A DEA BASED SORTING APPROACH FOR INDUSTRIAL R&D PROJECTS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

PINAR AKER

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
INDUSTRIAL ENGINEERING

DECEMBER 2010

Approval of the thesis:

A DEA BASED SORTING APPROACH FOR INDUSTRIAL R&D PROJECTS

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ABSTRACT

A DEA BASED SORTING APPROACH FOR INDUSTRIAL R&D PROJECTS

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December 2010, 228 pages

In this study, multicriteria sorting methods based on Data Envelopment Analysis (DEA) are developed to evaluate industrial Research and Development (R&D) projects proposed to Technology and Innovation Grant Programmes Directorate (TEYDEB) of the Scientific and Technological Research Council of Turkey (TÜBİTAK).

Even though DEA is used extensively as a multicriteria decision making (MCDM) tool for ranking; to our knowledge, this study is the first attempt utilizing DEA for sorting purpose.

A five level R&D project selection criteria hierarchy and an assisting point allocation guide with a scale of ten-points are derived to measure and quantify the performance of the proposals. The interval pairwise comparison matrices determined from the judgments of TEYDEB managers are used to obtain weight intervals from Analytic Hierarchy Process (AHP) model. These weights are employed as assurance region constraints.

Motivated from the fact that derived criteria constitute inputs and outputs of R&D projects; DEA determining efficiencies based on inputs and outputs is utilized for sorting. Based on this approach, two threshold estimation models, PM1 and PM2, and five assignment models, APM1, APM2, APM3, APM4 and APM5, are proposed.

The models are applied to a case study in which 60 projects are placed into four groups according to two reference sets composed of proposals from the year 2009. The well-known muticriteria sorting method, UTADIS, is also implemented for comparison. It is concluded that proposed methods are more stable than UTADIS and the integrated application of threshold estimation model PM2 and assignment model APM4 provides the best results.

Keywords: Muticriteria Sorting, DEA, Interval AHP, UTADIS

ÖZ

ENDÜSTRİYEL AR-GE PROJELERİ İÇİN VERİ ZARFLAMA ANALİZİNİ TEMEL ALAN SINIFLANDIRMA METODU

Aker, Pınar
Yüksek Lisans, Endüstri Mühendisliği Bölümü
Tez Yöneticisi: Doç. Dr. Esra Karasakal

Aralık 2010, 228 sayfa

Bu çalışmada, Teknoloji ve Yenilik Destek Programları Başkanlığı, TÜBİTAK TEYDEB'e başvurusu bulunan endüstriyel Ar-Ge projelerinin değerlendirilmesi için Veri Zarflama Analizini (VZA) temel alan sınıflandırma metotları geliştirilmiştir.

VZA modelinin çok amaçlı karar verme problemlerinde sıralama için yaygın kullanımı olmasına rağmen, bildiğimiz kadarıyla ilk kez bu çalışmada sınıflandırma amacıyla kullanılmaktadır.

Ar-Ge projelerinin performanslarının ölçülebilmesi için beş aşamalı kriterler hiyerarşisi ve her kriterin onluk skalada puanlandırılmasında yol gösterecek bir kılavuz oluşturuldu. TEYDEB yöneticilerinin görüşlerinden elde edilen aralıklı yargılardan oluşan ikili karşılaştırma matrisleri Analitik Hiyerarşi Yöntemi (AHY) ile çözülerek kriterlerin öncelikleri aralık değerler olarak hesaplandı. Bu öncelikler güven bölgesi kısıtları olarak kullanıldı.

Değerlendirme kriterlerinin Ar-Ge projelerinin girdi ve çıktılarını oluşturmasından yola çıkılarak, girdi ve çıktı değerlerinden verimlilik ölçen

VZA modeli baz alınarak iki adet eşik değer hesaplama yöntemi, PM1 ve PM2, ve beş adet atama yöntemi, APM1, APM2, APM3, APM4 ve APM5 geliştirildi.

2009 yılındaki proje başvuruları kullanılarak, modeller iki farklı referans set için 60 projenin dört gruba atanmasıyla gerçek bir uygulamada kullanıldı. Karşılaştırma amacıyla aynı uygulama UTADIS modeli için de çözüldü. Önerilen yöntemlerin UTADIS modeline göre daha kararlı olduğu ve eşik değer hesaplama yöntemlerinden PM2 modelinin atama yöntemi APM4 modeli ile birlikte kullanılmasının en iyi sonucu verdiği görüldü.

Anahtar kelimeler: Çok Ölçütlü Sınıflandırma, Veri Zarflama Analizi, Aralık Değerli Analitik Hiyerarşi Yöntemi, UTADIS

To My Family

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor Assoc. Prof. Esra Karasakal for her guidance, invaluable advices, encouragement, kind attitude and insight throughout the study.

I would like to thank Ercan Orhan for his support in technical and morale subjects and for his valuable suggestions and opinions.

I am grateful to my family for their endless support, patience, encouragement and making the life smooth for me.

I would like to express my thanks to Uran Işık for believing in me at all times and also for his patience.

I would like to thank to my managers and colleagues in TEYDEB for their support and help throughout the thesis.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
DEA	Data Envelopment Analysis
DM	Decision Maker
DMU	Decision Making Unit
LP	Linear Programming
MCDM	Multiple Criteria Decision Making
NLP	Non-linear Programming
R&D	Research and Development
TEYDEB	Technology and Innovation Grant Programmes Directorate
TÜBİTAK	The Scientific and Technological Research Council of Turkey

CHAPTER 1

INTRODUCTION

In this chapter, the purpose of this thesis and its content are presented first. Then, Technology and Innovation Grant Programmes Directorate (TEYDEB) of the Scientific and Technological Research Council of Turkey (TÜBİTAK), that constitute the problem structure of the study, is explained. Finally, the organization of the thesis is given.

1.1 Objective and the Content of the Study

Nowadays, the private sector companies should conduct Research and Development (R&D) projects in order to survive in the highly competitive global world. Many countries encourage the R&D activities of private sector to increase the number of successful firms and to improve the competitive power of the country. This is accomplished by executing industrial R&D projects support programs providing grants or loans.

However, deciding on the funded R&D projects that involve high uncertainties and risks is quite difficult. Moreover, the industrial R&D project selection criteria considered by the organizations conducting support programs are challenging, and making a decision requires trade-offs between these criteria. In addition, these decisions are always taken by a group of people, generally from different backgrounds with different point of views.

The aim of this study is to facilitate these kinds of decisions by providing sorting methods that can be used to classify the proposed industrial R&D projects. Throughout the study, Industrial R&D Projects Grant Program (1501) of Technology and Innovation Grant Programmes Directorate (TEYDEB) of the Scientific and Technological Research Council of Turkey (TÜBİTAK) is considered.

Generally, R&D project selection is performed by ranking all of the proposals from the best to the worst based on the importance of evaluation criteria and choosing the projects from the top of the list. Even if ranking provides more information about the importance of the projects, it can not be regarded as precise due to the uncertainties about the R&D projects and the complexity of the evaluation criteria. Furthermore, the need to propose robust and confident solutions to the decision makers orients us to sorting instead of ranking in this study.

R&D project selection criteria of TEYDEB are derived in a five level hierarchy after an extensive literature survey and discussions with TEYDEB personnel. Since the evaluation criteria are qualitative, a ten-point scale is constructed for each criterion by composing a point allocation guide. Due to the complexity of the criteria, uncertain and risky characteristics of R&D projects and group decision making approach of TEYDEB, the pairwise comparison matrices and importance of weights are decided to be interval values rather than crisp values. The weight intervals are obtained from the Analytic Hierarchy Process (AHP) model proposed by Öztürk (2009) by utilizing the interval pairwise comparison matrices determined from the questionnaire conducted to five managers of TEYDEB. The ratios of these interval weights are used as assurance region constraints of the proposed sorting models.

The sorting of the proposals are accomplished by comparing their efficiencies with the estimated thresholds that define the preference related groups. Investigating the derived criteria, it is realized that these criteria constitute the inputs and the outputs of the R&D projects. Since Data Envelopment Analysis (DEA) measures the efficiencies according to the conversion rate of the inputs into outputs, the efficiencies of the proposals are decided to be determined from DEA.

Thereby, two DEA based threshold estimation models, PM1 and PM2, are proposed. The first model allows the projects to be assessed by the best possible weighting structure of the criteria satisfying the assurance region constraints. The second one provides a more fair evaluation by keeping the criteria weightings of the projects close to each other. Furthermore, totally five assignment models, APM1 for the first and APM2, APM3, APM4 and APM5 for the second threshold model, are also suggested for the assessment of validation sample. The first assignment model is the basic DEA model with assurance region. The methodological disparities between the remaining assignment models are the addition of efficiency restrictions to the reference set projects and dealing with all projects in the validation sample at the same time or consideration of a single project each time.

To our knowledge, using DEA for sorting purpose is accomplished for the first time in this study. Furthermore, integrating AHP method that determines interval priorities from interval comparison matrices and DEA to acquire the assurance region constraints of DEA is also the first attempt in the literature. By this way, the shortcoming of inappropriate weight assignment of DEA is prevented. As far as we know, the hierarchy developed for selecting industrial R&D projects is the most complicated structure evaluated by AHP and this hierarchy is also a contribution to the literature. Besides, the other shortcoming of DEA, lack of discrimination, is also hindered by the threshold estimation model PM2 and its compatible assignment models by restricting the optimal weight dispersions.

The developed models are also implemented to a real case study considering the proposals of Industrial R&D Projects Grant Program (1501) from the year 2009. In the case study, assignments of 60 projects into four groups based on two reference sets with 20 and 46 projects are analyzed. The results of the proposed models are also compared with two different post optimality analysis applied to a well known multicriteria sorting method, UTADIS method.

1.2 Description of the Current System and the Problem Definition

The Scientific and Technological Research Council of Turkey (TÜBİTAK) is a state institution with the responsibilities of developing science, technology and innovation (STI) policies in accordance with the national priorities with the collaboration of all sectors and related establishments, assisting the establishment of infrastructure and instruments to implement the policies, supporting and conducting research and development activities and having a leading part in the creation of a science and technology culture with the purpose of improving the competitive power and prosperity of the country since 1963 (TÜBİTAK Catalogue, 2007).

One of the major functions of TÜBİTAK is to provide grants for innovative research and development projects of Turkish industry. Dedicated to this specific objective, Technology and Innovation Grant Programmes Directorate (TEYDEB) is founded within TÜBİTAK in order to improve the global competitiveness of the industrial sector in Turkey by supporting research, technology development and innovation capabilities since 1995 (TÜBİTAK Catalogue, 2007). The Technology and Innovation Grant Programs are grouped as follows:

- 1501 – Industrial R&D Projects Grant Program,
- 1503 – R&D Project Brokerage Events Grant Program,
- 1507 – SME RDI (Research, Development and Innovation) Grant Program,
- 1508 – Techno-Entrepreneurship Grant Program,
- 1509 – International Industry R&D Projects Grant Program.

Industrial R&D Projects Grant Program is the elementary one launched in 1995 with the aim of increasing research and technology development capability, innovation culture and technological competitiveness of both big enterprises and SMEs via R&D projects. This program had been jointly conducted by the Undersecretariat of Foreign Trade (DTM), responsible for sharing the funding, and TÜBİTAK, responsible for evaluating and monitoring R&D projects and sharing the funding until September 2010 (beyond this date the program responsibility is solely TÜBİTAK's).

The purpose of the Brokerage Event Grant Program is to encourage the universities, research institutions and industrial companies to collaborate by granting the brokerage event arranged to find partners.

SME RDI Grant Program provides advantageous supports to first two projects of SMEs in order to motivate them to start R&D activities since 2007.

New university graduates with entrepreneurial spirit are supported by Techno-Entrepreneurship Grant Program since 2007 to carry out innovative and R&D based project ideas that are likely to create high added value in near future. In this support program, project proposals are accepted by the way of annual calls announced in the website since 2009 and there is no active call offered in the year 2010.

International Industrial R&D Projects Grant Program, launched in 2007, aims to encourage private sector located in Turkey to cooperate with one or more Europe wide partners in a R&D project.

For the details of the programs and more information about TEYDEB, see (TÜBİTAK-TEYDEB, n.d.).

Since Brokerage Event Grant Program has different purpose and application criteria compared to other programs, it is excluded from the term Grant Programs in the remaining parts of the study.

