t \le v \\ 1, & if \quad t \ge v \end{cases} \tag{3.20}$$

Note that s, t, v ∊ [0,1] and Q(t) indicates the degree to which the proportion t is compatible with the meaning of the quantifier it represents. Examples of the relative quantifiers in the literature are as follows; “most” (0.3, 0.8), “at least half” (0,0.5) and “as many as possible” (0.5,1).

When the fuzzy quantifier Q is used for calculating the weights of the OWG operator $\Phi_W^G$, it is represented by $\Phi_Q^G$. Therefore, the collective multiplicative relative importance relation is obtained as follows (Chiclana et al., 2001):

$$p_{ij}^k = \Phi_Q^G\left(p_{ij}^{k1}, p_{ij}^{k2}, \ldots, p_{ij}^{kL_k}\right) \qquad 1 \le i \ne j \le N. \tag{3.21}$$

**Step 4 - Determining the importance of criteria**

The group opinion obtained from the $P^k$ matrix with Eq. (3.22) used to determine the importance weights of the criteria. The element ij represent the relative importance of criterion i compared to criterion j. Then, calculate the quantifier guided importance degree (*QGID*) of each criterion, which quantifies the importance of one criterion compared to others in a fuzzy majority sense. With using the OWG operator again, $\Phi_0^G$, defined as follows: (Chiclana et al., 2004)

$QGID_i^k = 1/2\left(1 + \log_9 \phi_Q^G\ (p_{ij}^k : j = 1, \ldots, N)\right)$ for all i= 1,…,N. (3.22)

As a final step, the $QGID_i$ values should be normalized as in Eq. (3.23), to obtain the importance degrees in percentage for the group *k*.

$QGID_i^k = QGID_i^k / \sum_i QGID_i^k$ (3.23)

These calculations should be made for all points in the evaluation model. The importance degree of each sub-criterion is calculated by multiplying its importance value with the importance values of main criterion.

**Step 5 – Unifying DMs evaluations for alternatives**

In this step, each individual evaluation is gathered from experts. The purpose of this step is to make DMs evaluations uniform. The DMs can give their importance value according to the following formats:

• Preference ordering of the alternatives: Each expert can express their preferences regarding the alternatives as a preference ordering.

In this case the alternatives are ordered from best to worst, without any other additional information. This order vector can be converted into a relative preference relation as it follows,

$p_{ij} = 9^{u_i - u_j}$ for all $1 \leq i \neq j \leq N$ where $u_i = (N - o(i))/(N - 1)$. (3.24)

•Utility values and preference relations: DMs can give their preferences as a set of utility values ($u_1, \ldots, u_N$) where $u_i \in [0,1]$ $i = 1, \ldots, N$. $u_i$ represents the utility evaluation given by the DMs to the alternatives by considering each criteria. Thus, the higher the evaluation, the better the alternative satisfies the DM. The higher the evaluation, the more satisfying the alternative (Herrera et al., 2001).

$$p_{ij} = u_i/u_j \quad \text{for all } 1 \leq i \neq j \leq N. \tag{3.25}$$

•DMs can give their evaluations as linguistically ($s_1, \ldots, s_N$) where $s_i$, i = 1, …, N can be one of "Very Poor (VP), Poor (P), Fair (F), Good (G) and Very Good (VG)". Membership functions for these linguistic terms can be VP = (0, 0, 0,25), P = (1, 3, 5), F = (3, 5, 7), G = (5, 7, 9) and VG = (7, 9, 10). Then, the linguistic term vector can be converted into a relative preference relation as it follows,

$$p_{ij} = 9^{bi^{-}bj} \quad \text{for all } 1 \leq i \neq j \leq N. \tag{3.26}$$

• DMs can give a *pair-wise comparison matrix*, where each term is characterized as the relative preference of one alternative against others. Pair-wise comparison matrices can be obtained with the help of a ratio scale which is proposed by Saaty originally. The matrix is multiplicatively reciprocal $x_{ij}$ = a and $x_{ji}$= 1/a for all a ∈ {1, …, 9}(Büyüközkan & Çifçi, 2015a).

• DMs can prefer to choose only a subset of criteria (R') that is important for them. In this case the preference relation described as it follows,

$$x_{ij} = \begin{cases} 9, i \in R', j \in R/R' \\ \frac{1}{9}, i \in R/R', j \in R' \\ 1, otherwise \end{cases} \tag{3.27}$$

**Step 6 - Aggregation of the evaluations:** After the decision makers' evaluations have been uniformed, the next step is to aggregate this uniformed preferences. The calculations in this step are the same as those previously described in step 4.

**Step 7 - Obtaining the decision matrix:** The group opinion obtained from the $P^k$ matrix with Eq. (3.28) is used for creating decision matrix. Next, calculate the *QGID* of each alternative, which quantifies the importance of one alternative compared to others in a fuzzy majority sense.

The weight values of the alternatives which were obtained as the results of the calculations made for each criterion are used to form the decision matrix that is needed for the VIKOR method. With using the OWG operator again, $\Phi_0^G$, defined as follows: (Chiclana et al., 2004)

$$QGID_i^k = 1/2\left(1 + \log_9 \phi_Q^G\,(p_{ij}^k : j = 1, \dots, N)\right) \text{ for all i= 1,…,N.} \qquad (3.28)$$

As a final step, the $QGID_i$ values in the decision matrix should be normalized using Eq.(3.29)

$$QGID_i^k = QGID_i^k \,/\, \textstyle\sum_i QGID_i^k \qquad (3.29)$$

**Step 8 – Calculation of the $f_i^*$ and $f_i^-$ values**

Determine the best rating $f_i^*$ and worst rating $f_i^-$ values for all criterion from decision matrix as seen in Eq. (3.30 – 3.31).

$$f_i^* = \max_j f_{ij}\,, f_i^- = \min_j f_{ij}, \qquad (3.30)$$

where, $\mathrm{i} = 1, 2, 3, \dots, \mathrm{n};\ \ \mathrm{i} - \mathrm{th\ criterion\ represents\ a\ benefit}$

$$f_i^* = \min_j f_{ij},\ f_i^- = \max_j f_{ij}, \qquad (3.31)$$

where, $\mathrm{i} = 1, 2, 3, \dots, \mathrm{n};\ \mathrm{i} - \mathrm{th\ criterion\ represents\ a\ cost}$

**Step 9 – Calculation of the $S_j$ and $R_j$ values**

Calculate the mean of group utility $S_j$ and maximal regret $R_j$, using Eq.(3.32) and Eq. (3.33) respectively j= 1, 2, ….J

$$S_j = \sum_{i=1}^{n} \frac{w_i(f_i^* - f_{ij})}{(f_i^* - f_i^-)} \tag{3.32}$$

$$R_j = \max_j \left[ \frac{w_i(f_i^* - f_{ij})}{(f_i^* - f_i^-)} \right] \tag{3.33}$$

$w_i$ are the weights of criteria and represent the relative importance of them.

**Step 10 – Calculation of the Q values**

Compute the values $Q_j$ by using Eq.(3.34) j=1, 2, …., J, by the relation

$$Q_j = \frac{v(S_j - S^*)}{(S^- - S^*)} + \frac{(1-v)(R_j - R^*)}{(R^- - R^*)} \tag{3.34}$$

where $S^* = \min_j S_j$, $S^- = \max_j S_j$, $R^* = \min_j R_j$, $R^- = \max_j R_j$ (3.35)

In Eq. (3.34), *v* represents the weight of the strategy of maximum group utility and (1-v) represents the weight of the individual regret.

**Step 11– Rank the alternatives**

Rank the alternatives increasingly according to $S_j$, $R_j$, and $Q_j$ values. The results are three ranking lists.

**Step 12 – Condition Check**

Propose a compromise solution the alternative ($A^1$) which is ranked the best by the measure Q (minimum) if the following two conditions are satisfied:

***Condition1 (C1)*** : “Acceptable advantage”

$$Q(A^2) - Q(A^1) \geq DQ \tag{3.36}$$

where $A^2$ is the second alternative in the ranking list by Q.

$DQ = \frac{1}{J-1}$ and j is the number of alternatives. If J<4 than the DQ value is take as 0,25.

***Condition2 (C2)***: “Acceptable stability in decision - making”

In this condition, it is checked whether Alternative$^{(1)}$ is listed first in both S and R lists.

When one of these conditions is not satisfied then a set of compromise solution is selected. These compromise solutions are consisting of:

1) If only second condition (C2) is not satisfied then alternatives $A^1$ and $A^2$ are determined as the best compromise solution.

2) If first condition (C1) is not satisfied, then $A^M$ is determined by using Eq. (3.37) for maximum M (the positions of these alternatives are “in closeness”)

$$Q(A^M) - Q(A^1) < \frac{1}{J-1} \tag{3.37}$$

## 4. CASE STUDY

In this section, a case study is conducted to show the applicability of the proposed methodology. The proposed methodology was applied to collaborative robot selection problem for machine tending process of ABC company.

### 4.1 Application of the Proposed Methodology

***Step 1. Determination of alternatives and evaluation criteria***

As mentioned in section 3.1.1 and 3.1.2, 5 collaborative robot alternatives (Kuka, Rethink, Universal, Staubli and F&P) and 17 evaluation criteria were used in decision-making process. The 17 evaluation criteria are summarized in Table 4.1.

Table 4.1 : Evaluation criteria

| MAIN CRITERIA | SUB-CRITERIA |
|---|---|
| Technical Criteria (C1) | (C11) Payload |
| | (C12) Degrees of Freedom |
| | (C13) Reach |
| | (C14) Speed |
| | (C15) Repeatability |
| Economic Criteria (C2) | (C21) Purchase Cost |
| | (C22) Maintenance Cost |
| | (C23) Operation Cost |
| | (C24) Energy Consumption |
| Technological Criteria (C3) | (C31) Easy Programming |
| | (C32) User Interface |
| | (C33) Sensors |
| Functionality (C4) | (C41) Multi Task |
| | (C42) Base Location |
| | (C43) IP Class |
| | (C44) Safety |
| | (C45) Warranty & Support |

***Step 2: Unifying the DMs' evaluations:*** The following steps were applied to calculate the importance weight of the sub-criteria under the functional criterion.

Member 1 gives an importance ordering {4, 5, 3, 1, 2}

Member 2 gives an importance degree vector {0.5, 0.6, 0.8, 0.9, 0.9}

Member 3 gives an incomplete evaluation matrix

| | **C41** | **C42** | **C43** | **C44** | **C45** |
|---|---|---|---|---|---|
| **C41** | - | M | X | L | L |
| **C42** | M | - | X | VL | VL |
| **C43** | X | X | - | X | X |
| **C44** | H | VH | H | - | M |
| **C45** | H | VH | H | M | - |

Member 4 gives a pairwise matrix

| | **C1** | **C2** | **C3** | **C4** | **C5** |
|---|---|---|---|---|---|
| **C1** | 1,00 | 3,00 | 0,33 | 0,25 | 0,20 |
| **C2** | 0,33 | 1,00 | 0,25 | 0,13 | 0,17 |
| **C3** | 3,00 | 4,00 | 1,00 | 0,50 | 0,25 |
| **C4** | 4,00 | 8,00 | 2,00 | 1,00 | 0,50 |
| **C5** | 5,00 | 6,00 | 4,00 | 2,00 | 1,00 |

Member 5 says C4 and C5 are important that C1, C2 and C3.

Member 6 evaluates each criterion in linguistic terms {MI, I, I, I, VI}

With the help of conversion functions mentioned in chapter 3.2 importance relation matrices ($p^{11}$, $p^{12}$, $p^{13}$, $p^{14}$, $p^{15}$,$p^{16}$) are computed.

<u>*Member 1:*</u> The ordered importance vector of member1can be converted into a relative importance relation as $p_{13}^{11} = 9^{u^1-u^3} = 9^{0.25-0.5}$ by using Eq.(3.1). Also as seen in Eq.(3.1) the $u^1$ and $u^3$ values are calculated as $u^1$ = (5-4)/(5-1) = 0.25 and $u^3$ = (5-3)/(5-1) = 0.5 .

<u>*Member 2:*</u> The importance degree vector of member2 can be converted into a relative importance relation as $p_{13}^{11} = u^1/u^3 = 0.5/0.7 = 0.71$ by using Eq. (3.2).

*Member 3:* To complete the missing values Eq. (3.6-3.7-3.8) are used. The estimation procedure of $cp_{13}$ as follows:

$H_{23}^{1} = \{1\}\, as\ cp_{23}^{41} = p_{14} + p_{43} - 0.5 = 0.3 + 0.7 - 0.5 = 0.5$

$H_{23}^{2} = \{1\}\, as\ cp_{23}^{42} = p_{43} - p_{41} + 0.5 = 0.7 - 0.7 + 0.5 = 0.5$

$H_{23}^{3} = \{1\}\, as\ cp_{23}^{43} = p_{14} + p_{34} + 0.5 = 0.3 - 0.3 + 0.5 = 0.5$

So $cp_{23} = 0.5$

After missing values are computed, consistency should be checked. The consistency level matrix is constructed as follows.

| | C41 | C42 | C43 | C44 | C45 |
|---|---|---|---|---|---|
| C41 | 0.86 | 0.93 | 0.89 | 0.98 | 0.98 |
| C42 | 0.93 | 0.86 | 0.89 | 0.98 | 0.98 |
| C43 | 0.89 | 0.89 | 0.64 | 0.93 | 0.98 |
| C44 | 0.98 | 0.98 | 0.93 | 1.00 | 1.00 |
| C45 | 0.98 | 0.98 | 0.93 | 1.00 | 1.00 |

For instance for $p_{13}$, the consistency level was computed using Eq. (3.33) to (3.41) as follows,

EV1 = {(1,2), (1,4), (1,5), (2,1), (4,1), (5,1)}

EV2 = {(1,2), (4,2), (5,2), (1,5), (2,1), (2,4), (2,5)}

EV3 = {(3,4), (3,5), (4,3), (4,5)}

EV4= { 1,4), (2,4), (3,4), (5,4), (4,1), (4,2), (4,3) (4,5)}

EV5= {(1,5), (2,5), (3,5), (4,5), (5,1), (5.2), (5,3), (5,4)}

CP1 = 6/8, CP2 = 6/8, CP3= 4/8, CP4= 8/8, CP5=8/8

$\alpha_{13}$ = 1 – [(4+6-0)/(4*(5-1)-2)] = 1 – (10/14) = 0.29

For $p_{34,}$ since there is no estimated value other than 0.7 in the calculations made therefore $\mathcal{E}p_{34} = 0$.

$CL_{34}$ = (1-0.29)*(1-0) + 0.29* ((4/8+6/8)/2) = 0.93

*Member 5:* In this section member 5 says that safety (C44) and warranty & support (C45) criteria are more important than the other criteria so $p_{41}^{15}, p_{42}^{15}, p_{43}^{15},\ p_{51}^{15}, p_{52}^{15}$ *and* $p_{53}^{15}$ equals 9.

*Member 6:* The linguistic importance vector of member6 converted into a relative importance relation as $p_{23}^{16} = 9^{0.25-0.75} = 0.33$ by using Eq. (3.3). As a result of the calculations, the matrices were obtained as follow

P11 =

| | | | | |
|---|---|---|---|---|
| 1.00 | 1.73 | 0.58 | 0.19 | 0.33 |
| 0.58 | 1.00 | 0.33 | 0.11 | 0.19 |
| 1.73 | 3.00 | 1.00 | 0.33 | 0.58 |
| 5.20 | 9.00 | 3.00 | 1.00 | 1.73 |
| 3.00 | 5.20 | 1.73 | 0.58 | 1.00 |

P12 =

| | | | | |
|---|---|---|---|---|
| 1.00 | 1.67 | 0.71 | 0.63 | 0.71 |
| 0.60 | 1.00 | 0.43 | 0.38 | 0.43 |
| 1.40 | 2.33 | 1.00 | 0.88 | 1.00 |
| 1.60 | 2.67 | 1.14 | 1.00 | 1.14 |
| 1.40 | 2.33 | 1.00 | 0.88 | 1.00 |

P13 =

| | | | | |
|---|---|---|---|---|
| 0.5 | 0.5 | 0.5 | 0.3 | 0.3 |
| 0.5 | 0.5 | 0.68 | 0.125 | 0.125 |
| 0.5 | 0.32 | 0.5 | 0.3 | 0.3 |
| 0.7 | 0.875 | 0.7 | 0.5 | 0.5 |
| 0.7 | 0.875 | 0.7 | 0.5 | 0.5 |

P14 =

| | | | | |
|---|---|---|---|---|
| 1.00 | 3.00 | 0.33 | 0.20 | 0.33 |
| 0.33 | 1.00 | 0.20 | 0.14 | 0.20 |
| 3.00 | 5.00 | 1.00 | 0.33 | 1.00 |
| 5.00 | 7.00 | 3.00 | 1.00 | 3.00 |
| 3.00 | 5.00 | 1.00 | 0.33 | 1.00 |

P15 =

| | | | | |
|---|---|---|---|---|
| 1.00 | 1.00 | 1.00 | 0.11 | 0.11 |
| 1.00 | 1.00 | 1.00 | 0.11 | 0.11 |
| 1.00 | 1.00 | 1.00 | 0.11 | 0.11 |
| 9.00 | 9.00 | 9.00 | 1.00 | 1.00 |
| 9.00 | 9.00 | 9.00 | 1.00 | 1.00 |

P16 =

| | | | | |
|---|---|---|---|---|
| 1.00 | 1.73 | 0.58 | 0.33 | 0.58 |
| 0.58 | 1.00 | 0.33 | 0.19 | 0.33 |
| 1.73 | 3.00 | 1.00 | 0.58 | 1.00 |
| 3.00 | 5.20 | 1.73 | 1.00 | 1.73 |
| 1.73 | 3.00 | 1.00 | 0.58 | 1.00 |

***Step3: Aggregation of DMs evaluations***

After the importance relation matrices are conducted, all DM's opinions should be unified by using Eq.5.