From 1995 to the end of 2009, 10.161 project proposals are applied to the Grant Programs from 4.755 companies. The number and the percentage of projects supported by Industrial R&D Projects Grant Program, SME RDI Grant Program, Techno-Entrepreneurship Grant Program and International Industrial R&D Projects Grant Program is given in Figure 1 (TÜBİTAK-TEYDEB, n.d.).

There are five divisions under TEYDEB organization who take and evaluate the project proposals:

- Biotechnology, Agriculture, Environment and Food Technologies Group (BİYOTEG),
- Electrical and Electronic Technologies Group (ELOTEG),
- Information Technologies Group (BİLTEG),
- Machinery and Manufacturing Technologies Group (MAKİTEG),
- Materials, Metallurgical and Chemical Technologies Group (METATEG).

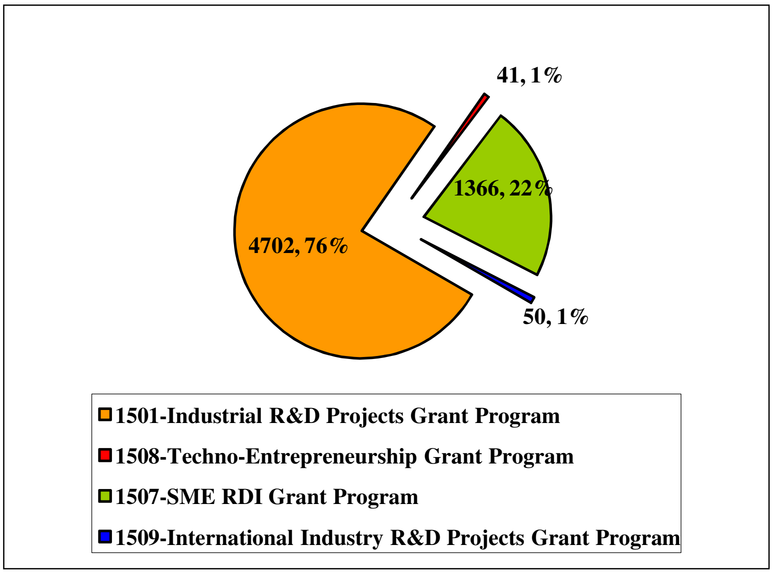

Figure 1: The number and the percentage of projects supported by 1501, 1507, 1508 and 1509 Grant Programs of TEYDEB

The proposals are initially subjected to pre-assessment in the first phase, application and evaluation phase, by the relevant group's technical staff. The proposal eliciting preliminary conditions is then submitted to independent referees usually from universities or research centers who evaluate the projects not only through examining the document but also making an on-site visit to the location where the project will be conducted. The number of referees assigned to a project changes with respect to the technology fields contained in the project or its budgetary size. Final evaluation and decision is up to the technology group committee whose decision is basically based on the referee reports. The committee decides either on accepting the project to the program or rejecting it. Furthermore, the project monitoring referee who will monitor and report the technical progress semi-annually to TÜBİTAK is also stated in the committee's decision.

After a project is accepted to the program and the project grant agreement is signed between the company and TÜBİTAK, the second phase, which is monitoring and granting phase, begins by the company's submission of the first semi-annual Report for R&D Support Request to TÜBİTAK. The submitted Report includes both the data and information regarding the project progress and the related expenses. The expenses declared in the forms of the Report should have been examined and approved as to their compliance to the financial documents and procedures by independent finance auditors before the submission of the Report to TÜBİTAK. The received Report for R&D Support Request is pre-evaluated by TEYDEB's technical staff and then sent to the monitoring referee. The referee examines the report, analyzes the performance of the company by making an on-site visit for the period that the report has been prepared for and writes his/her project monitoring report. Upon the completion of technical and financial evaluations, the accepted expenses are determined and the relevant grant ratio is applied to the documented and approved expenses. Finally, the respective amount of grant is paid to the company by TÜBİTAK.

The two phases of the programs implemented in TEYDEB are illustrated in Figure 2.

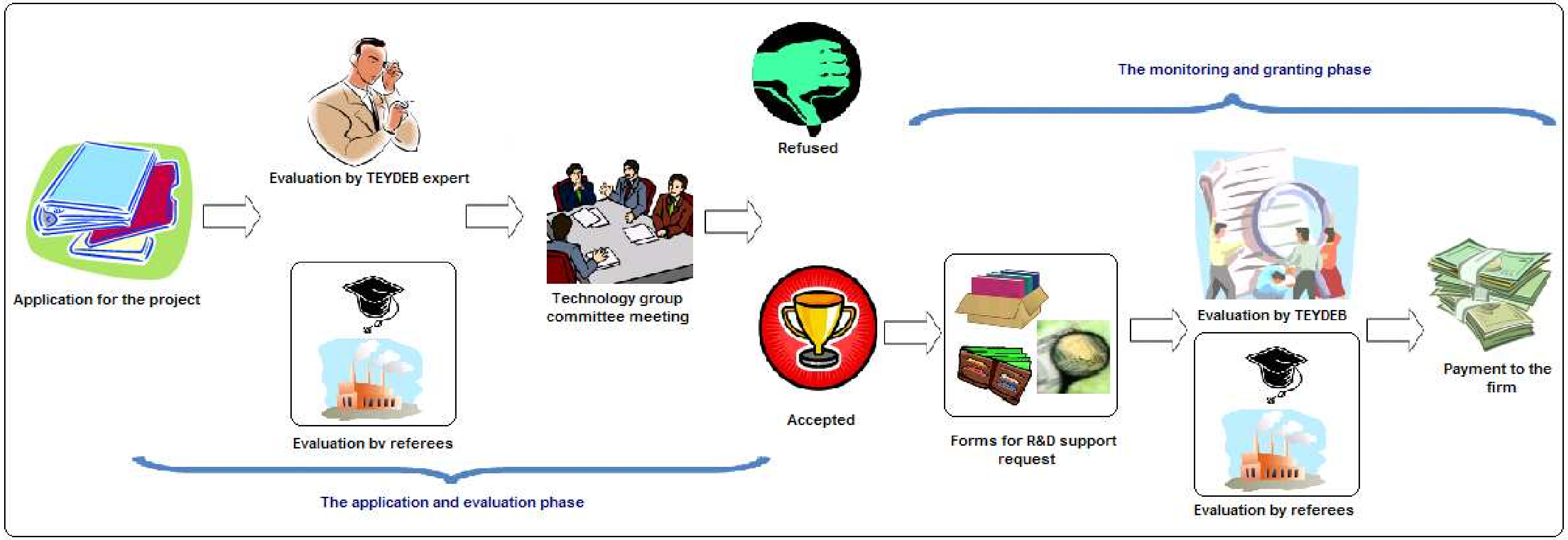

Figure 2: The two phases of the Technology and Innovation Grant Programs of TEYDEB

The scope of a project that may be granted by the mentioned programs covers the internationally classified R&D activities such as conceptual design, technical and financial feasibility studies, product design, laboratory work, trial or pilot scale production and tests. The Grant Programs do not cover the expenses of production and marketing activities. Expenses of personnel, travel, tool, equipment, software, technical document, consultancy from universities and private experts, services from private industry, supplies and materials belonging to the supported activities can be presented in the Forms for R&D Support Request.

The first phase, namely the project proposal application and evaluation phase, is very critical for an applicant company, as explained above, because the essential decision of whether the proposed project is accepted to the Program or not is taken in the end of a very detailed process in this stage. Moreover, this phase identifies if the Grant Programs reach their ultimate impacts, such as formation of R&D culture and structure, increasing the number of successful firms competing with word markets and increasing productivity and product quality by improving product technologies. More emphasis should be put on this phase in order to effectively manage the grant allocated from government. Therefore, the main concern in this thesis is on the first phase of the operation of the Grant Programs.

When the statistical data on Technology and Innovation Grant Programs is examined as presented in Figure 3, it is realized that the number of project applications and the number of companies applied to the Grant Programs increases about five times from 2003 to 2009. In addition, total grant provided by TÜBİTAK accelerates six times from 2003 to 2009 as shown below in Figure 4 (TÜBİTAK-TEYDEB, n.d.). Because of these accelerations in the recent years, evaluation of the projects gets more difficult nowadays. On this account, this study aims at facilitating the application and evaluation phase of the grant programs.

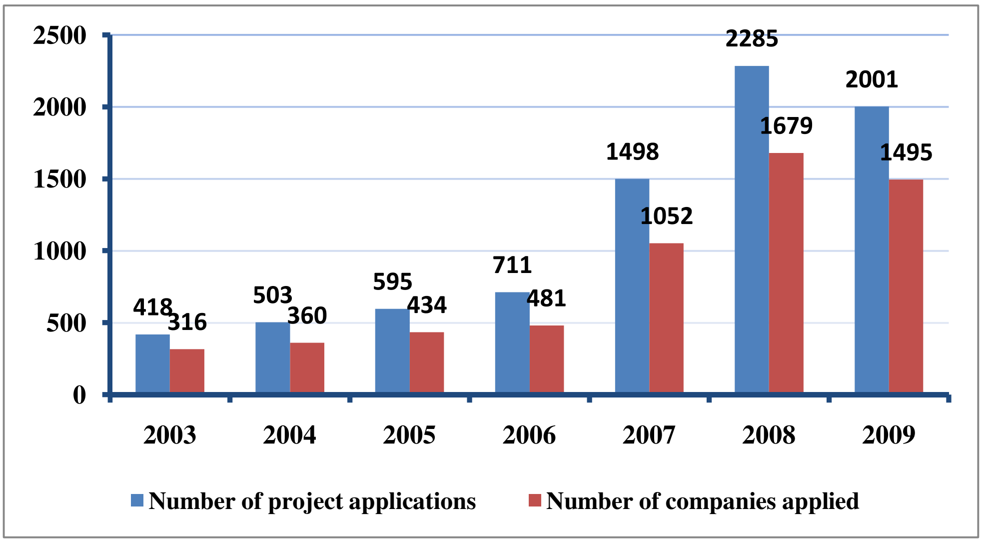

Figure 3: The number of projects and companies applied to Grant Programs in between 2003-2009

As mentioned before, Industrial R&D Projects Grant Program is the prime program suitable for both big enterprises and SMEs. Furthermore, 76% of the supported projects of Grant Programs belong to this program as indicated in Figure 1. Therefore this program has the biggest amount of available data which facilitates analyzing the program. Due to the fact that there is no project budget restriction and the allowable project duration is the longest with 36 months, this program is also the one with the most complicated and generally the longer evaluation period. Because of these reasons, Industrial R&D Projects Grant Program is chosen as the subject of this study.

A project proposal is composed of the following five sections:

- Summary of the project and general information about the company,
- The industrial R&D content of the project, its technological level and its innovational aspects,
- The project plan, the R&D capabilities of the company and the adequacy of the company infrastructure,

- Economic or social outcomes of the project,
- The cost breakdown of the project budget.

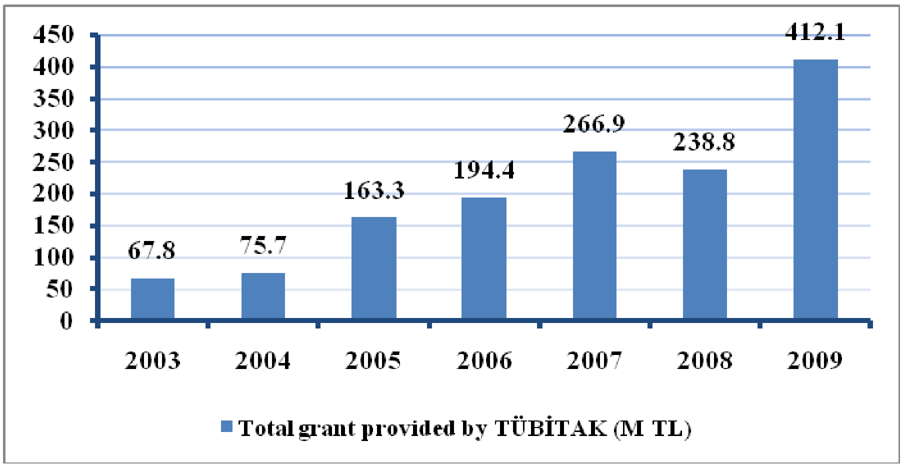

Figure 4: Total Grant provided by TÜBİTAK in between 2003-2009

Gathering the required information from the company via proposals, assessment of the project is done by considering "three dimensional" evaluation criteria developed in cooperation with researchers and reviewers from universities, public organizations and private industry (Cebeci, et al., 2006). The "three dimensions", which are equally weighted throughout the evaluation, are explained as technology level of the research, innovative level of the product/outcome and feasibility of the process for technological and innovation driven research conducted by the private sector. Instead of Likert scale, in which the respondents select the number generally from one to five that best corresponds to their views, "Phrase anchored rating scale", defining the subcriteria phrases belonging to the features of "very competitive", "competitive" and "not competitive" for each of the "three dimensions" with the scores of three, two and zero respectively, is used. In this model, the reviewers choose the phrases that are already available and also add new phrases demonstrating their opinions and finally decide on a single feature representing their final decision for each dimension. At the end, each proposal receives a total score between zero and nine. It is disscussed that “Phrase anchored rating scale” has the advanges of reducing the burden of the review process on the reviewers, decreasing subjectivity and variability of views and guiding the researchers about the subcriteria used to evaluate their proposals.