In this step OWG operator with the linguistic quantifier "**at least half**" is used to calculate the group importance relation matrix. (Büyüközkan & Cįfçi 2013) As a first step, calculate the weighting vector by using Eq.(3.19) and Eq.(3.20) to obtain the group relation matrix. The weights can be obtained as follows:

$W_1$ = Q(1/6) - Q(0/6) = 0.333 $W_2$ = Q(2/6) - Q(1/6) = 0.333

$W_3$ = Q(3/6) - Q(2/6) = 0.333 $W_4$ = Q(4/6) – Q(3/6) = 0

$W_5$ = Q(5/6) – Q(4/6) = 0 $W_6$ = Q(6/6) – Q(5/6) = 0

As a result of these calculations the weighting vector obtained as (0.333, 0.333, 0.3333, 0, 0, 0). Then by using Eq.(3.21) group importance relation matrix is conducted as follows.

| | C41 | C41 | C43 | C44 | C45 |
|---|---|---|---|---|---|
| C41 | 1.00 | 2.08 | 0.74 | 0.40 | 0.52 |
| C42 | 0.70 | 0.79 | 0.46 | 0.17 | 0.22 |
| C43 | 2.47 | 3.98 | 1.44 | 0.80 | 1.44 |
| C44 | 6.16 | 8.28 | 4.33 | 1.00 | 2.08 |
| C45 | 4.33 | 6.16 | 2.50 | 0.80 | 1.00 |

As an example for calculation,

$$p_{13}^{1} = \prod_{l=1}^{6} \left(p_{13}^{1[l]}\right)^{W_l} = \Phi_{\mathbb{Q}}^{G}(p_{13}^{11},\ p_{13}^{12},\ p_{13}^{13}, p_{13}^{14},\ p_{13}^{15},\ p_{13}^{16})$$

$$= 1^{0.333} \times 0.714^{0.333} \times 0.577^{0.333} \times 0.577^{0} \times 0.5^{0} \times 0.33^{0} = 0.74$$

***Step 4: Obtaining the priorities***

Eq.22 and Eq.23 are used to compute group aggregated importance values with weighting vector (0.4, 0.4, 0.2, 0, 0) corresponding to the fuzzy linguistic quantifier "at least half". The weighting vector is calculated as explained in the previous step.

With these calculations, the associate importance values of the group are computed as (0.55, 0.41, 0.725, 0.92, 0.84). Then the normalized values obtained as (0.160, 0.119, 0.210, 0.268, 0.243). The calculations are as follows.

$$QGID_1^1 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1,2,3,4,5\right)\right)$$

$$= 1/2(1 + \log_9(2.08^{0.4} \times 1^{0.4} \times 0.74^{0.2} \times 0.52^0 \times 0.40^0)) = 0.55$$

$$QGID_1^2 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1,2,3,4,5\right)\right)$$

$$= 1/2(1 + \log_9(0.79^{0.4} \times 0.70^{0.4} \times 0.46^0 \times 0.22^0 \times 0.17^0)) = 0.41$$

$$QGID_1^3 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1,2,3,4,5\right)\right)$$

$$= 1/2(1 + \log_9(3.98^{0.4} \times 2.47^{0.4} \times 1.44^{0.2} \times 1.44^0 \times 0.8^0)) = 0.725$$

$$QGID_1^4 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1,2,3,4,5\right)\right)$$

$$= 1/2(1 + \log_9(8.68^{0.4} \times 5.72^{0.4} \times 3.78^{0.2} \times 1.2^0 \times 1^0)) = 0.92$$

$$QGID_1^5 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1,2,3,4,5\right)\right)$$

$$= 1/2(1 + \log_9(6.16^{0.4} \times 4.33^{0.4} \times 2.50^{0.2} \times 1^0 \times 0.8^0)) = 0.84$$

$$QGID_i = QGID_i / \sum_i QGID_i$$

$QGID_1 = 0.55/3.454 = 0.160$

$QGID_2 = 0.41/3.454 = 0.119$

$QGID_3 = 0.725/3.454 = 0.210$

$QGID_4 = 0.92/3.454 = 0.268$

$QGID_5 = 0.84/3.454 = 0.243$

Each step has been applied for all sub-criteria and main criteria too. At the end of these calculations priorities and global priorities for criteria are calculated as in Table 4.1.

Table 4.2: Priorities of criteria

| Main Criteria | Priority | Sub – Criteria | Priority | Global Priorities |
|---|---|---|---|---|
| Technical Criteria | 0.314 | (C11) Payload | 0.241 | 0.076 |
| | | (C12) Degrees of Freedom | 0.121 | 0.038 |
| | | (C13) Reach | 0.209 | 0.066 |
| | | (C14) Speed | 0.170 | 0.054 |
| | | (C15) Repeatability | 0.258 | 0.081 |
| Economic Criteria | 0.211 | (C21) Purchase Cost | 0.260 | 0.055 |
| | | (C22) Maintenance Cost | 0.273 | 0.058 |
| | | (C23) Operation Cost | 0.247 | 0.052 |
| | | (C24) Energy Consumption | 0.220 | 0.047 |
| Technological Criteria | 0.302 | (C31) Easy Programming | 0.355 | 0.061 |
| | | (C32) User Interface | 0.300 | 0.052 |
| | | (C33) Sensors | 0.344 | 0.060 |
| Functionality | 0.173 | (C41) Multi Task | 0.160 | 0.048 |
| | | (C42) Base Location | 0.119 | 0.036 |
| | | (C43) IP Class | 0.210 | 0.063 |
| | | (C44) Safety | 0.268 | 0.081 |
| | | (C45) Warranty & Support | 0.243 | 0.073 |

***Step 5: Decision Makers' Evaluations for Alternatives***

The following steps have been taken in determining the common group idea for the alternative evaluations for the payload criterion

Member 1 expressed their preference using preference ordering {1, 5, 2, 3, 4}

Member 2 expressed their preference using utility vector {0.8, 0.2, 0.6, 0.6, 0.4}

Member 3 said A1 is the best one.

Member 4 evaluated each alternative in linguistic terms {VG, P, G, G, F}

Member 5 gave a pairwise matrix

| | A1 | A2 | A3 | A4 | A5 |
|---|---|---|---|---|---|
| **A1** | 1.00 | 5.00 | 3.00 | 3.00 | 5.00 |
| **A2** | 0.20 | 1.00 | 0.20 | 0.20 | 0.33 |
| **A3** | 0.33 | 5.00 | 1.00 | 1.00 | 3.00 |
| **A4** | 0.33 | 5.00 | 1.00 | 1.00 | 3.00 |
| **A5** | 0.20 | 3.00 | 0.33 | 0.33 | 1.00 |

With the help of conversion functions mentioned in chapter 3, relation matrices ($p^{11}$, $p^{21}$, $p^{31}$, $p^{41}$, $p^{51}$) are computed.

*Member 1:* The preference ordered vector of member1can be converted into preference relation as $p_{13}^{11} = 9^{u^1-u^3} = 9^{1-0.75}$ by using Eq. (3.24). Also as seen in Eq.(3.24) the $u^1$ and $u^3$ values are calculated as $u^1$ = (5-1)/(5-1) = 1 and $u^3$ = (5-2)/(5-1) = 0.75 .

*Member 2:* The utility vector of member2 can be converted into a preference relation as $p_{13}^{11} = u^1/u^3 = 0.8/0.6 = 1.33$ by using Eq. (3.25).

*Member 3:* In this section member 3 says that A1 is the best alternative so $p_{21}^{31}, p_{22}^{31}, p_{23}^{31}, p_{24}^{31}, p_{25}^{31}$ equals 9.

*Member 4:* The linguistic preferences of member 4 can be converted into preference relation as $p_{23}^{14} = 9^{0.25-0.75} = 0.33$ by using Eq. (3.26). As a result of the calculations, the matrices were obtained as follows:

$P_{11}$ =

| | | | | |
|---|---|---|---|---|
| 1.00 | 9.00 | 1.73 | 3.00 | 5.20 |
| 0.11 | 1.00 | 0.19 | 0.33 | 0.58 |
| 0.58 | 5.20 | 1.00 | 1.73 | 3.00 |
| 0.33 | 3.00 | 0.58 | 1.00 | 1.73 |
| 0.19 | 1.73 | 0.33 | 0.58 | 1.00 |

$P_{12}$ =

| | | | | |
|---|---|---|---|---|
| 1.00 | 4.00 | 1.33 | 1.33 | 2.00 |
| 0.25 | 1.00 | 0.33 | 0.33 | 0.50 |
| 0.75 | 3.00 | 1.00 | 1.00 | 1.50 |
| 0.75 | 3.00 | 1.00 | 1.00 | 1.50 |
| 0.50 | 2.00 | 0.67 | 0.67 | 1.00 |

$P_{13}$ =

| | | | | |
|---|---|---|---|---|
| 1.00 | 9.00 | 9.00 | 9.00 | 9.00 |
| 0.11 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.11 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.11 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.11 | 1.00 | 1.00 | 1.00 | 1.00 |

$P_{14}$ =

| | | | | |
|---|---|---|---|---|
| 1.00 | 5.20 | 1.73 | 1.73 | 3.00 |
| 0.19 | 1.00 | 0.33 | 0.33 | 0.58 |
| 0.58 | 3.00 | 1.00 | 1.00 | 1.73 |
| 0.58 | 3.00 | 1.00 | 1.00 | 1.73 |
| 0.33 | 1.73 | 0.58 | 0.58 | 1.00 |

$P_{15}$ =

| | | | | |
|---|---|---|---|---|
| 1.00 | 5.00 | 3.00 | 3.00 | 5.00 |
| 0.20 | 1.00 | 0.33 | 0.33 | 1.00 |
| 0.33 | 3.00 | 1.00 | 1.00 | 3.00 |
| 0.33 | 3.00 | 1.00 | 1.00 | 3.00 |
| 0.20 | 1.00 | 0.33 | 0.33 | 1.00 |

***Step 6**: Aggregation of DMs evaluations*

After the relation matrices are conducted, all DM's opinions should be unified by using Eq.5. In this step OWG operator with the linguistic quantifier "**at least half**" is used to calculate the group importance relation matrix. (Büyüközkan & Cịfçi 2013) As a first step, the weighting vector calculated by using Eq.(3.19) and Eq.(3.20) to obtain the group relation matrix. The weights can be obtained as follows:

$W_1 = Q(1/5) - Q(0/5) = 0.333$ $W_2 = Q(2/5) - Q(1/5) = 0.333$

$W_3 = Q(3/5) - Q(2/5) = 0.333$ $W_4 = Q(4/5) – Q(3/5) = 0$

$W_5 = Q(5/5) – Q(4/5) = 0$

As a result of these calculations the weighting vector obtained as (0.4. 0.4. 0.2. 0. 0). Then by using Eq.(3.21) group importance relation matrix is conducted as follows.

| | C41 | C41 | C43 | C44 | C45 |
|---|---|---|---|---|---|
| C41 | 1.00 | 8.06 | 4.17 | 4.66 | 6.42 |
| C42 | 0.22 | 1.00 | 0.52 | 0.52 | 0.90 |
| C43 | 0.64 | 3.74 | 1.00 | 1.25 | 2.69 |
| C44 | 0.57 | 3.00 | 1.00 | 1.00 | 2.16 |
| C45 | 0.35 | 1.833 | 0.76 | 0.76 | 1.00 |

As an example for calculation,

$$p_{13}^{1} = \prod_{l=1}^{5} \left(p_{13}^{1[l]}\right)^{W_l} = \Phi_{\mathbb{Q}}^{G}(p_{13}^{11}.\ p_{13}^{12}.\ p_{13}^{13}.p_{13}^{14}.\ p_{13}^{15})$$

$$= 9^{0.4} \times 9^{0.4} \times 5.19^{0.2} \times 5^{0} \times 4^{0} = 8.06$$

***Step 7: Obtaining the priorities***

Eq.28 and Eq.29 are used to compute group aggregated importance values with weighting vector (0.4, 0.4, 0.2, 0, 0) corresponding to the fuzzy linguistic quantifier “at least half”. The weighting vector is calculated as explained in the previous step. With these calculations, the associate importance values of the group are computed as (0.93, 0.46, 0.72, 0.67, 0.543). Then the normalized values obtained as (0.280, 0.138, 0.217, 0.202, 0.163). The calculations are as follows,

$$QGID_1^1 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1.2.3.4.5\right)\right)$$

$$= 1/2(1 + \log_9(8.06^{0.4} \times 6.42^{0.4} \times 4.66^{0.2} \times 4.17^{0} \times 1^{0})) = 0.93$$

$$QGID_1^2 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1.2.3.4.5\right)\right)$$

$$= 1/2(1 + \log_9(1^{0.4} \times 0.90^{0.4} \times 0.52^{0,2} \times 0.52^{0} \times 0.22^{0})) = 0.44$$

$$QGID_1^3 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1.2.3.4.5\right)\right)$$

$$= 1/2(1 + \log_9(3.74^{0.4} \times 2.69^{0.4} \times 1.25^{0.2} \times 1^{0} \times 0.64^{0})) = 0.74$$

$QGID_1^4 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1.2.3.4.5\right)\right)$

$= 1/2(1 + \log_9(3.00^{0.4} \times 2.16^{0.4} \times 1^{0.2} \times 1^0 \times 0.57^0)) = 0.69$

$QGID_1^5 = 1/2\left(1 + \log_9 \emptyset_Q^G\left(p_{1j}^5 : j = 1.2.3.4.5\right)\right)$

$= 1/2(1 + \log_9(1.83^{0.4} \times 1^{0.4} \times 0.76^{0.2} \times 0.76^0 \times 0.35^0)) = 0.56$

$QGID_i = QGID_i / \sum_i QGID_i$

$QGID_1 = 0.93/3.322 = 0.280$

$QGID_2 = 0.44/3.322 = 0.138$

$QGID_3 = 0.74/3.322 = 0.217$

$QGID_4 = 0.69/3.322 = 0.202$

$QGID_5 = 0.56/3.322 = 0.163$

Each step has been applied for all sub-criteria. At the end of these calculations priorities for alternatives are calculated as in Table 4.3. These steps are applied to all criteria to construct the decision matrix. After all calculations, the decision matrix was constructed as seen in Table 4.3.

***Step 8**: Determining the $f^*$ and the $f^-$ values*

In VIKOR's first step is determine the best ($f^*$) and the worst ($f^-$) values. In this step it is important to define the criteria function properly. The best and the worst values for the study are shown in Table 4.4.

Table 4.3: Decision matrix

| | A1 | A2 | A3 | A4 | A5 |
|---|---|---|---|---|---|
| (C11) Payload | 0.280 | 0.138 | 0.217 | 0.202 | 0.163 |
| (C12) Degrees of Freedom | 0.262 | 0.262 | 0.159 | 0.159 | 0.159 |
| (C13) Reach | 0.197 | 0.271 | 0.180 | 0.211 | 0.141 |
| (C14) Speed | 0.179 | 0.161 | 0.227 | 0.279 | 0.155 |
| (C15) Repeatability | 0.178 | 0.149 | 0.215 | 0.279 | 0.178 |
| (C21) Purchase Cost | 0.120 | 0.253 | 0.175 | 0.222 | 0.230 |
| (C22) Maintenance Cost | 0.203 | 0.203 | 0.198 | 0.198 | 0.198 |
| (C23) Operation Cost | 0.244 | 0.172 | 0.172 | 0.241 | 0.172 |
| (C24) Energy Consumption | 0.144 | 0.189 | 0.268 | 0.172 | 0.227 |
| (C31) Easy Programming | 0.259 | 0.167 | 0.258 | 0.184 | 0.132 |
| (C32) User Interface | 0.204 | 0.142 | 0.189 | 0.177 | 0.288 |
| (C33) Sensors | 0.218 | 0.185 | 0.177 | 0.260 | 0.160 |
| (C41) Multi Task | 0.264 | 0.198 | 0.193 | 0.208 | 0.138 |
| (C42) Base Location | 0.259 | 0.275 | 0.165 | 0.157 | 0.144 |
| (C43) IP Class | 0.262 | 0.270 | 0.186 | 0.138 | 0.145 |
| (C44) Safety | 0.267 | 0.254 | 0.171 | 0.147 | 0.161 |
| (C45) Warranty & Support | 0.202 | 0.284 | 0.152 | 0.158 | 0.204 |

Table 4.4: Best and worst values

| | Best Value ($f_i$*) | Worst Value($f_i^-$) |
|---|---|---|
| (C11) Payload | 0.280 | 0.138 |
| (C12) Degrees of Freedom | 0.262 | 0.159 |
| (C13) Reach | 0.271 | 0.141 |
| (C14) Speed | 0.279 | 0.155 |
| (C15) Repeatability | 0.279 | 0.149 |
| (C21) Purchase Cost | 0.253 | 0.120 |
| (C22) Maintenance Cost | 0.203 | 0.198 |
| (C23) Operation Cost | 0.244 | 0.172 |
| (C24) Energy Consumption | 0.268 | 0.144 |
| (C31) Easy Programming | 0.259 | 0.132 |
| (C32) User Interface | 0.288 | 0.142 |
| (C33) Sensors | 0.260 | 0.160 |
| (C41) Multi Task | 0.264 | 0.138 |
| (C42) Base Location | 0.275 | 0.144 |
| (C43) IP Class | 0.270 | 0.138 |
| (C44) Safety | 0.267 | 0.147 |
| (C45) Warranty & Support | 0.284 | 0.152 |

***Step 9: Calculating the S and R values***

S and R values are calculated using Eq. (3.32) and (3.33) respectively. S and R values for each alternative are shown in Table 4.5. As we mentioned before all $w_i$ values in the calculation are obtained from previous section

Table 4.5: S and R values

| | **S** | **R** |
|---|---|---|
| **A1** | 0.342 | 0.063 |
| **A2** | 0.457 | 0.081 |
| **A3** | 0.647 | 0.062 |
| **A4** | 0.545 | 0.066 |
| **A5** | 0.283 | 0.081 |

***Step 10: Calculating the Q values***

In the next step using with Eq. (3.35) $S^*$, $S^-$, $R^*$ and $R^-$ values are calculated. Then using Eq. (3.34) Q values for each alternative are computed. In calculation the weight of the strategy of the maximum group utility (*v*) is assumed to be 0,5. The $S^*$, $S^-$, $R^*$ and $R^-$ values are calculated as 3.340, 2.562, 0.053, 0.368 respectively. Q values for each alternative are shown in Table 4.6.