Currently, Project Proposal Evaluation Report of Industrial R&D Projects Grant Program which is based on the model advanced by Cebeci et al. (2006) are employed by the referees after examining the project proposal and visiting the company. This report also reveals the evaluation criteria and subcriteria used throughout the program. The “three dimensions” of the report are:

- Industrial R&D content of the project, its technological level and its innovational aspect,
- The project plan, the capabilities of the company and the adequacy of the company’s infrastructure,
- Economic or social outcomes of the project.

Project Proposal Evaluation Report is given in Appendix A. Each proposal is analyzed by usually more than one referee and therefore at least two reports are available for each proposal. These reports can be in contradiction with each other, which makes the decision process more complicated. This difficulty can increase when there are more than two referees.

As it is often encountered with the case that a project does not perform well in all dimensions, evaluation of the criteria in each of the three dimensions concurrently generates the complexity in selecting the projects to be funded. Moreover, as mentioned before, six committee members of each technology group, five of them from universities or research institutes and one of them is the secretary of the corresponding technology group, meet and discuss each proposal evaluated by independent referees and make the final decision of acceptance and rejection periodically. During the group decision making process, each member has one vote and decisions are taken by the majority of the votes. Due to the fact that each committee member has a different background and viewpoint, group decision making environment of TEYDEB also increases the difficulty of decision making.

Therefore, a supporting method that facilitates the selection of funded R&D projects from all fields can be very beneficial in TEYDEB. Moreover, it can provide a fair evaluation by decreasing the subjectivity of decision making and reduces the time requirements for evaluation.

In consequence, a sorting method in accordance with the preferences and judgments of the decision makers and taking into account the uncertainties and risks involved in the R&D project proposals is decided to be developed for Industrial R&D Projects Grant Program (1501) of TEYDEB.

1.3 Organization of the Thesis

In Chapter 2, the surveys about R&D project selection criteria, the basics of AHP and interval judgments in AHP, multicriteria sorting methods, DEA and its integrated applications are given.

In Chapter 3, the theoretical background information on AHP, DEA and UTADIS approaches, that form the building blocks of the proposed models, are mentioned.

In Chapter 4, the R&D project selection criteria and an assisting point allocation guide derived in the study are presented. The independence of the criteria is also explained in detail.

In Chapter 5, the proposed AHP approaches and DEA based sorting methods are analyzed explicitly.

In Chapter 6, the implementation of the proposed methods to a real case study, the results and the discussions of this implementation are presented. Finally, the conclusions and suggestions for the next studies are given in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the reviews on the topics of R&D project selection criteria, Analytic Hierarchy Process (AHP), multicriteria sorting methods and Data Envelopment Analysis (DEA) are presented respectively.

2.1 R&D Project Selection Criteria

An extensive literature review is carried out on the subject of R&D project selection and evaluation criteria. It is realized that the number of studies related with R&D project selection for government funding is insignificant. Only two studies, Hsu et al. (2003) and Huang et al. (2008) deal with selection of R&D projects for government-sponsored technology development program. However, the funding programs examined in these studies focus on innovative technology development projects rather than innovative product or process development ones as in TEYDEB. Therefore, some of the project selection criteria used in these studies are not applicable to this study.

In another study which is based on R&D project selection within a government department (Cook et al., 1982), factors such as political and senior management support and prioritization of some subjects like security attain more importance as a nature and strategy of the department. Although some subjects are also prioritized in TEYDEB, such as informatics, genetic engineering and biotechnology, this prioritization does not cause a change in the acceptance or rejection decision but recorded as statistics. As a result, it is not considered as a criterion in this study.

The rest of the studies found in the literature are interested in choosing R&D projects within a company. Due to the fact that the reasons of companies for conducting R&D activities differentiate from the main reasons of government funding of private sector R&D projects, some criteria considered by the companies for selecting R&D projects may not be suitable for the case of government funding.

It should be noted that, the project proposals received in TEYDEB have not been started during the application and evaluation phase. For this reason, criteria measuring the performance of projects such as percentage of milestones achieved or technical progress are not suitable for this case.

R&D project selection criteria available in the literature are categorized into five factors; technical, marketing, financial, environmental and organizational factors. The criteria belonging to these categories with their corresponding sources are provided in Table 1. Similar criteria to the ones represented in bold and italics in Table 1 are also used in the study. The definitions and discussions of these criteria are given in the following pages.

Table 1: R&D project selection criteria used in literature

Category	Criterion	Source
Technical	Probability of technical success	Liberatore (1987), Martino (1995), Pillai et al. (2002), Meade et al. (2002), Mohanty et al. (2005), Huang et al., (2008)
	Degree of innovativeness	Balachandra et al. (1997), Pillai et al. (2002), Hsu et al. (2003), Huang et al. (2008)
	Advancement of technology	Hsu et al. (2003), Huang et al. (2008)
	Key of technology	Huang et al. (2008)
	Proprietary technology	Hsu et al. (2003), Huang et al. (2008)
	Patentability	Souder et al. (1978), Balachandra et al. (1997), Linton et al. (2002)
	Technological connections	Meade et al. (2002), Hsu et al. (2003), Huang et al. (2008)
	Technological extendibility	Mohanty (1992), Hsu et al. (2003), Huang et al. (2008)
	Evidence of scientific feasibility	Hsu et al. (2003), Huang et al. (2008)
	Existence of technology	Mohanty (1992), Pillai et al. (2002)
	Contributions to the state of knowledge	Huang et al. (2008)

Table 1 Continued: R&D project selection criteria used in literature

Category	Criterion	Source
Marketing	***Probability of market success***	Cook et al. (1982), Martino (1995), Pillai et al. (2002), Meade et al. (2002), Mohanty et al. (2005), Huang et al. (2008)
	Potential size of the market	Martino (1995), Pillai et al. (2002), Meade et al. (2002), Hsu et al. (2003), Mohanty et al. (2005), Huang et al. (2008)
	Potential market share	Pillai et al. (2002), Mohanty et al. (2005)
	Potential growth of the market	Balachandra et al. (1997), Hsu et al. (2003)
	Degree of competition	Martino (1995), Balachandra et al. (1997), Pillai et al. (2002), Meade et al. (2002), Hsu et al. (2003), Mohanty et al. (2005)
	Rate of product introduction	Balachandra et al. (1997)
	Perceived value	Balachandra et al. (1997), Hsu et al. (2003)
	Product life cycle	Maidique et al. (1984), Liberatore (1987), Martino (1995), Balachandra et al. (1997), Pillai et al. (2002), Meade et al. (2002), Mohanty et al. (2005)
	Intellectual property life cycle	Linton et al. (2002)
	Timing of the project	Hsu et al. (2003), Huang et al. (2008)
Financial	***Cost of development, investment and production***	Linton et al. (2002), Pillai et al. (2002), Mohanty et al. (2005), Huang et al. (2008)
	Discounted cash flow	Linton et al. (2002)
	Net present value (NPV)	Porter(1978), Martino(1995), Alidi(1996), Pillai et al.(2002), Meade et al.(2002)
	Internal rate of return (IRR)	Martino (1995), Alidi (1996), Pillai et al. (2002)
	Productivity improvement	Cook and Seiford (1982)
	Expected savings	Cook and Seiford (1982)

Table 1 Continued: R&D project selection criteria used in literature

Category	Criterion	Source
Environmental	Availability of raw materials	Martino (1995), Balachandra et al. (1997), Pillai et al. (2002), Mohanty et al. (2005), Huang et al. (2008)
	Political factors	Mohanty (1992), Martino (1995), Balachandra et al. (1997), Pillai et al. (2002), Meade et al. (2002), Mohanty et al. (2005)
	Environmental considerations	Cook et al. (1982), Mohanty (1992), Martino (1995), Pillai et al. (2002), Meade et al. (2002), Hsu et al. (2003), Mohanty et al. (2005), Huang et al. (2008)
	Safety considerations	Mohanty (1992), Martino (1995), Pillai et al. (2002), Meade et al. (2002), Hsu et al. (2003), Mohanty et al. (2005), Huang et al. (2008)
	Benefits to human life	Hsu et al. (2003), Huang et al. (2008)
	Social acceptability	Cook et al. (1982), Alidi (1996), Pillai et al. (2002), Mohanty et al. (2005)
	Job creation opportunity	Cook and Seiford (1982)
Organizational	***Existence of a project champion***	Lockett (1986), Mohanty (1992), Martino (1995), Meade et al. (2002), Mohanty et al. (2005)
	Degree of internal competition for resources	Martino (1995), Pillai et al. (2002)
	Existence of required competence	Cook et al. (1982), Liberatore (1987), Mohanty (1992), Martino (1995), Linton et al. (2002), Pillai et al. (2002), Meade et al. (2002), Hsu et al. (2003), Mohanty et al. (2005), Huang et al. (2008)
	Degree of internal commitment	Martino (1995)
	Existence of required facilities	Liberatore (1987), Mohanty (1992), Pillai et al. (2002), Meade et al. (2002), Mohanty et al. (2005), Huang et al. (2008)
	Intrinsic merit of research	Martino (1995), Henriksen et al. (1999), Huang et al. (2008)
	Quality of the project plan	Henriksen et al. (1999), Hsu et al. (2003), Huang et al. (2008)
	Fitting organizational strategy	Morris et al.(1991), Martino(1995), Henriksen et al. (1999), Meade et al. (2002)

1. **Technical Factors**

In this part, issues related with the technology used in the project and outputs influencing the technology of the company and other parties are described.

<u>Probability of Technical Success</u>

This criterion considers the probability of meeting technical specifications targeted at the beginning of the project. Opportunity of technical success is highly related with technical risks of the project. As technical risks reduce, the probability of technical success increases. Furthermore, other aspects like competency of the project team and quality of the project plan have a great impact on technical success. Thus, it is not possible to determine the probability of technical success directly.

Although this criterion is important; since it can not be measured directly and initial subjective probability estimates performed at the beginning of the project may not be reliable as stated by Martino (1995), this criterion is not taken into account as a selection criterion of Grant Programs of TEYDEB. Instead, the aspects affecting this criterion are considered.

<u>Degree of Innovativeness</u>

This criterion considers if the obtained product, process or technology is innovative. Since R&D projects are addressed in this study, it is inevitable to deal with innovation. In the study of Hsu et al. (2003), innovativeness is divided into two; incremental improvement and radical innovation.

TEYDEB expects developing new products or processes or improving them as the targets of the submitted R&D projects. Therefore, this criterion is chosen for a selection criterion of Grant Programs of TEYDEB. On the other hand, differentiation of incremental improvement and radical innovation is not done since there is no preference between them in TEYDEB.

Advancement of Technology, Key of Technology and Proprietary Technology

The criterion of advancement of technology considers the level of improvement made in the technology compared with the existing technology. Key of technology analyzes if the proposed technology is critical for a product or industry development. Proprietary technology means the generation of a proprietary position through the intellectual property rights.

As explained above, technology development is not expected in the Grand Programs of TEYDEB. Hence, these criteria related with technology development are not considered in the study.

Patentability

Patentability of the project outcome is considered as a project selection criterion in some studies (e.g., Souder et al., 1978; Linton et al., 2002).

Possibility of procuring a patent is also asked in Project Proposal Evaluation Report of Industrial R&D Projects Grant Program. However, it is believed that planning to apply for a patent without an idea about the technical success of the project is not so realistic. Therefore, patentability can not give an accredited view about the project proposal and it is not taken into account.

Technological Connections and Technological Extendibility

Technological connections analyzes if the proposed technology is applicable for many products while the technological extendibility considers if further technology developments can be accomplished based on the proposed technology.

Because these criteria are related with technology development, they are not chosen as the project selection criteria in this study.

Evidence of Scientific Feasibility

This criterion takes into consideration the research evidences of the proposed project like proof of concept, experimentation or sound theoretical thinking. It can be thought as the technical feasibility study of the project. This study reveals the risky and problematic parts of the project.