Table 4.6: Q values

| | Q |
|---|---|
| A1 | 0.023 |
| A2 | 0.620 |
| A3 | 0.317 |
| A4 | 0.326 |
| A5 | 0.994 |

***Step 11**: **Ranking alternatives***

Next step is the rank the alternatives according to S, R and Q values by increasingly. In Table 4.7 the ranking list is seen.

Table 4.7: The ranking list

| | S | R | Q |
|---|---|---|---|
| 1 | A1 | A3 | A1 |
| 2 | A2 | A1 | A3 |
| 3 | A4 | A4 | A4 |
| 4 | A3 | A5 | A2 |
| 5 | A5 | A2 | A5 |

***Step 12: Condition Check***

After ranking the alternatives, the two conditions that explained in VIKOR stage should be checked. According the first condition in other word acceptable advantage condition to satisfy this condition $Q(A^2)$-$Q(A^1) \geq DQ$ should be satisfied. In the study $Q(A^2)$-$Q(A^1)$ equals 0.29 and DQ equals 25.

So according to these values the first condition is satisfied. In second condition, acceptable stability, the first alternative Q list should be the first alternative in S or/and R lists In the study A1 is the first one on the S and Q list so condition 2 is satisfied.

***Step 13: Selection***

When we look at the two conditions that need to be checked in the VIKOR method, it is seen that both two condition is satisfied. In this case A1 is selected as the best alternative.

## 4.2 Obtained Results and Discussion

In the study evaluation criteria and collaborative robot alternatives are evaluated for the machine tending process in company. Using more than one decision maker in the decision making process, multiple preference and incomplete preference techniques ensures more reliable results.

### 4.2.1 Results for Criteria

In this study 17 sub-criteria under 4 main-criteria were evaluated by 6 experts. Table 4.2 present the final results of the priorities and the global priorities of the evaluation criteria. Multiple preferences relations and incomplete preferences relations techniques were used to calculate the importance weight of the evaluation criteria by aggregating DMs' evaluations As it is seen in the table 4.2, it has been determined that the most important evaluation criterion among the main criteria is the technical criterion. As also shown in the Table 4.2, it has been determined that the most important evaluation criterion among sub criteria is payload criterion.

### 4.2.2 Results for Alternatives

In this study 5 collaborative robot alternatives were evaluated by 6 experts. Multiple preferences relations and incomplete preferences relations techniques have been used to construct the decision matrix to be used in VIKOR by aggregating decision makers' evaluations. The decision matrix is constructed as in Table4.3.
After the decision matrix is constructed, the ranking of the alternatives is obtained by the VIKOR method. The ranking of the alternatives according to these results obtained as A1-A3-A4-A2-A5. When we look at the two conditions that need to be checked in the VIKOR method, it is seen that Condition 1 and 2 was satisfied. As a result Alterative 1 (Kuka) is selected as a best alternative.

## 5. CONCLUSION AND PERSPECTIVES

This study presented an integrated VIKOR with multiple preference relations approaches and a case study about collaborative robot selection problem. In GMCDM process, decision makers' can express their preferences in different ways. Even they can provide incomplete evaluations. To aggregate all assessment under different preferences and incomplete evaluations, multiple preference relations and incomplete preference relations technique was used. With these techniques every decision makers' evaluations can be aggregated and incomplete evaluations can be defined. VIKOR is a commonly used method to propose a compromise ranking and compromise solution which is obtained with the importance weight of evaluation criteria. It focuses on ranking and selecting from set of alternatives. In the study 5 collaborative robot alternatives for machine tending process were evaluated under 17 evaluation criteria.

When we examine the literature, there are many studies that work with multiple preferences and VIKOR method. However there is not any study that integrated VIKOR with multi preference and incomplete preference to deal with collaborative robot selection problem. We can summarize the contributions of the study as follows:

- Detailed literature review about all methods and problem are conducted
- VIKOR, multiple preferences and incomplete preferences has been used together to determine the importance weight of evaluation criteria and aggregate the alternative assessments
- For the first time in the literature, collaborative robot selection problem is studied. For the further studies;
- Other ranking methods like TOPSIS, ELECTRE can be used, and the results can be compared.

- The number of experts and groups can be increased.
- The number of criteria to be considered in the study can be increased.
- The number of alternatives can be increased
- The number of alternatives to be used in the study can be increased
- This selection process can be applied to different operation processes such as packaging, assembly, pick-n-place.
- Different aggregation operators can be used. Such as induced ordered weighted averaging (IOWG), ordered weighted averaging (OWA).

This study has limitations as follows;

- Inadequate number of the experts.
- Lack of information about some criteria.

## REFERENCES


Anvari, A., Norzima, Z. and Omid, A. (2014). Application of a modified VIKOR method for decision-making problems in lean tool selection., The International Journal of Advanced Manufacturing Technology 71: 829-841.

Adakane, R. V. and Narkhede, A. R. (2014). Multi Attribute Decision Making : A Tool for Robot Selection., International Journal of Engineering Development and Research 2(1) : 589–596.

Amin, G. R. and Emrouznejad, A. (2012). A new DEA model for technology selection in the presence of ordinal data., The International Journal of Advanced Manufacturing Technology 65(9–12): 1567–1572.

Athawale, V. M. and Chakraborty, S. (2011). A comparative study on the ranking performance of some multi-criteria decision-making methods for industrial robot selection., International Journal of Industrial Engineering Computations 2: 831–850.

Awasthi, A. and Govindan, K. (2016). Green supplier development program selection using NGT and VIKOR under fuzzy environment., Computers & Industrial Engineering 91:100-108.

Aydin, S., and Kahraman, C. (2014). Vehicle selection for public transportation using an integrated multi criteria decision making approach: A case of Ankara., Journal of Intelligent and Fuzzy Systems 26(5): 2467-2481.

Azimi, M. H., Taghizadeh, H., Farahmand, N. F. H. and Pourmahmoud, J. (2014). Selection of industrial robots using the polygons area method., International Journal of Industrial Engineering Computations 5(4) : 631–646.

Babashamsi, P., Golzadfar, A., Yusoff, N. I. M., Ceylan, H. and Nor, N. G. M. (2016). Integrated fuzzy analytic hierarchy process and VIKOR method in the prioritization of pavement maintenance activities., International Journal of Pavement Research and Technology 9(2): 112-120.

Bahadir, M. C. and Satoglu, S. I. (2012). A Decision Support System for Robot Selection based on Axiomatic Design Principles, Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management Istanbul, Turkey, pp. 674–683.

Bairagi, B., Dey, B., Sarkar, B. and Sanyal, S. (2014). Selection of robot for automated foundry operations using fuzzy multi-criteria decision making approaches. International Journal of Management Science and Engineering Management, 9(3): 231-232

Bay, O. (2015). Collaborative Robotics Market Exceeds US$1 Billion by 2020 | ABI Research.

**URL:** https://www.abiresearch.com/press/collaborative-robotics-market-exceeds-us1-billion-/ [accessed April 10, 2017]

Bhattacharya, A., Sarkar, B. and Mukherjee, S. K. (2005). Integrating AHP with QFD for robot selection under requirement perspective. International Journal of Production Research, 43(17): 3671–3685.

Büyüközkan, G. and Çifçi, G. (2012). A new incomplete preference relations based approach to quality function deployment., Information Sciences 206 : 30-41.

Büyüközkan, G. and Çifçi, G. (2013). An integrated QFD framework with multiple formatted and incomplete preferences: A sustainable supply chain application., Applied Soft Computing 13: 3931-3941.

Büyüközkan, G. and Çifçi, G. (2015a). An Extended Quality Function Deployment Incorporating Fuzzy Logic and GDM Under Different Preference Structures., International Journal of Computational Intelligence Systems 8(3): 438-454.

Büyüközkan, G. and Görener, A. (2015b). Evaluation of product development partners using an integrated AHP-VIKOR model. 44(2) : 220-237.

Büyüközkan, G., and Güleryüz, S. (2015c). Extending Fuzzy QFD Methodology with GDM Approaches: An Application for IT Planning in Collaborative Product Development., International Journey of Fuzzy Systems. 544-558.

Celik, E., Nezir A. and Taskin, A. (2014). A multi attribute customer satisfaction evaluation approach for rail transit network: A real case study for Istanbul, Turkey., Transport Policy 36: 283-293.

Chaghooshi, A. J., Fathi, M. R. and Kashef, M. (2012). Integration of fuzzy Shannon's entropy with fuzzy TOPSIS for industrial robotic system selection., Journal of Industrial Engineering and Management, 5(1) : 102–114.

Chakraborty, S. (2011). Applications of the MOORA method for decision making in manufacturing environment., International Journal of Advanced Manufacturing Technology 54(9) : 1155–1166.

Chakraborty, S., Zavadskas, E. K. and Antucheviciene, J. (2014). Applications of WASPAS Method as a Multi-Criteria Decision-Making Tool., Informatica 25(1) : 1-20.

Chang, S.C., Chang, P. H. and Tsai, S. C. (2015). A hybrid fuzzy model for selecting and evaluating the e-book business model: A case study on Taiwan e-book firms., Applied Soft Computing 34: 194-204.

Chatterjee, P., Athawale, V. M. and Chakraborty, S. (2010). Selection of industrial robots using compromise ranking and outranking methods., Robotics and Computer-Integrated Manufacturing 26(5) : 483–489.

Chiclana, F. E. Herrera, F., and Herrera-Viedma, E., (2001). Integrating multiplicative preference relations in a multipurpose decision-making model based on fuzzy preference relations., Fuzzy Sets and Systems. 122:277-291

Chiclana, F. E. Herrera-Viedma, E. Herrera, F. and Alonso, S. (2004). Induced Ordered Weighted Geometric Operators and Their Use in the Aggregation of Multiplicative Preference Relations., International Journal Of Intelligent Systems 19: 233-255.

Chiclana, F., Herrera-Viedma, E. and Alonso. S. (2009). A note on Two Methods for Estimating Missing Pairwise Preference Values., IEEE Transactions On Systems, Man, And Cybernetics—Part B 39(6): 1628-1633.

Chou, W. C. and Cheng, Y. P. (2012). A hybrid fuzzy MCDM approach for evaluating website quality of professional accounting firms. Expert Systems with Applications 39: 2783-2793.

Çelikbilek, Y. and Tüysüz, F. (2016). An integrated grey based multi-criteria decision making approach for the evaluation of renewable energy sources., Energy 115:1246–1258.

Chu, T. C. and Lin, Y. C. (2003). A fuzzy TOPSIS method for robot selection., International Journal of Advanced Manufacturing Technology 21(4 ): 284–290.

Cid-López, A., Hornos, M.J., Carrasco, R. A. and Herrera-Viedma, E. (2015). A hybrid model for decision-making in the Information and Communications Technology sector., Technological and Economic Development of Economy, 21(5) : 720–737.

Cobots Guide, (2016). Glossary of Robotic Terms
**URL:** http://cobotsguide.com/glossary/ [accessed: February 9, 2017]

Dai, C. Y., Zhang, X. L., Wang, E. C. and Liu, S. L. (2012). Multi-Criteria Renewable Energy Planning Decision-Making Model Based on VIKOR., Advanced Materials Research, 512–515 : 1174–1180.

Datta, S., Samantra, C., Mahapatra, S. S., Banerjee,S. and Bandyopadhyay, A. (2015). Green supplier evaluation and selection using VIKOR method embedded in fuzzy expert system with interval-valued fuzzy numbers.» International Journal of Procurement Management 5(12): 647-678.

Devi, K. (2011). Extension of VIKOR method in intuitionistic fuzzy environment for robot selection., Expert Systems with Applications 38(11) : 14163–14168.

Dong, Y. and Zhang, H. (2013). Multiperson decision making with different preference representation structures: A direct consensus framework and its properties. Knowledge – Based Systems 58: 45-47.

Dong, M., Li, S. and Zhang, H. (2015). Approaches to group decision making with incomplete information based on power geometric operators and triangular fuzzy AHP., Expert Systems with Applications 42(21): 7846-7857.

Dopazo, E., and Ruiz-Tagle, M. (2011). A parametric GP model dealing with incomplete information for group decision-making., Applied Mathematics and Computation 218 : 514-519.

Escalé, J. V. (2015). Human-robot interaction in the industry, Master's thesis, Aalto University.

Ghorabaee, M. K. (2016). Developing an MCDM method for robot selection with interval type-2 fuzzy sets., Robotics and Computer-Integrated Manufacturing, 37 : 221–232.

Gong, Z. Guo, C. and He, Y. (2012). Group decision making methods of the incomplete IFPRs and IPRs., International Journal of Computational Intelligence Systems 5(3) 542-552.

Gul, M. Celik, E. Aydin, N. Gumus, A. and Guneri, A. (2016). A state of the art literature review of VIKOR and its fuzzy extensions on applications., Applied Soft Somputing Journal.

Herrera, F., Herrera-Viedma, E. and Chiclana, F. (2001). Multiperson decision-making based on multiplicative preference relations., European Journal of Operational Research 129(2) : 372–385.

Herrera-Viedma, E. Chiclana, F. Herrera, F. and Alonso, S. (2007). Group Decision – Making Model with Incomplete Fuzzy Preference Relations Based on Additive Consistency., IEEE Transactions On Systems, Man, and Cybernetics—Part B: Cybernetics, 37(1).

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

Huang, S. Su, Hu, Y. Mahadevan, S. and Deng, Y. (2014). A new decision-making method by incomplete preferences based on evidence distance. Knowledge - Based Systems 56 : 264-272.

Igoulalene, I. and Benyoucef, L. (2014). Consensus-based fuzzy TOPSIS approach for supply chain coordination: Application to robot selection problem, Proceedings of the 19th World Congress The International Federation of Automatic Control, Cape Town, South Africa, pp: 772-777.

İç, Y.T. (2012). An experimental design approach using TOPSIS method for the selection of computer-integrated manufacturing technologies., Robotics and Computer-Integrated Manufacturing 28(2) : 245–256.

Imanya, M. M. and Schlesinger, R. J. (1989). Decision Models for Robot Selection: A Comparison of Ordinary Least Squares and Linear Goal Programming Methods, Decision Sciences, 20(1): 40-53.

Jiang, Y. Xu, Z. and Yu, X. (2013). Compatibility measures and consensus models for group decision making with intuitionistic multiplicative preference relations., Applied Soft Computing Journal 13(4) :2075-5086.

Jiang, Y. and Xu. Z. (2014). Aggregating information and ranking alternatives in decision making with intuitionistic multiplicative preference relations., Applied Soft Computing 22: 162-177.

Jiang, Y. Xu, Z. and Yu, Z. (2015). Group decision making based on incomplete intuitionistic multiplicative preference relations., Information Sciences 295 : 33-52.

Ju, Y, and Wang, A. (2013). Extension of VIKOR method for multi-criteria group decision making problem with linguistic information. Applied Mathematical Modelling 5(37): 3112-3125.

Kahraman, C., Çevik, S., Ateş, N. Y. and Gülbay, M. (2007). Fuzzy multi-criteria evaluation of industrial robotic systems. Computers and Industrial Engineering, 52(4), pp.414–433.

Kapoor, V. and Tak, S. S. (2005). Fuzzy application to the analytic hierarchy process for robot selection., Fuzzy Optimization and Decision Making, 4(3) : 209–234.

Karande, P., Zavadskas, E. K. and Chakraborty, S. (2016). A study on the ranking performance of some MCDM methods for industrial robot selection problems., International Journal of Industrial Engineering Computations 7(3) : 399–422.

Karsak, E. E. and Ahiska, S. S. (2005). Practical common weight multi-criteria decision-making approach with an improved discriminating power for technology selection., International Journal of Production Research, 43(8) : 1537–1554.

Karsak, E. E. (2008a). Robot selection using an integrated approach based on quality function deployment and fuzzy regression., International Journal of Production Research, 46(3) : 723–738.

Karsak, E. E. and Ahiska, S. S. (2008b). Improved common weight MCDM model for technology selection., International Journal of Production Research, 46(24) : 6933–6944.

Karsak, E. E., Sener, Z. and Dursun, M. (2012). Robot selection using a fuzzy regression-based decision-making approach., International Journal of Production Research, 50(23) : 6826–6834.

Kentli, A. and Kar, A. K. (2011). A satisfaction function and distance measure based multi-criteria robot selection procedure., International Journal of Production Research 49(19) : 5821–5832.

Khalid, A. and Beg, I. (2016). Incomplete interval valued fuzzy preference relations., Information Sciences 348: 15–24.

Khandekar, A. V. and Chakraborty, S. (2015). Selection of industrial robot using axiomatic design principles in fuzzy environment., Decision Science Letters, 4(2) : 181–192.

Kim, Y., Park, D., Um, M. J. and Lee, H. (2015). Prioritizing alternatives in strategic environmental assessment (SEA) using VIKOR method with random sampling for data gaps., Expert Systems With Applications 42: 8550-8556.

Koulouriotis, D. E. and Ketipi, M. K. (2011). A fuzzy digraph method for robot evaluation and selection., Expert Systems with Applications 38(9) : 11901–11910.

Koulouriotis, D. E. and Ketipi, M. K. (2014). Robot evaluation and selection Part A: An integrated review and annotated taxonomy., International Journal of Advanced Manufacturing Technology, 71(5) : 1371–1394.

Kumar, R. and Garg, R. K. (2010). Optimal selection of robots by using distance based approach method., Robotics and Computer-Integrated Manufacturing 26(5) : 500–506.

Kuo, M. S. and Liang, G. S. (2012). A soft computing method of performance evaluation with MCDM based on interval-valued fuzzy numbers., Applied Soft Computing 12: 476-485.