Selection of scientifically feasible projects is quite important in TEYDEB, therefore a similar criterion is defined in the study.

Existence of Technology

This criterion is related with the availability of technology within the company or attainability of it from foreign sources.

The company proposing the project should investigate the existence of technology while planning the resources required for the project. Availability of the technology is not a suitable criterion for selecting the projects to be funded. Instead of it, resource planning is evaluated in TEYDEB.

Contributions to the State of Knowledge

This criterion considers if the proposal can contribute to the state of technical knowledge.

The main anticipated outcome of the projects funded by TEYDEB is not the contribution to the state of knowledge since basic researches carried out to obtain a greater understanding of a phenomenon are not supported. But it is one of the outcomes of the successful projects and has an impact on increasing number of firms, which are able to compete with world markets as an aimed influence of Grant Programs. As a result, a similar criterion is used in the study measuring the knowledge contribution at the national level.

2. Marketing Factors

In this part, issues affecting the commercialization of the projects are investigated.

Probability of Market Success

This criterion is used in terms of two measures; adaptation of the project output by potential users and the number of potential users of the output. In both cases, total sales must exceed the investments to consider the project as a commercial success.

The third dimension of the current project selection criteria is the applicability of the project outcomes into economical profits. Moreover, getting financial success is also an aimed influence of the Grant Programs. Therefore, a similar criterion is defined for the study.

Potential Size of the Market, Potential Market Share and Potential Growth of the Market

Potential size of the market relative to the size of the company that can provide profitability in terms of commercial success, and market share opportunity of the company are considered as project selection criteria. In addition, expected growth rate of the market for the project outcome is said to have an impact on the marketing of the output.

While these measures are important in terms of evaluating the commercial success of the project, it is hard to make estimates about them at the start of the R&D project which involves uncertainties and risks. Even for the finished projects, an extensive market survey has to be performed to obtain these measures. Moreover, a technically successful project may not be commercially successful due to the external factors making changes in the market environment. Therefore, carrying out a survey on the targeted market and making plans to reach that market are considered instead of these criteria.

Degree of Competition and Rate of Product Introduction

The number and strength of the competitors in the market are important factors influencing commercial success of the project. Many companies work on R&D projects to be more competitive by improving their products or processes. Market success also depends on rate of product introduction. Rate of product introduction can represent the life cycle of the product; hence higher rate can be seen as a greater chance of success. On the other hand, higher rate can also means aggressive competition affecting the market success negatively.

These factors should be considered by the companies while selecting the content and type of innovation of their R&D projects. However, it is not a matter for selecting the projects to be funded by TEYDEB. Instead, opportunity of market success which is a more direct measure is used in the study.

Perceived Value

Value added to the product can be described as the ratio of perceived benefits that a product delivers and its perceived price against the requirements of customers and offerings of the competitive products available in the market. The companies try to increase their market offerings compared to the offerings of their customers by focusing on the targeted customers.

Although this criterion is essential for companies to hold a good market share; opportunity of market success, which also represents the expected perceived value, is used as a project selection criterion for Grant Programs.

Product Life Cycle, Intellectual Property Life Cycle and Timing of the Project

Product and intellectual property life cycle can be defined as the length of time that the product or process will remain competitive for its intended purpose. Linton et al. (2002) classify the life cycles as future, emerging, widespread and declining, and give more credit to the projects that are emerging and future oriented. Timing of the project examines if the time is right to conduct the project.

Since these measures are hard to find out and also express the probability of market success, they are not considered in this study.

3. Financial Factors

In this part, financial factors affecting selection and implementation of the project and results of the project that cause a change in the financial position of the company are analyzed.

Cost of Development, Investment and Production

In this criterion, total amount of money required to develop the project and implement the project results are considered. These can be prototype development, pilot plant construction and production investment monetary costs. Additionally, the probability of not being able to produce the required quantity at the required cost, namely the economic risk of the project, is also included in this criterion.

This factor not only measures the economic feasibility of the project but also highly affects the market success of the project outcome. The project that can not be implemented, therefore can not be commercialized is not supported by TEYDEB since it does not meet the third dimension of the current evaluation system. Due to its importance in selecting the funded projects, a criterion similar to this is defined in the study.

Discounted Cash Flow, Net Present Value (NPV) and Internal Rate of Return (IRR)

Conventionally, these quantitative expressions are used as project selection criteria by measuring and comparing the profitability of the projects. However, due to the uncertain and risky environment of R&D projects, it is difficult to obtain reliable measures for them. Linton et al. (2002) offer using most likely, optimistic and pesimistic discounted cash flow; thereby the risk can also be taken into account.

Even if the suggestion of Linton et al. (2002) is regarded, it is again hard to decide on flow rates of incomes and outcomes and also interest rates. Therefore, these criteria are not used as selection criteria of supported projects.

Productivity Improvement and Expected Savings

Possible advancement of the productivity by the way of process improvement activities, savings in capital, user, operational and maintenance costs are also considered while selecting among project alternatives.

A similar criterion based on the opportunity of improvements in productivity and costs is also defined in this study since it is also an application of the project outcomes into profit, the third dimension of the current evaluation system.

4. Environmental Factors

In this part, external factors which can not be controlled by the company and the results of the projects that have an effect on the environment are studied.

Availability of Raw Materials

Availability of raw materials required for the product or process is regarded as an important issue for project selection due to the fact that it determines the total production amount and contributes to the production costs. As Balachandra et al. (1997) states, this factor is not so critical under normal circumstances but can be essential in case of market-induced shortages, hostilities or embargos.

Although it is believed that the availability and access to raw materials should be investigated by the company while conducting feasibility of the project, it can not be a project selection criterion considered by TEYDEB. Therefore, this factor is not defined in the study.

Political Factors, Environmental and Safety Considerations

While deciding on the R&D project to carry out, companies should pay attention to political factors such as governmental regulations, policies and standards in order to implement the project and commercialize the project output. Furthermore, environmental and safety considerations like disposability, recyclability, workplace safety and product safety regulations should be also regarded.

These considerations should be accounted while planning the project, so that necessary precautions, licences and arrangements in the design, product or process can be accomplished. These are also required for production, introducing the products into the market and obtaining economic profits. As a result, these factors are taken into account in the project planning criterion.

Benefits to Human Life

This criterion is related with the project results providing benefits to human life such as quality of life and health.

A similar criterion with the addition of benefits of the project to the environment is also available in Project Proposal Evaluation Report. Therefore, this factor is taken into consideration in this study.

Social Acceptability

The importance of the societal dimension should be regarded in order to choose projects that are acceptable in terms of public. The projects that do not satisfy public interest have no chance to success in the market.

In spite of the fact that social acceptability is a significant factor greatly influencing the market success of the project and hence should be considered by the company, probability of market success which is a more direct and comprehensive measure than social acceptability is considered instead of it.

Job creation opportunity

This factor deals with the probability of increasing employment by creating new line of businesses at the end of the project.

This criterion is included in the current Project Proposal Evaluation Report and it is also stated in the Fundamental Principles of Industrial R&D Projects Grant Program. Hence, it is mentioned in the study.

5. **Organizational Factors**

In this part, factors depending on the capabilities of the company and results of the project that have influence on the organization are examined.

Existence of a Project Champion and Degree of Internal Competition for Resources

Project champion is the project leader supervising the project team with the capabilities of managing the project effectively and motivating the team. Internal competition for resources takes place in a multi-project environment which requires the same resources of the company such as personnel, budget and facilities. The project champion can provide necessary resources of the project by supporting it during higher management reviews against other projects.

In this study, a criterion related with the existence of a project champion affecting the coordination and management of the project is also defined. However, since the degree of internal competition for resources can not be identified from the outside of the organization and should be managed by the company, it is not chosen as a project selection criterion of TEYDEB.

Existence of Required Competence and Degree of Internal Commitment

Existence of the required competence means the adequacy of the project team in terms of skills and experience in the context of the project. Degree of internal commitment is related with the sufficiency of the commitments of the project team, higher management and outside consultants and experts to the project.

Since capability of the research team influences the feasibility of the project, a criterion measuring this factor is included in the study. Moreover, degree of commitment of the project personnel with respect to the contributions of the outside experts in critical fields of the project is also measured because it is required that the main contribution to the project belongs to the project team, not the consultants.

Existence of Required Facilities

In this criterion, existence of the facilities within the company that are required for the activities belonging to the project is considered.

This criterion should be accounted by the company while preparing and scheduling the project plan and arranging the budget. On the other hand, it can not be a measure to select the projects that are funded by TEYDEB. Instead of it, the resource planning of the project is mentioned in the study.

Intrinsic Merit of Research

Intrinsic merit of research means enhancing the skills and competence of the project team which can result in new projects.

One of the expected influences of the Grant Programs performed in TEYDEB is the formation of R&D culture and structure in the companies. Therefore, a criterion based on improving competence of the firms and attaining continuity of carrying out R&D projects is defined in the study.

Quality of the Project Plan

A good project plan should include clear and measurable goals, resource and manpower planning and a realistic schedule related with the activities that will be accomplished.

The proposals submitted to TEYDEB should have a good quality of project plan because of the fact that TEYDEB experts do not visit the companies on site and evaluate the projects from the proposal prepared by the company and from the reports of the referees. As a result, a similar criterion is described in the study.

Fitting Organizational Strategy

The project should match with the mission and long-term strategies of the company in order to develop a capability for future work and achieve strategic positioning.

Since this criterion is related with the objectives of the company, it is not defined as a project selection measure of TEYDEB.

In addition to the literature review explained in detail above, different R&D projects funding programs are also investigated. These are EUREKA Programs, ERA-NET Collective Research Networking (CORNET), ERA-NET Materials (MATERA), Research for the benefit of SMEs (FP7-SME), Advanced Technology Program (ATP) and Technology Development Program of Technology Development Foundation of Turkey (TTGV).

Applications to first five programs can be done within a partnership structure, in which partners are from different countries participating to the programs, mainly from Europe. Therefore, formal agreement between partners and partnership analysis are considered while proposals are evaluated. It should be mentioned that the number of projects with partners submitted to TEYDEB is insignificant. As a result, the criteria related with partnership are not taken into consideration.

In EUREKA Programs, financial capacity needed to implement the project is analyzed as a crucial criterion. In TEYDEB, a criterion measuring the financial statement of the company is not available. However, it is thought to be an important factor evaluating the implementation and therefore probability of commercialization of the project. Hence, it is decided to be considered in the study.

In CORNET, MATERA and FP7-SME, dissemination and exploitation of project results are accounted as a project selection criterion since these programs aim at providing economic benefits to large communities. Because of the fact that dissemination and exploitation of the project results contribute to the state of knowledge; as discussed above in technical factors, a criterion related with this issue is defined in the study.

In Technology Development Program of TTGV, innovation is categorized as new product development, new process development, product improvement and process improvement, which are the same with the expected targets of the projects submitted to TEYDEB. Moreover, university-industry collaboration is also mentioned in Technology Development Program which is one of the aimed influences of the Grand Programs of TEYDEB. Criteria related with innovation and cooperation is also described in the study.

As projects that contain high level of technical innovation are funded while product development projects are not, project selection criteria mentioned in ATP is not applicable to TEYDEB.

2.2 Analytic Hierarchy Process (AHP)

In this part, firstly the fundamentals of AHP are analyzed. Then, the methodologies concerning the interval judgments in AHP are mentioned.

2.2.1 The Basics of AHP

Analytic Hierarchy Process (AHP) developed by Saaty (1980) is a structured decision making method for analyzing discrete set of alternatives which are affected by multiple and conflicting criteria.

An important characteristic of AHP is the permission of inconsistency in the judgments of decision makers until the predefined tolerance level which makes the method more realistic and practical. Considering not only quantitative but also qualitative criteria is another significant property of AHP.