Lee, L.W. (2012). Group Decision making with incomplete fuzzy preference relations based on the additive consistency and the order consistency., Expert Systems with Applications 39 : 11666-11676.

Li, Y. L. Tang, J. F. Chin, K. S. Luo, X. G. Pu, Y. and Jiang, Y. S. (2012). On integrating multiple type preferences into competitive analyses of customer requirements in product planning., International Journal Production Economics 139: 168-179.

Liao, H. and Xu, Z. (2013). A VIKOR-based method for hesitant fuzzy multi-criteria decision making., Fuzzy Optimization and Decision Making 12 : 373–392.

Liu, F. and Zhang, W. G. (2014). TOPSIS-Based Consensus Model for Group Decision-Making with Incomplete Interval Fuzzy Preference Relations. IEEE Transactions On Cybernetics. 44(8): 1283-1294.

Liu, H. C., Liu, L. and Wu, J. (2013a). Material selection using an interval 2-tuple linguistic VIKOR method considering subjective and objective weights., Materials & Design 52: 158-167.

Liu, H. C., Mao, L. X., Zhang, Z. Y. and Li, P. (2013b). Induced aggregation operators in the VIKOR method and its application in material selection. Applied Mathematical Modeling 37(9): 6325-6338.

Liu, H. C., Tzeng, G. H., Lee, M. H. and Lee, P. Y. (2013c). Improving metro–airport connection service for tourism development: Using hybrid MCDM models., Tourism Management Perspectives 6: 95-107.

Liu, H. C., Ren, M. L., Wu, J. and Lin, Q. L. (2014a). An interval 2-tuple linguistic MCDM method for robot evaluation and selection., International Journal of Production Research, 52(10): 2867-2880.

Liu, H. C., You, J. X., Fan, X. J. and Chen, Y. Z. (2014b). Site selection in waste management by the VIKOR method using linguistic assessment., Applied Soft Computing 21: 453-461.

Liu, H. C., Qin, J. T., Mao, L. X. and Zhang, Z. Y. (2015). Personnel Selection Using Interval 2-Tuple Linguistic VIKOR Method., Human Factors and Ergonomics in Manufacturing & Service Industries 25(3): 370-384.

Liu, P. and Wu, X. (2012). A competency evaluation method of human resources managers based on multi-granularity linguistic variables and VIKOR method., Technological and Economic Development of Economy 18(4): 696-710.

Mazumder, B. P. (2009). Decision-Making In Manufacturing Environment Using Electre Methods Decision-Making In Manufacturing Environment Using Electre Methods, Jadavpur University

Meng, F. and Chen, X. (2015). A new method for group decision making with incomplete fuzzy preference relations., Knowledge-Based Systems, 73: 111-123.

Mirfakhradin, S. H., Abadi, A. N. S., Dehghan, M. and Moosazade, M. (2016). An Integration of MCDM Methods for Technology Selection ( Case Study : EEFA CERAM )., Global Journal of Management Studies and Researches 3(2) : 62–66.

Momeni, M., Reza, F. M. and Abdol, J. (2012). Integration of Interval TOPSIS and Fuzzy AHP for Technology Selection., Nature and Science 10(6) : 99–107.

Mondal, S. and Chakraborty, S. (2013). A solution to robot selection problems using data envelopment analysis., International Journal of Industrial Engineering Computations 4(3) : 355–372.

Nahm, Y. E. Ishikawa, H. and Inoue, M. (2013). New rating methods to prioritize customer requirements in QFD with incomplete customer preferences., International Journal of Advanced Manufacturing Technology 65(9-12): 1587-1604

Omoniwa, B. (2014). A Solution to Multi Criteria Robot Selection Problems Using Grey Relational Analysis., International Journal of Computer and Information Technology 3(2) : 328–332.

Opricovic, S. and Tzeng, G. H. (2004). Compromise Solution By Mcdm Methods: A Comparative Analysis Of Vıkor And Topsıs., European Journal Of Operational Research 156: 445-455.

Özgürler, Ş., Güneri, A. F., Gülsün, B. and Yılmaz, O. (2011). In Robot Selection for a flexible manufacturing system with AHP and TOPSIS methods. Proceedings of the 15th International Research7Expert Conference, TMT2011, Prague, Czech Republic, pp. 333–336.

Parameshwaran, R., Kumar, S. P. and Saravanakumar, K. (2015). An integrated fuzzy MCDM based approach for robot selection considering objective and subjective criteria., Applied Soft Computing Journal 26(C) : 31–41.

Park, J. (2015). Potential games with incomplete preferences., Journal of Mathematical Economics 61 : 58-66.

Rao, R. V. and Padmanabhan, K. K. (2006). Selection, identification and comparison of industrial robots using digraph and matrix methods., Robotics and Computer-Integrated Manufacturing 22(4) : 373–383.

Rao, R. V., Patel, B. K. and Parnichkun, M. (2011). Industrial robot selection using a novel decision making method considering objective and subjective preferences., Robotics and Autonomous Systems 59(6) : 367–375.

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

Rianthong, N. Dumrongsiri, A. and Kohda, Y. (2016). Improving the multidimensional sequencing of hotel rooms on an online travel agency web site., Electronic Commerce Research and Applications 17: 74-86.

Rostamzadeh, R., Govindan, K., Esmaeili, A. and Sabaghi, M. (2015). Application of fuzzy VIKOR for evaluation of green supply chain management practices., Ecological Indicators 49 : 188-203.

Sakthivel, G., Nagarajan, M., Ilangkumaran, G. and Shanmugam, P. (2013). Selection of best biodiesel blend for IC engines: an integrated approach with FAHP-TOPSIS and FAHP-VIKOR., International Journal of Oil, Gas and Coal Technology (IJOGCT) 6(5) : 239-256.

Selek, A. (2016). Endüstri Tarihine Kısa Bir Yolculuk. URL: http://www.endustri40.com/endustri-tarihine-kisa-bir-yolculuk

Sen, D. K., Datta, S. and Mahapatra, S. S. (2015). Extension of TODIM combined with grey numbers: an integrated decision making module., Grey Systems: Theory and Application 5(3) : 367–391.

Sen, D. K., Datta, S. and Mahapatra, S. S. (2016). Extension of PROMETHEE for robot selection decision making., Benchmarking 23(4): 983–1014.

Sen, D. K., Datta, S. and Mahapatra, S. S. (2017). Extension of TODIM for decision making in fuzzy environment: a case empirical research on selection of industrial robot., International Journal of Services and Operations Management 26(2) : 238–276.

Shahrabi, M. (2014). Identification and selection of robot using FAHP and FTOPSIS hybrid model, International Journal of Modern Engineering Sciences 3(1) : 16-28

Shyi-Ming C., Tsung-En L. and Li-Wei L., (2013). A new method for group decision making using incomplete fuzzy preference relations based on the additive consistency and the order consistency., International Conference on Machine Learning and Cybernetics. Lanzhou, China, pp:1256–1261.

Singh, D. and Rao, R. V. (2011). A hybrid multiple attribute decision making method for solving problems of industrial environment., International Journal of Industrial Engineering Computations, 2(3) : 631–644.

Tan, C., and Chen, X. (2013). Interval-Valued Intuitionistic Fuzzy Multi-criteria Group Decision Making Based on VIKOR and Choquet Integral., Journal of Applied Mathematics 1-16.

Tavana, M., Mavi, R. K., Santos-Arteaga, F. J. and Doust, E. R. (2016). An extended VIKOR method using stochastic data and subjective judgments., Computers & Industrial Engineering 97: 240-247.

Tosun, Ö., and Akyüz, G. (2015). A Fuzzy TODIM Approach for the Supplier Selection Problem., International Journal of Computational Intelligence Systems 8(2): 317-329.

Urena, R., Chiclana, F,. Alonso, S., Morente-Molinera, J. A. and Herrera-Viedma, E. (2014). On Incomplete Fuzzy and Multiplicative Preference Relations In Multi-Person Decision Making ., Procedia Computer Science, 31:793–801.

Urena, R., Fujita, F., Chiclana, H. and Herrera-Viedma, E. (2015). Confidence-consistency driven group decision making approach with incomplete reciprocal intuitionistic preference relations., Knowledge-Based Systems 89 : 86-96.

Vahdani, B., Mousavi, S. M. and Tavakkoli-Moghaddam, R. (2011). Group decision making based on novel fuzzy modified TOPSIS method. Applied Mathematical Modelling, 35(9) : 4257–4269.

Vahdani, B., Tavakkoli-Moghaddam, R., Mousavi, S. M. and Ghodratnama, A. (2013). Soft computing based on new interval-valued fuzzy modified multi-criteria decision-making method., Applied Soft Computing Journal 13(1) : 165–172.

Vahdani, B., Tavakkoli-Moghaddam, R., Mousavi, S. M., Ghodratnama, A. and Mohammadi, M. (2014). Robot selection by a multiple criteria complex proportional assessment method under an interval-valued fuzzy environment., International Journal of Advanced Manufacturing Technology 73(5) : 687–697.

Vetschera, R. Sarabando, P. and Dias, L. (2014). Levels of incomplete information in group decision models–A comprehensive simulation study. Computers & Operations Research 51: 160-171.