Since its development by Saaty (1980), AHP is used widely in many applications because of its simplicity and flexibility. Some surveys highlight the uses of AHP in specific fields. For example, Apostolou and Hassel (1993) point out the different uses of AHP in accounting research until that time. Steuer and Na (2003) review the multiple criteria decision making techniques applied to the area of finance such as capital budgeting and portfolio analysis and reveal that AHP is studied in 18 papers in this area. Liberatore and Nydick (2008) present the review of 50 articles about the implication of AHP to the issues of medical and health care and mention the importance of AHP as a supporting tool in that subject. Besides these area specific researches, some studies overview the applications of AHP in different fields and show the various approaches and areas in which AHP is implemented. Vaidya and Kumar (2006) analyze 150 application papers of AHP and categorize the papers based on the themes such as selection, evaluation, benefit-cost analysis and allocations, and based on areas of application such as manufacturing, engineering, political and education. They find out that AHP is mostly used in the themes of selection and evaluation and in the areas of engineering, personal and social categories. They also note that as the familiarity with the method increases, the number of studies that combine AHP with other techniques starts to increase. Ho (2008) mentions that combining AHP with other methods, called as integrated AHP, will result in a more realistic and promising decision than stand-alone AHP. He also reviews the articles about integrated AHP published from 1997 to 2006 and states that from the five tools that generally combined with AHP, mathematical programming (linear, integer, mixed integer and goal programming), quality function deployment (QFD), meta-heuristic, SWOT analysis and data envelopment analysis (DEA), AHP and goal programming and AHP and QFD are the two most commonly used integrated AHP approaches. Sipahi and Timor (2010) analyze 232 papers published in the period of 2005 – 2009 on the subject of AHP and conclude that applications of AHP increase exponentially especially on the areas of manufacturing, environmental management and agriculture field, power and energy industry, transportation industry, construction industry and healthcare.

In spite of the fact that AHP is studied theoretically by many researchers and executed extensively in practice, there are some criticisms about the method. The main criticisms of AHP, grouped in five, are based on rank reversal in which relative priorities of the alternatives change in case of an alternative or criterion is added or removed from the problem (e.g., Belton and Gear (1983), Barzilai and Golany (1994) and Perez et al. (2006)), inconsistent judgments and order preservation (e.g., Bana e Costa and Vansnick (2008)), the way priorities are derived and synthesized (e.g., Barzilai (1997)), nine point fundamental scale (e.g., Salo and Hamalainen,1997; Pöyhönen et al. ,1997) and pairwise comparisons axioms (e.g., Dyer, 1990). Saaty et al. (2009) survey all these criticisms and reply to them.

2.2.2 Interval Judgments in AHP

The pairwise comparison matrices providing the judgments of the decision makers are mostly used to estimate the relative weights of the criteria in a multiple criteria decision making environment. These matrices are conventionally constructed by the crisp comparison values of nine point scale of Saaty (1980). However; handling interval judgments becomes more realistic and feasible when the complexity and uncertainty of the problem in consideration increase (e.g., Bryson and Mobolurin, 1996; Wang et al., 2005b; Lan et al., 2009). Moreover, interval judgments are more rational due to the subjectivity of the human judgments (e.g., Entani et al., 2001; Wang et al., 2005a). Another point is that; interval judgments are easier to be utilized in case of group decision making (e.g., Islam et al., 1997; Arbel and Vargas, 2007).

Using interval judgments in order to compensate for the uncertainty of the decision makers in AHP is introduced by Saaty and Vargas (1987). In order to determine interval weights from interval comparison matrices that are assumed to be uniformly distributed, Saaty and Vargas (1987) propose a Monte Carlo simulation approach. In this study, they also noted the complexity of the proposed approach. Different simulation methods for interval AHP, (see e.g. Levary and Wan (1998) and Banuelas and Antony (2004)), are also mentioned in many studies. In the study of Cox (2007), the accuracy and computation time of the proposed complete enumeration approach is compared to simulation approaches and it is concluded that simulation methods do not provide any advantages over enumeration.

In Arbel (1989), the interval values obtained from the decision maker and normalization of precise weights are considered as the constraints of a linear programming (LP) model to obtain the feasible region of weight space. Then, vertices of the feasible region are used to obtain a preference order. Kress (1991) show that the method proposed by Arbel (1989) can not be used for inconsistent comparison matrices since feasible region is empty in that case. Salo and Hämäläinen (1992, 1995) improve Arbel's method for hierarchically structured problems by obtaining the minimum and maximum feasible values of each weight using LP techniques and synthesizing the interval weights for attaining global interval priorities. Haines (1998) develops a statistical method based on the approach of Arbel (1989) in which the distribution of weights, that is used to acquire some quantities of interest such as overall ranking of the alternatives, on the feasible region is analyzed. Two distributions, uniform distribution and distribution of random convex combinations, are thought to be interesting and appropriate; therefore they are investigated in detail.

Arbel and Vargas (1993) present two approaches. The first one is a simulation approach in which several comparison matrices obtained from randomly sampled interval judgments under the assumption that they are uniformly distributed are used to determine priority vectors by using eigenvalue method.

The average of the feasible ones obtained from this analysis is taken to get the final weights. In the second approach, an LP including the interval judgments as inequalities is solved to find out the feasible region.

Bryson and Mobourin (1996) propose an action learning process that achieves convergence systematically while synthesizing local interval weights starting from a completely ambiguous case with interval estimates, continuing with a tightened interval estimates and ending at point estimates.

Islam et al. (1997) suggest a lexicographic goal programming (LGP) method to attain precise priority weights from inconsistent interval comparison matrices. In the same study, an algorithm from which the most inconsistent judgment can be identified is also proposed. Wang (2006) shows that the method proposed by Islam et al. (1997) is erroneous since the priorities obtained from LGP method are different for the lower and upper triangular judgments of an interval comparison matrix even if the two judgments provide the same information on weights. Chandran et al. (2005) present a two stage LP approach to acquire precise priority weights originally from crisp comparison matrices or from interval or mixed matrices by taking the geometric mean of the interval judgments. In the first stage, inconsistency of the comparison matrix is minimized while in the second stage interval priority weights are determined by satisfying the minimum inconsistency found in the first step. Podinovski (2007) proposes a multicriterial symmetrical-lexicographic optimization approach to acquire precise priority weights from interval comparison matrices. Lan et al. (2009) present a precise priority weight generation approach from interval comparison matrices by solving LP models to determine a set of vertices of the feasible region of weights, taking the convex combination of the vertices to obtain the crisp comparison matrix and determining precise priority weight by the method of deviation degree. This method is suitable for consistent interval comparison matrices therefore; inconsistent ones should be transformed to consistent ones before applying the solution procedure. Conde and Perez (2010) propose a precise weight determination method from consistent or inconsistent interval comparison matrices based on an LP model. Their model searches for weight vectors that are close to satisfying all the bound requirements obtained from the decision maker simultaneously.

Sugihara and Tanaka (2001) state that no matter the pairwise comparison matrices are constructed as crisp or interval judgments, the priority weights should be assessed as intervals because of the uncertainty of the judgments. Motivated by this opinion, they propose an LP model in which interval priority weights are obtained from the crisp comparison matrices. In this study, additive normalization of precise weights is also extended for normalization of interval priority weights to remove the redundancy of the weight intervals. Entani et al. (2001) consider the interval weights determined from an interval comparison matrix as a center and radius and propose an approach in which center is found by the principal right eigenvector method and radius is obtained by interval regression analysis. Sugihara et al. (2004) present two models, the lower and upper approximation models that provide interval priority weights from interval comparison matrices. Due to the fact that the lower approximation model is based on the greatest lower bound, a feasible solution can not be determined from inconsistent comparison matrix by this method; however the upper approximation model based on least upper bounds always find out an optimal solution. In addition to the models, an interval preference relation is also mentioned to attain the partial order relation of interval weights. Wang et al. (2005a) propose a consistency test in order to realize whether the interval comparison matrix is consistent or not. For a consistent one, they suggest to use the model presented by Arbel (1989) with modifying the original model generating precise priorities to obtain interval priorities. For an inconsistent one, a non-linear programming model based on eigenvector method (EM) is recommended to get interval priorities. Moreover, the local interval weights obtained from the method can be aggregated to get the global priorities for hierarchies by solving the developed LP model. Finally, the global weights can be compared and the alternatives can be ranked by the preference ranking method. Wang and Elhag (2007) propose a goal programming method in which interval priorities are obtained from interval comparison matrices by solving a single LP model. In Arbel and Vargas (2007), Euclidian center approach is used to find out precise or interval priority weights from consistent interval comparison matrices. Wei et al. (2007) suggest a model evaluating the consistency of the interval comparison matrices based on Geometric Consistency Index (GCI) and present two mathematical programming models to identify the interval priority weights for the satisfactorily consistent matrices. Liu (2009) proposes an interval priority weight determination approach from interval comparison matrices in which an acceptably consistent interval comparison matrix is transformed into a crisp comparison matrix by the convex combination method from which precise priority weights are obtained by the geometric mean and finally these precise weights are aggregated to attain interval priority weights.

The multiplicative normalization is defined in the study of Barzilai (1997) as an alternative to conventional additive normalization that is used to facilitate the comparisons of the alternatives. Stam et al. (2003) investigate the characteristics of Multiplicative Analytic Hierarchy Process (MAHP) in which multiplicative normalization is utilized. Moreover, they point out the significant differences in terms of ratings, rankings and rank reversal of alternatives between the additive and multiplicative AHP by conducting two simulation experiments and conclude that MAHP is not only a theoretical approach but also presents a flexible preference framework appropriate for real life decisions. Wang et al. (2005b) propose two stage logarithmic goal programming method in which interval priority weights are obtained from interval comparison matrices by considering multiplicative normalization constraint. Firstly, inconsistency of the comparison matrix is minimized and then the minimum and the maximum interval values for the minimum inconsistency case are determined from two LP models. In addition, a non-linear LP model is proposed to aggregate the multiplicative local weights to get interval global weights. The preference ranking method is suggested to be used for comparing the interval global weights and ranking alternatives. Öztürk (2009) develops an LP model that minimizes total error and generates interval weights from interval comparison matrices based on multiplicative weights. Two variants, adding a second stage model minimizing the maximum error under the condition of minimum total error and changing the objective function as the minimum of the largest error, are also suggested as alternative approaches. Furthermore, a heuristic method instead of non-linear LP model presented by Wang et al. (2005b) for synthesizing interval local weights is also mentioned. The performances of the proposed methods and the synthesizing heuristic approach are observed for some different sizes of randomly generated comparison matrices and first variation of the presented method is found to be the best performer.

2.3 Methods for Sorting

The multicriteria sorting methods are developed for assigning a set of alternatives into predefined, homogeneous and ordinal groups by constructing a criteria aggregation model. A literature survey on this subject is provided by Zopounidis and Doumpos (2002).

The basic sorting methods can be divided into four classes according to the way the criteria models are formed (Doumpos and Zopounidis, 2002). Main approaches of these methods and studies related with them are explained below.

The first type of sorting methods is based on the outranking relation theory developed by Bernard Roy in 1960s. In this approach, the strength of the preference, namely the outranking degree, of an alternative over another one is evaluated by defining binary relations. The developed outranking relations are then used for allocating alternatives into groups by some heuristics. The most famous sorting method build on this methodology is the ELETRE-TRI method (Yu, 1992). The main drawback of this method is the requirement of several parameters from the decision makers, such as the reference profiles of the criteria, three different thresholds for each criterion and cut-off points. Some recent studies provide ways of improving this weakness. For example, Dias et al. (2002) present two approaches; the parameters are estimated from the assignment examples obtained from decision makers in the first approach while in the second approach the imprecise information provided by the decision makers are considered as the constraints of parameters that are used to identify the best and worst classes for each alternative. Some other studies suggesting the utilization of sample assignments determined from decision makers to estimate the parameters of ELECTRE TRI are Mousseau and Slowinski (1998), Lourenço and Costa (2004), Köksalan et al. (2009) and Dias et al. (2010) in which characteristic alternatives are defined by the decision maker through an interactive process. Moreover, the stability of the parameters used in ELECTRE TRI is also analzed by a stochastic multicriteria acceptability anaysis (SMAA) (Tervonen et al., 2009).

Another method based on outranking relation theory is the PROMETHEE method proposed by Brans and Vincke (1985) for mainly ranking purposes. However, there are some multicriteria sorting methods based on PROMETHEE (e.g. Araz and Özkarahan, 2007). For example, Doumpos and Zopounidis (2004a) develop a sorting method based on pairwise comparison of alternatives in the reference set and utilize pairwise judgments to construct a preference model in the framework of PROMETHEE. A detailed literature review of methodologies and applications of PROMETHEE is presented by Behzadian et al. (2010).

The second way of constructing criteria aggregation models are built on the utility function approach. In utility function, the preferences of decision makers are modeled as a utility/value function including all the quantitative and qualitative criteria by considering marginal utility functions. The assignments of the alternatives into preference related classes are based on the global utilities of alternatives. MAUT method proposed by Keeney and Raiffa (1993) is an example of the approaches originating from the utility theory. The main concerns in MAUT are the form of the marginal utility functions and criteria trade-offs which can be defined by the interactive contribution of the decision maker to the analysis as mentioned by Keeney and Raiffa (1993). The reviews of develeopments in MAUT are presented by Wallenius et al. (2008) and Bragge et al. (2010).

Requiring the specification of a set of technical and preferential information directly from decision maker is explained as the shortcoming of the methods since this process demands some amount of time and cognitive effort from the decision maker. The preference disaggregation approach is presented to overcome this shortcoming by analyzing the global judgments of the decision maker via a reference set, containing a set of previously decided alternatives or a subset of alternatives that need to be sorted or a set of artificial alternatives representing the decision makers judgments. A review of preference disaggregation methods and their applications is given by Jacquet-Lagreze and Siskos (2001). UTADIS (Zopounidis and Doumpos, 1999) is developed as a linear programming model for sorting problems based on the combination of utility function and preference disaggregation paradigm. In order to facilitate the application of UTADIS, different multi-criteria decision support systems are suggested, such as PREFDIS (Zopounidis and Doumpos, 2000) providing an interactive methodology to identify additive utility models by implementing UTADIS and its three variants, and FINCLAS (Zopounidis and Doumpos, 2001) for the specific purpose of financial classification problems. The effect of the parameters of UTADIS on the performance and stability of the acquired model is investigated by Doumpos and Zopounidis (2004b) by using Monte Carlo simulation. An interactive approach assigning alternatives into best and worst possible classes based on UTADIS is also proposed by Köksalan and Özpeynirci (2009).

In the third class, the methodology of constructing models from the examples forms the basis of some other methods such as the rough sets theory (Pawlak,

1982) in which the models are expressed by symbolic or sub-symbolic forms rather than functions. Some recent studies of this method are proposed by Greco et al. (2002), Dombi and Zsiros (2005) and Dembuzynski et al. (2009).

In the fourth class, there are some studies utilizing linear or quadratic discriminant functions as criteria aggregation models for nominal classification problems (Doumpos and Zopounidis, 2002).

2.4 Data Envelopment Analysis (DEA)

In this part, the basics of DEA and the main DEA models are explained in the first sub-section. Then, the developments in the implementation of DEA as a multiple criteria decision making model are given in the next part. Later, DEA and AHP applications and finally utilization of DEA as a sorting method are presented in the subsequent parts.

2.4.1 The Basic DEA Models

Data Envelopment Analysis (DEA), developed firstly by Charnes et al. (1978), is a data oriented mathematical model for measuring the performances of a set of entities, namely decision making units (DMUs), that are evaluated by multiple and common inputs and outputs. The model separates DMUs as efficient and inefficient ones based on their performances, which are the relative efficiencies obtained from the ratio of weighted sum of outputs to the weighted sum of inputs. The weights of the inputs and outputs are the variables and they are obtained by solving the model to find the best relative efficiency of each DMU individually. Therefore, the inputs and outputs in which DMU has better achievements are weighted higher than the others for each DMU.

In DEA, explicit form of the relation between inputs and outputs are not required. Moreover, it can deal with multiple inputs and outputs in any units provided that they are the same for every DMU under evaluation. This characteristic of DEA is called units invariance property. Therefore; the main advantages of DEA are demanding minimum amount of information from the decision maker and units invariance property.

The basic DEA model is introduced by Charnes, Cooper and Rhodes (1978), abbreviated as the CCR model. In the CCR model, the inputs and outputs are linearly scaled such that their ratio remains constant in the production frontier formed by the efficient DMUs.

Another DEA model is proposed by Banker, Charnes and Cooper (1984), abbreviated as the BBC model. The BCC model allows variable returns to scale in the production frontier by introducing a convexity constraint to the CCR model. The CCR and BCC models have two orientations; the first one is the input oriented model which aims to minimize inputs while satisfying at least the given output level and the second one is the output oriented model which aims to maximize outputs without requiring additional amount of inputs.

Both the CCR and BCC models measure the radial efficiency, the weak efficiency, and require a second linear model to find out the input excesses and output shortfalls. By the motivation of this limitation, the additive model in which input and output orientations are combined in a single model is proposed by Charnes et al. (1985). It considers input excesses and output shortfalls directly. This model also has the advantage of translation invariance that means translating the original input and output data do not result in a change in the relative efficiency. However, an efficiency measure as in the CCR and BCC models is not developed in this study. Later, Tone (2001) develops a slack based measure of efficiency for the additive model that has unit invariance and is monotone decreasing as the input and output slacks increase.

Beside the theoretical developments as explained above, DEA also has been applied to many real life problems in different areas such as banking, education, health care, manufacturing and management situations. Literature review about theoretical approaches and practical implementations of DEA is proposed by Seiford (1997), Gattoufi et al. (2004) and Cook and Seiford (2009).

2.4.2 Multiple Criteria Decision Making (MCDM) Methods and DEA

Multiple Criteria Decision Making (MCDM) deals with selecting the best alternative, ranking the alternatives from the best to the worst, classifying or sorting the alternatives into appropriate groups and description of the alternatives in the presence of multiple and conflicting criteria by providing a set of criteria aggregation approaches consistent with the preferences and judgments of the decision makers (DMs) (Doumpos and Zopounidis, 2002). DEA, as mentioned in the previous section, compares DMUs by inspecting their relative efficiencies in translating inputs into outputs.

Even if the philosophies and backgrounds of DEA and MCDM are different, both methods can contribute to other in solving problems (Stewart, 1996; Joro et al., 1998). Stewart (1996) mentions that while DEA can screen the alternatives in a MCDM problem, input and output weights of DEA can be bounded by using MCDM ideas and principles to avoid unrealistic and extreme cases. Moreover, Bouyssou (1999) explains the equivalence between efficiency in DEA and convex efficiency in MCDM. He also proposes some remarks on using DEA for the purposes of choosing an alternative or ranking alternatives.

The first attempt of using DEA as a MCDM tool is the interactive multi-objective LP method developing a set of alternative efficient points based on the production functions determined from DEA (Golany, 1988). Belton and Vickers (1993) propose a visual interactive decision support system by combining DEA and multi-attribute value function for the problems in which number of DMUs are limited. They state that it is easier to understand the developed method compared to DEA, even if DMs do not possess technical knowledge in the subject. Therefore, the acceptance of the results by DMs is declared to be enhanced. Furthermore, it is mentioned that the method provides the comfort of controlling and monitoring the analysis due to the interactive and visual characteristics. Joro et al. (1998) point out the similarities between DEA and the Reference Point model of Multiple Objective Linear Programming (MOLP) and explain some complementary characteristics of the methods. For example, they state that the efficient frontiers can be searched by varying the projection direction in DEA by using MOLP approach. Furthermore; DEA is mentioned to present new point of views to decision making in MOLP. Halme et al. (1999) propose a value efficiency analysis in order to include to preferences of DMs in DEA. In this method, the most preferred input-output vector is identified interactively and the value function estimated by the tangent cones at the most preferred vector is used to obtain the efficiencies of DMUs. Later, Joro et al. (2003) expanded the work of Halme et al. (1999) and develop an interactive approach to figure out value efficiency scores more precisely for the case of small number of DMUs.

When DEA is applied as a MCDM method, DMUs are replaced by alternatives, inputs with criteria to be minimized and outputs with criteria to be maximized (Bouyssou, 1999).

The two main shortcomings of DEA are the lack of discrimination power and inappropriate weight dispersion. The lack of discrimination power occurs when the number of DMUs is smaller compared to the total number of inputs and outputs. In this case, many DMUs become efficient. In the second shortcoming, some DMUs are found to be efficient due to the fact that some weights are extremely large or small which is practically unrealistic or undesirable (Angulo-Meza and Lins, 2002; Bal et al., 2010).

In order to solve the problem of lack of discrimination power, the method of cross-efficiency is proposed by Sexton et al. (1986). The main point in cross-efficiency is the consideration of peer-evaluation, the evaluation of each DMU according to the optimal weights of other DMUs, and self-evaluation, as in classic DEA, simultaneously. Obtaining the peer and self-evaluations, a cross-efficiency matrix including all the efficiency values of DMUs is constructed. The final efficiency value of each DMU is determined by taking the corresponding column average of the matrix. Besides averaging efficiencies, the median, minimum or variance of scores can also be used as stated in Adler et al. (2002). It is emphasized that while the efficiencies of the DMUs obtained from classical DEA model can not be comparable because of utilizing different weights for each DMU, cross-efficiencies of DMUs are more meaningful since each set of weight is equally important in finding out the final scores (Adler et al., 2002). Mavrotas and Trifillis (2006) present an NLP model synthesizing cross-efficiency DEA and multi-attribute value theory (MAVT) in which each DMU gets the most favorable weights and value functions in self-evaluation.

Besides, one of the main handicaps of the cross-efficiency method is the non-uniqueness of optimal weights in self-evaluation. Sexton et al. (1986) suggest adding secondary goals to the main goal of maximizing self-efficiency, like minimizing other DMUs cross-efficiency values, namely aggressive context, or maximizing all DMUs cross-efficiency, called benevolent context. Alternative secondary goals are also presented by Doyle and Green (1995). Another handicap of this method is favoring the DMUs that are close to each other and penalizing the ones that are different from the majority. Therefore, this approach is suitable for the problems in which there is no crowding in some parts of the frontier and the extreme DMUs are not desirable by the DMs (Tohumcu, 2007). In addition, providing only cross and self-efficiency scores without presenting a new set of weights consistent with new final scores is criticized by Li and Reeves (1999).

Another method suggested to avoid discrimination problem for the efficient DMUs is the super-efficiency method (Andersen and Petersen, 1993). In super-efficiency method, DEA model is solved again for efficient DMUs by removing the constrains that prevent efficient DMUs to have efficiency values greater than one. The shortcomings of this approach are the probability that the model can have an infeasible solution and favoring extreme DMUs that are different from the majority.

Furthermore, multiple criteria DEA approach is also proposed as an alternative approach to single criterion efficiency evaluation methods for the purpose of preventing lack of discrimination (Li and Reeves, 1999). The proposed multi objective linear programming model contains three objectives; the first one is the maximization of the evaluated DMU efficiency, same as the original DEA, the second one is the minimization of the maximum inefficiency and the final one is the minimization of the sum of inefficiencies of DMUs. It is also explained that this approach provides reasonable weights even if there is no information about the weight preferences. Bal et al. (2010) mention the difficulty of solving the multi-objective model proposed by Li and Reeves (1999) and convert that model into a simpler, single objective goal programming model for CCR and BCC types of DEA.

In the original DEA model, it is assumed that there is no a priori knowledge about the weights of the inputs and outputs and the only restriction is the non-negativity of weights. However, this weight flexibility can result in solutions that are in contradiction with the judgments of decision makers or solutions that are difficult or impossible to attain in real life (Dyson and Thannassoulis, 1988; Adler et al., 2002; Angulo-Meza and Lins, 2002). As a remedy, it is recommended to add restrictions on weights when the preferential information of decision makers is available. One approach based on this idea is assurance region presented by Thompson et al. (1986). In assurance region method, upper and lower bounds on the relative magnitude of weights are introduced to DEA as a set of weight restriction constraints. Due to addition of new constraints, the efficiencies obtained by this model are generally lower than the ones found from original DEA. Therefore, this approach also increases the discrimination power of DEA.

Another methodology aims at restricting weight distributions in DEA is developed by Dyson and Thannassoulis (1988). In this study, output weights are assumed as the resource amounts required per unit of output and lower bounds to those weights are obtained by finding the minimum resource required for a unit output in case of a single input situation. Moreover, Cook et al. (1990) implement numerical lower and upper bounds, namely absolute bounds, to input and output weights for evaluating the efficiency of highway maintenance patrols. Furthermore, Cook et al. (1992) propose different methods for restricting the input and output weights to prioritize the efficient DMUs further. These methods are; minimizing the range of the lower and upper bounds of the weights, maximizing the differences of the weights with ordinal relationships described by the DMs and setting absolute bounds to the weights. Besides, Wong and Beasley (1990) utilize proportions to constrain weight flexibility by providing lower and upper bounds to the ratio of an input/output measure to the overall input/output measure for each DMU. Bal et al. (2008) touch on the point of non-homogeneity of input and output weight dispersions and offer a multi-objective DEA model by adding the second objective of minimizing the coefficient of variation of weights, which is the ratio of the standard deviation of weights to the mean of weights. They conclude that the dispersion of weights is balanced and efficient DMUs are reduced in this model.