Wan, S. P., Dong, Q. Y. and Wang, J. Y. (2013). The extended VIKOR method for multi-attribute group decision making with triangular intuitionistic fuzzy number., Knowledge-based systems, (52): 65-77.

Wang, F. K., Hsu, C. H. and Tzeng, G. H. (2014). Applying a Hybrid MCDM Model for Six Sigma Project Selection., Mathematical Problems in Engineering, 1-13

Wang, H. and Xu, Z. (2016). Interactive algorithms for improving incomplete linguistic preference relations based on consistency measures., Applied Soft Computing 42 : 66-79.

Wang, Y. M. (2012). Assessing the relative importance weights of customer requirements using multiple preference formats and nonlinear programming., International Journal of Production Research 50(16): 4414-4425.

Wang, J. C. and Chen. T. Y. (2015a). A simulated annealing-based permutation method and experimental analysis for multiple criteria decision analysis with interval type-2 fuzzy sets., Applied Soft Computing 36: 57-69.

Wang, J. C. and Chen, T. Y. (2015b). An interval type-2 fuzzy permutation method and experimental analysis for multiple criteria decision analysis with incomplete preference information., Journal of Industrial and Production Engineering 32(5) : 298–310.

Wang, Z. J. and Li, K. W. (2012). An interval-valued intuitionistic fuzzy multi attribute group decision making framework with incomplete preference over alternatives., Expert Systems with Applications 39(18): 13509-13516.

Wang, Z. J. and Li, K. W. (2016). Group decision making with incomplete intuitionistic preference relations based on quadratic programming models., Computers & Industrial Engineering, 93 : 162–170.

Wu, J., F., Chiclana, F. and Herrera-Viedma, E. (2015). Trust based consensus model for social network in an incomplete linguistic information context., Applied Soft Computing 35 : 827-839.

Wu, Z., Ahmad, J. and Xu, J. (2016). A group decision making framework based on fuzzy VIKOR approach for machine tool selection with linguistic information., Applied Soft Computing 42 : 314-324.

Xia, M. and Xu, Z. (2013). Group decision making based on intuitionistic multiplicative aggregation operators., Applied Mathematical Modelling 37(7): 5120-5133.

Xu, Y., Da,Q. and Wang, H. (2011). A note on group decision-making procedure based on incomplete reciprocal relations., Soft Computing 15(7): 1289-1300.

Xu, Y. and Wang, H. (2013a). Eigenvector method, consistency test and inconsistency repairing for an incomplete fuzzy preference relation., Applied Mathematical Modelling 37(7): 5171–5183.

Xu, Y., Patnayakuni R. and Wang, R. (2013b). Logarithmic least squares method to priority for group decision making with incomplete fuzzy preference relations., Applied Mathematical Modeling 37(4): 2139-2152.

Xu, Y., Li, K.W. and Wang, H. (2014). Incomplete interval fuzzy preference relations and their applications. Computers and Industrial Engineering, 67, pp.93–103

Xu, Y., Chen, L. and Wang, H. (2015a). A least deviation method for priority derivation in group decision making with incomplete reciprocal preference relations., International Journal of Approximate Reasoning 66: 91-102 .

Xu, Y., Chen, L., Li, K. W. and Wang, H. (2015b). A chi-square method for priority derivation in group decision making with incomplete reciprocal preference relations., Information Sciences 306: 166-179.

Xu, Y., Patnayakuni, R., Tao, F. and Wang, H. (2015c). Incomplete interval fuzzy preference relations for supplier selection in supply chain management., Technological and Economic Development of Economy 21(3) : 379–404.

Xu, Y., Chen, L., Rodriguez, R. M., Herrera, F. and Wang, H. (2016). Deriving the priority weights from incomplete hesitant fuzzy preference relations in group decision making., Knowledge-Based Systems 99: 71–78.

Xu, Z. (2012). A consensus reaching process under incomplete multiplicative preference relations., International Journal of General Systems 41(4): 333-351.

Xu, Z. and Cai, X. (2014). Group Decision Making with Incomplete Interval-Valued Intuitionistic Preference Relations., Group Decision and Negotiation 24 : 193-215.

Xue, Y. X., You, J. X., Zhao, X. and Liu, H. C. (2016). An integrated linguistic MCDM approach for robot evaluation and selection with incomplete weight information., International Journal of Production Research 54(18) : 5452–5467.

Yalcin, N., Bayrakdaroglu, A. and Kahraman, C. (2012). Application of fuzzy multi-criteria decision making methods for financial., Expert Systems with Applications 39: 350-364.

Yan, H. B. and Ma, T. (2015). A group decision-making approach to uncertain quality function deployment based on fuzzy preference relation and fuzzy majority. European Journal of Operational Research 241(3): 815-829.

Yang, W. E. and Wang, J. Q. (2013). Multi-criteria semantic dominance: A linguistic decision aiding technique based on incomplete preference information., European Journal of Operational Research 231(1):171-181.

You, X. Y., Liu, J. X., You, H. C. and Lu, Z. (2015). Group multi-criteria supplier selection using an extended VIKOR method with interval 2-tuple linguistic information., Expert Systems with Applications 42(4): 1906-1916.

Yücenur, G. N. and Demirel, N. (2012). Group decision making process for insurance company selection problem., Expert Systems with Applications 39 : 3702-3707.

Zhang, G., Dong, Y. and Xu, Y. (2012). Linear optimization modeling of consistency issues in group decision making based on fuzzy preference relations., Expert Systems with Applications 39(3) : 2415-2420.

Zhang, N. and Wei, G. (2013). Extension of VIKOR method for decision making problem based on hesitant fuzzy set., Applied Mathematical Modelling 37(7): 4938-4947.

Zhang, Q., Chen, J. C. H. and Chong, P. P. (2004). Decision consolidation: Criteria weight determination using multiple preferences formats ., Decision Support Systems 38(2): 247-258.

Zhang, Q., Xu, Z. and Zhou, B. (2015). Group consensus measurement in MADM with multiple preference formats., Journal of Decision Systems 24(2):146–158.

Zhang, S., Zhu, J., Liu, X. and Chen, Y. (2015). Regret theory-based group decision-making with multidimensional preference and incomplete weight information., Information Fusion 31: 1-13.

Zhang, X. and Xu, Z. (2014). Interval programming method for hesitant fuzzy multi-attribute group decision making with incomplete preference over alternatives., Computers & Industrial Engineering 75 : 217-229.

Zhang, X., Ge, B., Jiang, J. and Tan, Y. (2016). Consensus building in group decision making based on multiplicative consistency with incomplete reciprocal preference relations., Knowledge-Based Systems 106 : 96–104.

Zhang, Z., and Guo, C. (2014). An approach to group decision making with heterogeneous incomplete uncertain preference relations. Computers & Industrial Engineering, 71(1): 27-36.

Zhang, Z., Wang, C. and Tian. X. (2015). Multi-criteria group decision making with incomplete hesitant fuzzy preference relations. Applied Soft Computing 36: 1-23.

Zhang, Z. (2016a). Approaches to group decision making based on interval-valued intuitionistic multiplicative preference relations., Neural computing and applications 1-41

Zhang, Z. and Guo, C. (2016b). Fusion of heterogeneous incomplete hesitant preference relations in group decision making., International Journal of Computational Intelligence Systems 9(2):245-262

Zhao, X., Tang, S., Yang, S. and Huang, K. (2013). Extended VIKOR method based on cross-entropy for interval-valued intuitionistic fuzzy multiple criteria group decision making., Journal of Intelligent and Fuzzy Systems 25(4): 1053-1066.

Zhou, L., He, Y., Chen, H. and Liu, J. (2014). On compatibility of uncertain multiplicative linguistic preference relations based on the linguistic COWGA., Applied Intelligence 40(2): 229-243.

Zhu, B. and Xu, Z. (2014). A fuzzy linear programming method for group decision making with additive reciprocal fuzzy preference relations., Fuzzy Sets and Systems 246:19-33

Zhu, G. N., Hu, J., Qi, J., Gu, C. C. and Peng, Y. H. (2015). An integrated AHP and VIKOR for design concept evaluation based on rough number., Advanced Engineering Informatics 29(3): 408-418.

Zulueta, Y., Rodriguez, D., Bello, R. and Martinez, L. (2016). A linguistic fusion approach for heterogeneous environmental impact significance assessment., Applied Mathematical Modelling 40(2) : 1402–1417.

## BIOGRAPHICAL SKETCH

Burcu Bahadır was born in 1993 in Samsun. She received her high school education in Samsun Atatürk Anatolian High school. She graduated from Yildiz Technic University in 2015 with a B.Sc. in Industrial Engineering. She is now a M.Sc. candidate in the Industrial Engineering Department at Galatasaray University. Her areas of interest include: Multi-criteria decision making. industry 4.0. She participated in the 14th International Logistics and Supply Chain Congress (LMSCM – 2016) and presented her first paper.

## PUBLICATIONS

- Bahadır, B. and Büyüközkan, G., "Robot Selection for Warehouses", Proceeding of the 14th International Logistics and Supply Chain Congress - LMSCM-2016, 341-349, İzmir, 1-2 December 2016