Moreover, it is also expressed that evaluating the DMUs by using common set of weights instead of the most promising ones is more fair and provides more information about the DMUs, especially for the ones that are found to be efficient in classical DEA method (Troutt, 1997; Despotis, 2002). Troutt (1997) proposes using common weights obtained by maximizing the efficiency of the DMU which has the minimum score in order to discriminate the DMUs from the group of efficient ones. Despotis (2002) develops global efficiency approach to find out DMUs that remain efficient under the evaluation of common weights. He propose a non pre-emptive goal programming model in order to estimate a group of global efficiencies under common weighting structure with two objectives; minimization of the mean deviation and maximum deviation between efficiency scores obtained from classical DEA and global efficiency scores. Calculating the global efficiencies for different weightings of two objectives, the final global efficiency is attained by averaging them. Liu and Peng (2008) also suggest an LP that derives common weights based on minimizing the sum of gaps between the efficiencies of DMUs and efficient frontier. In case of alternative solutions, they propose a second LP that search for the weights with the minimum total output weights and maximum total input weights by keeping the total gaps at minimum.

A review of the methods proposed for increasing discrimination power of DEA and adding weight restrictions to DEA is presented by Angula-Meza and Lins (2002) and Adler et al. (2002).

2.4.3 Applications Integrating DEA and AHP

As explained in the previous parts of this section, there has been extensive research about AHP and DEA. Moreover, combining AHP and DEA in order to develop methodologies that comprise advantages of both methods is receiving attention in recent years. When the studies integrating AHP and DEA are investigated, it is realized that there is diversity in the purpose of this combination. The studies are grouped according to the way of combining DEA and AHP in Table 2.

In the first group, AHP is used to obtain the assurance region constraints of DEA in order to introduce the preferences of decision makers to DEA. Zhu (1996) proposes to use pairwise comparison judgemens of AHP directly as assurance region constraints and implement this idea to evaluate the efficiencies of textile factories. Seifort and Zhu (1998) modify the additive DEA and present a weighted constant returns to scale additive DEA in which weights of the slacks are determined approximately from the pairwise comparisons of AHP provided by the DMs. They suggest using these judgements in two different ways; in the first approach the weights are used in the objective function showing the relative importances of slacks while in the second method ratios of weights are used as assurance region of DEA. Takamura and Tone (2003) suggest finding the relative improtance of criteria weights from AHP by taking the maximum and minimum ratios of the weights obtained from the judgments of different DMs. They use these ratios as the assurange region constraints of DEA to solve a site selection problem. Chiang and Che (2010) implement fuzzy AHP to get the relative importances of each evaluation criteria and use these ranges as assurange region in weight-restricted fuzzy DEA for ranking purpose.

Table 2: The studies according to the way of combining DEA and AHP

The purpose of using AHP and DEA together	**Related studies**
AHP is used to determine the assurance region in DEA	Zhu (1996), Seifort and Zhu (1998), Takamura and Tone (2003), Chiang and Che (2010)
AHP is used for incorporating value judgments in DEA	Lozano and Villa (2009)
AHP is used to obtain the missing values of DEA inputs and outputs	Saen et al. (2005)
AHP is used to reduce the number of inputs and outputs of DEA by aggregation	Korhonen et al. (2001), Cai and Wu (2001), Feng et al. (2004)
AHP is used to identify relevant DEA inputs and outputs	Shang and Sueyoshi (1995), Yang and Kuo (2003), Yoo (2003), Ertay et al. (2006), Korpela et al. (2007), Azadeh et al. (2008), Wang et al. (2010), Mohajeri and Amin (2010), Lee et al. (2010)
DEA is used to derive pairwise comparison values for AHP	Sinuany-Stern et al. (2000), Ma and Li (2008), Tseng and Lee (2009)
DEA is used to generate relative importance vectors from AHP pairwise comparison matrices	Ramanathan (2006), Wang et al. (2008a), Wang et al. (2008b), Wang and Chin (2009), Ramanathan and Ramanathan (2010)
AHP and DEA used separately and then the results are combined	Wang et al. (2008c), Sueyoshi et al. (2009), Tseng et al. (2009)

In the second group, the judgments of DMs attained from AHP are used in DEA to obtain solutions that match with the priorities of the decision makers better. It should be noted that using AHP results as assurance region of DEA can also be added to this group but due to the methodological differences it is mentioned as another group. Lozano and Villa (2009) develop two multi-objective DEA approaches for target setting. The first method is an interactive approach in which DM identifies the inputs and outputs desired to be improved, no change is allowed and worsening can be allowed. Then, AHP is utilized for finding the weights of the improved and worsened inputs and outputs. Finally, DEA model maximizing the weighted improvements of all inputs and outputs by considering the AHP weights as the objective function coefficients is solved. The process is repeated until the DM is satisfied with the result. The second method is a lexicographic approach based on establishing priority levels and defining inputs and outputs in each priority level. AHP is solved for each priority level and relative importance of inputs and outputs are taken as the objective function coefficients of DEA. Finally, DEA seeking the maximum improvement along the weight vector in each priority level is solved.

In the third group, the missing values of DEA inputs and outputs are suggested to be determined from AHP. Saen et al. (2005) deal with obtaining relative efficiencies of slightly non-homogeneous DMUs that means some of the inputs and outputs are not common to all units. They recommend interpolating missing factors by measuring the potential of DMU by AHP and determining efficiencies by chance-constrained DEA.

In the next group, the aim of AHP and DEA integration is to reduce the number of inputs and outputs used in DEA by AHP. Korhonen et al. (2001) define sets of indicators explaining the criteria for measuring academic research performance at universities and research institutes. These indicators are aggregated to represent a scale for each criterion by using importance weights found from AHP. Lastly, the input and output data are evaluated by value efficiency analysis. Cai and Wu (2001) and Feng et al. (2004) develop a similar approach and identify several indicators, determine their relative importances by AHP, aggregate them to obtain synthetic indicator(s) and use DEA to evaluate financial position of enterprices in an industry and university R&D performance respectively.

The other group of studies focuses on the utilization of AHP to identify DEA inputs and outputs. Shang and Sueyoshi (1995) use an accounting procedure to get the inputs, utilize AHP and simulation model to examine qualitative and quantitative outputs respectively and evaluate manufacturing systems by DEA considering the inputs and outputs obtained from previous analysis. Yang and Kuo (2003) and Ertay et al. (2006) apply AHP to collect qualitative performance data and solve the layout design problem by DEA considering qualitative and quantitative data. Yoo (2003) deals with measuring the efficiencies of total quality management activities in Korean companies by DEA and uses AHP to determine the input and output data of DEA. Korpela et al. (2007) apply AHP to find out preferences for service related criteria and obtain the efficiencies by taking the results of AHP analysis as output data and cost related factors as input data for warehouse operator selection problem. Azadeh et al. (2008) utilize simulation model and AHP to identify quantitative and qualitative data for the DEA model presenting the best alternatives for railway systems improvement and optimization. Wang et al. (2010) use fuzzy AHP to gather the performance related data and solve DEA using this data for the problem of bank loan decision for small and medium enterprises. Mohajeri et al. (2010) employ AHP to find the local priorities and use these priorities as the multiple outputs and assume the same amount of input for all DMUs in a DEA model to identify the optimal railway station site location. Lee et al. (2010) obtain the relative importance of the evaluation criteria by fuzzy AHP and normalize the quantitative data by synthesizing with relative weight. This normalized data is divided into two as inputs and outputs, and finally output oriented CCR model is solved to evaluate the relative efficiency of the R&D performance in the national hydrogen energy technology development.

In the next group of researches, pairwise comparison values for AHP are derived from DEA. Sinuany-Stern et al. (2000) apply DEA for two DMUs at a time until all the DMUs are evaluated. These results are then entered as the values of pairwise comparison matrices from which full ranking of DMUs are obtained by AHP. Tseng et al. (2009) follow the same approach for investigating human resource practices and their influence on organizational performance. Ma and Li (2008) use methodological approach of AHP and DEA to propose a ranking method based on pairwise comparisons. They modify DEA to provide reasonable upper and lower bounds of preference ratios and then DM is asked to specify fuzzy preferences by referring the ranges obtained from DEA. Lastly, a goal programming method similar to fuzzy AHP is solved.

The other group of studies is related with the generation of relative importance vectors from the pairwise comparison matrices of AHP by DEA. Integrating DEA and AHP for this purpose is firstly attempted by Ramanathan (2006) with the DEAHP method in which each row of the comparison matrix is viewed as a DMU, each column as an output and a dummy input of 1 is added for each DMU. Aggregating local weights obtained from DEAHP model to find out final weights is also analyzed. Wang et al. (2008a) discuss the main drawbacks of DEAHP and propose a DEA model, namely DEA/AR model, with assurance region for deriving weights from comparison matrices. Wang et al. (2008b) propose a linear program based on the variable weighting property of DEA to generate the most favorable weights for criteria and alternatives from a pairwise comparison matrix. Wang and Chin (2009) present two DEA models that derive best local priorities from a perfectly consistent or inconsistent pairwise comparison matrix and extend the approach when there are more than one judgment matrices in case of group decision making. Ramanathan and Ramanathan (2010) discuss that the judgments in AHP provided by the DMs in verbal scale should be considered as qualitative information rather than quantitative information. Based on this methodology, they develop DEA models that consider both qualitative and quantitative factors to derive weights.

In the last group, DEA and AHP are used separately to attain some information and the results obtained from these methods are utilized in the final analysis. Wang et al. (2008c) apply AHP to realize the relative importance of criteria for the bridge risk assessment problem. The scores of the alternatives in each criterion are expressed as linguistic terms and values of these terms are obtained from DEA. Finally, the alternatives are evaluated by simple additive weighting providing the overall risk scores. Sueyoshi et al. (2009) utilize AHP to analyze qualitative information and DEA for quantitative data for internal audit prioritization in a rental car company. The overall risk of each alternative is obtained by adding the AHP and DEA results after normalizing. Tseng et al. (2009) define indicators of business performance in a manufacturing company and determine the weights of indicators by AHP. Performance score of quantitative and qualitative data are obtained from DEA and fuzzy approach respectively. After normalizing the data, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is utilized to achieve the final ranking.

2.4.4 DEA Based Sorting Methods

Most of the studies mentioned in the previous part are used for ranking purposes, such as the ones proposed for increasing discrimination and restricting weights of DEA. However, Bouyssou (1999) explains some weaknesses of DEA utilization as a ranking method. Firstly, he mentions the arbitrariness of the ranking of convex dominated alternatives when using different types of DEA models. He further shows the problem of ranking convex efficient alternatives before convex dominated ones, which is not so realistic in some cases. Moreover, the additional deficiency of super-efficiency model is expressed as rank reversal in case of adding an inefficient alternative that is close to a top ranked one. He states that different rankings are obtained by cross-efficiency model when the aggressive and benevolent types of models are used. Furthermore, it is discussed that these models do not ensure the single set of optimal weights which also causes different rankings. Another problem related with cross-efficiency model is the non-monotonicity property indicated by an example in which the ranking of an alternative, from a set of alternatives that are equally ranked, is improved when the score in one criterion is decreased.

Besides, the number of methods focusing on sorting is quite limited in DEA. DEA based sorting methods are shortly explained below.

Johnson and Zhu (2003) deal with candidate selection problem in two-stages by grouping the candidates into four classes that are prioritized. In the first stage, efficient candidates obtained from the BCC model are further differentiated by calculating the benchmarking shares. In the second stage, efficient DMUs after the implementation of the CCR model are subjected to stratification DEA in which sequence of CCR models are run by removing the efficient DMUs in each run until no DMU remains for evaluation. In this step, all the efficient DMUs are separated into efficiency levels. Then the performances of DMUs in each level are found out by context-dependent DEA according to the level just below the evaluated DMUs'. Finally, all the DMUs are assigned to the corresponding groups based on benchmarking share and context-dependent scores. A similar approach is also proposed by Ulucan and Atıcı (2010) to evaluate the efficiencies of World Bank supported Social Risk Mitigation projects. In this study, DMUs are separated into efficiency levels by using context-dependent DEA as in the previous study. Later, target values only for some inputs or outputs of inefficient DMUs are specified by measure-specific DEA because it is expressed that improving all inputs and outputs proportionally may not be possible.

Chen et al. (2008) propose a model similar to DEA in order to estimate the linear additive utility function by aggragating ordinal and cardinal criteria. Furthermore, they also suggest three types of sorting algorithms based on the manipulation of the lower bounds on criteria weights. In the first algortihm, the lower bounds on weights are fixed at the lowest level so that the largest possible efficienct set and minimum number of classes are constructed while in the second second one lower bounds on weights are gradually increased to minimize the number of alternatives in a group and maximize the group count. The third one is an interactive method allowing decision maker to adjust the size of the group and count of the groups. These approaches are applied to an inventory classification case study.

Madlener et al. (2009) indicate that assigning DMUs to ordered efficiency categories provides more robust and confident results since it is less affected by the changes in data or preferences of decision makers in comparison to efficiency measures. They compare the efficiency values obtained from DEA and the groups that DMUs are placed to by IRIS/ELECTRE-TRI approach for evaluating the performances of biogas plants. They consider the ratios between the outputs and inputs of DEA as the evaluation criteria of IRIS/ELECTRE-TRI. They state the complementary characteristics of the two methods and the improvements in the DEA results in respect to incorporate the preferences of DMs and to eliminate impractical weightings.

In another study, a new approach that is built on the concepts of preference disaggregation analysis is developed by Sowlati et al. (2005). They mention that it is easier for DMs to provide the samples of really good and bad DMUs and their priority scores compared to specify the weights of the factors. Based on this idea, they present a type of BCC model, which compares real DMUs with the samples and assigns priority scores to real DMUs while satisfying the priorities of the samples defined by DMs. The model is checked for the problem of information system project prioritization by setting 18 sample projects to evaluate 41 real projects. Not affecting the priorities of previously analyzed projects while evaluating new projects, introducing managerial judgments about relative importance of weights by some constraints, eliminating unrealistic weight assignment and requiring less process time compared to AHP are described as the advantages of the model.

CHAPTER 3

THEORETICAL BACKGROUND

In this chapter, the background information about the methodologies used in this thesis is provided. Firstly, AHP approach is explained. Then, DEA, some variants of DEA and UTADIS methods which are the cornerstones of the proposed methods are described.

3.1 Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is one of the multiple criteria decision making methods used extensively for dealing with complex decisions since proposed by Saaty (1980). AHP provides a structured technique starting from constructing a hierarchy by decomposing the problem into simpler sub-problems, making comparisons of the hierarchy elements pairwisely and concluding obtaining priorities of the hierarchy by combining the judgments determined by comparisons.

One of the main advantages of AHP is handling both subjective and objective evaluation measures which are frequently encountered in decision making environments.

The first step of AHP is the arrangement of the linear hierarchy. The overall goal of the problem is placed at the top level. Then, the group of factors that have influence on the defined goal is assigned to the second level of the hierarchy. Finally, the lowest level of the hierarchy includes all the available alternatives. An illustrative four level hierarchy is provided in Figure 5. The goal and criteria can be further broken down into sub-goals and sub-criteria to examine the problem in more detail. As the components of the hierarchy depend on the problem statement and the knowledge, background, aims, etc. of the participants of the process; the hierarchy differs not only from problem to problem but also from practitioner to practitioner.

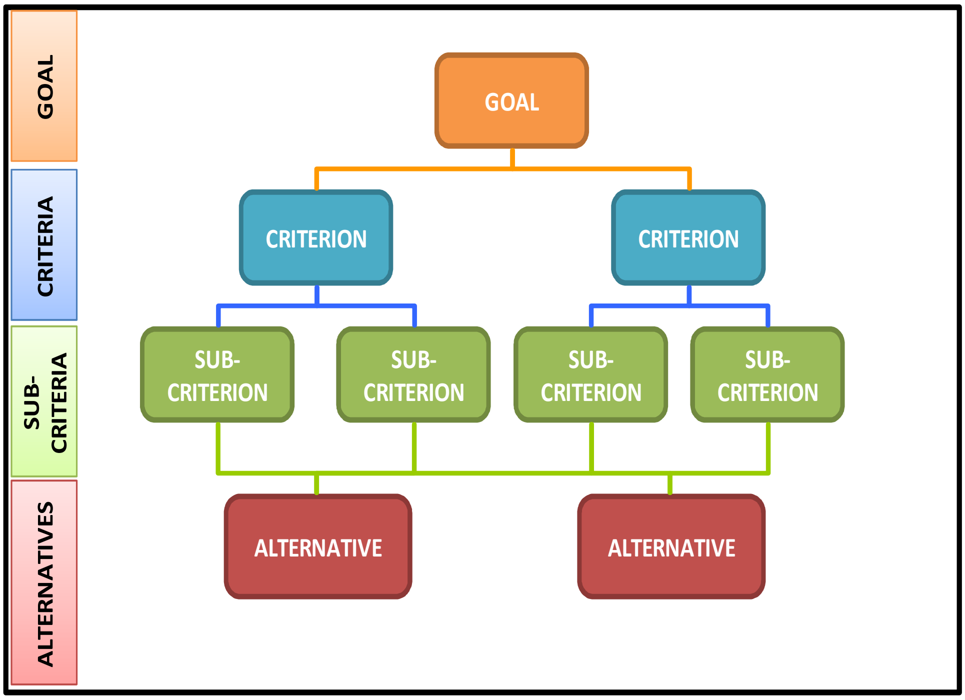

Figure 5: An illustrative four level AHP hierarchy

The second step of AHP is establishing priorities, namely relative weights, of the criteria and alternatives. The pairwise comparisons of the elements in each level of the hierarchy are accomplished on the basis of each one level higher hierarchy element. In this manner, the relative dominance of one element over another in the same level with respect to a common attribute is determined. A representation of a pairwise comparison matrix for a level including n elements is given in Figure 6. A pairwise matrix has the following properties:

i. $a_{ij} = 1 \quad for\ i = j$

ii. $a_{ij} = \dfrac{1}{a_{ji}} \quad for\ i \neq j$

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix}$$

Figure 6: A representation of a pairwise comparison matrix

While comparing the elements of the hierarch to construct the pairwise comparison matrix, Saaty (1980) proposes a nine point scale, The Fundamental Scale, as presented in Table 3. Intermediate values of 2, 4, 6 and 8 can also be used when compromise is required. Pairwise comparison matrices are determined for the goal, criteria and sub-criteria that are mentioned in the hierarchy.

Table 3: The Fundamental Scale proposed by Saaty (1980)

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

The third step of AHP is the calculation of local priority weights, that are the relative weights of the elements within the same level with respect to the one level higher hierarch element by using the Eigenvalue Method. Furthermore, the consistency of the matrix is also found since it is not possible to obtain full consistency in the real life due to the fact that matrices are formed by the judgments of the decision makers. If the matrix is not found to be consistent, it should be revised by the decision maker until a consistent one is obtained.

In the last step of AHP, local priority weights that are obtained from consistent comparison matrices are synthesized to obtain global priorities of the alternatives. This is accomplished by multiplying the local priorities of the alternatives with each local priority of the criterion and summing the obtained values for all criteria.

3.2 Data Envelopment Analysis

In this section, DEA related methods, namely the basic CCR model, the cross-efficiency method and assurance region approach as a weight restriction method in DEA, which are concentrated in this thesis, are described in detail.

3.2.1 DEA CCR Model

As mentioned in the second chapter, there is no assumption about the functional form of the technology utilized by DMUs in DEA. The efficiencies of DMUs are evaluated by only requiring the corresponding input and output data and identifying the efficient frontier constructed by the most preferred DMUs.

The input-oriented basic DEA model, CCR model (Charnes et al., 1978), is considered in this study. Let n be the number of DMUs and m and s be the number of common inputs and outputs. The CCR model for DMU_o is given below:

$$Maximize \quad \theta_o = \frac{\sum_{i=1}^{s} u_i y_{io}}{\sum_{j=1}^{m} v_j x_{jo}}$$

s.to

$$\frac{\sum_{i=1}^{s} u_i y_{ik}}{\sum_{j=1}^{m} v_j x_{jk}} \leq 1 \quad k = 1, \ldots, n$$

$$v_j \geq 0 \quad j = 1, \ldots, m$$

$$u_i \geq 0 \quad i = 1, \ldots, s$$

where x_{jk} denote the value of input j for DMU k, y_{ik} denote the value of output i for the same DMU, v_j and u_i denote the weights of input j and output i, respectively.

The objective of the model is to determine the optimum weights for inputs and outputs while maximizing the ratio of the weighted outputs to weighted inputs for DMU_o and restricting this ratio to be less than or equal to 1 for all DMUs. Therefore, all the DMUs receive an efficiency score between 0 and 1 and the efficient ones take the value of 1.

Since this model is nonlinear, it is converted into a linear model by setting the weighted inputs of DMU_o to a constant value. Finally, the model presented below is obtained.

$$Maximize \quad \theta_o = \sum_{i=1}^{s} u_i y_{io}$$

s.to

$$\sum_{j=1}^{m} v_j x_{jo} = 1$$

$$\sum_{i=1}^{s} u_i y_{ik} - \sum_{j=1}^{m} v_j x_{jk} \leq 0 \quad k = 1, \ldots, n$$

$$v_j \geq 0 \quad j = 1, \ldots, m$$

$$u_i \geq 0 \quad i = 1, \ldots, s$$

This model is solved for each DMU to determine the best efficiency values under the most favorable weighting scheme.

3.2.2 Cross-Efficiency Approach

Cross-efficiency method (Sexton et al., 1986) considers two types of evaluations; the first one is called self-evaluation which is accomplished by solving the original DEA model for each DMU and the second one is the peer-evaluation, also named cross-evaluation, which is the assessment of a DMU by the optimal weights of another DMU. The cross-efficiency of DMU_p based on the optimal weights of DMU_o, v_{jo} and u_{io}, can be calculated from the expression given below.

$$\theta_{po} = \frac{\sum_{r=1}^{s} u_{io} y_{ip}}{\sum_{j=1}^{m} v_{jo} x_{jp}} \tag{3.1}$$

Then, cross-efficiency approach can be formulated as below.

$$\begin{aligned}
&\textit{Maximize} \quad \theta_{oo} = \sum_{i=1}^{s} u_{io} y_{io} \\
&s.to \\
&\quad \sum_{j=1}^{m} v_{jo} x_{jo} = 1 \\
&\quad \sum_{i=1}^{s} u_{io} y_{ik} - \sum_{j=1}^{m} v_{jo} x_{jk} \leq 0 \quad k = 1, \ldots, n \\
&\quad v_j \geq 0 \quad j = 1, \ldots, m \\
&\quad u_i \geq 0 \quad i = 1, \ldots, s
\end{aligned}$$

After calculating all the efficiency values by self-evaluation solving the model above and peer-evaluation utilizing (3.1), the final efficiency of each DMU is obtained by averaging the values as provided below.

$$\theta_p = \frac{\sum_{k=1}^{n} \theta_{pk}}{n} \tag{3.2}$$

In order to overcome the main drawback of this method, non-uniqueness of the weights of the cross-efficiency model, a secondary objective is suggested to be added to this model. Additional objectives are proposed according to two different views by Sexton et al. (1986). In the first one, the aggressive one, the objective of the model is improved by searching for a set of optimal weights not only maximizing the self-efficiency but also minimizing the averages of the cross-efficiencies belonging to other DMUs. In the second approach, the benevolent one, the objective function aims to maximize the self-efficiency and the averages of the cross-efficiencies of other DMUs.

3.2.3 Assurance Region Approach

The methodology of the assurance region (Thompson et al., 1986) is to tighten the ranges of the weights that a DMU can take by introducing the preferences of decision makers on weights. Since the possible weight space is reduced, the efficiency values attained from DEA model using assurance region are also reduced.

Assurance regions can be defined for only inputs or outputs as given below:

$$
\begin{aligned}
LB_{jt} &\leq \frac{v_j}{v_t} \leq UB_{jt} \\
LB_{iz} &\leq \frac{u_i}{u_z} \leq UB_{iz}
\end{aligned}
\tag{3.3}
$$

where LB_{jt} / UB_{jt} and LB_{iz}/ UB_{iz} are the lower/upper bounds on the weight ratios of inputs j & t and outputs i & z respectively.

Moreover, some bounds can also be set for inputs and outputs. These additional constraints provide a single type of weighting and facilitate the absolute comparison of input and output weights. This relation can be represented by the inequality given below:

$$LB_{ji} \leq \frac{v_j}{u_i} \leq UB_{ji} \tag{3.4}$$

where LB_{ji} / UB_{ji} are the lower/upper bounds on input j and output i.

3.3 UTADIS

UTADIS, which is the combination of utility function-based framework with the preference disaggregation paradigm, is a sorting method with the aim of partitioning a set of l alternatives, $a_1, \ldots, a_l$, into predefined, preference related, homogeneous q classes, $C_1, \ldots, C_q$, by developing a criteria aggregation model (Doumpos and Zopounidis, 2002). General structure of UTADIS can be seen in Figure 7.

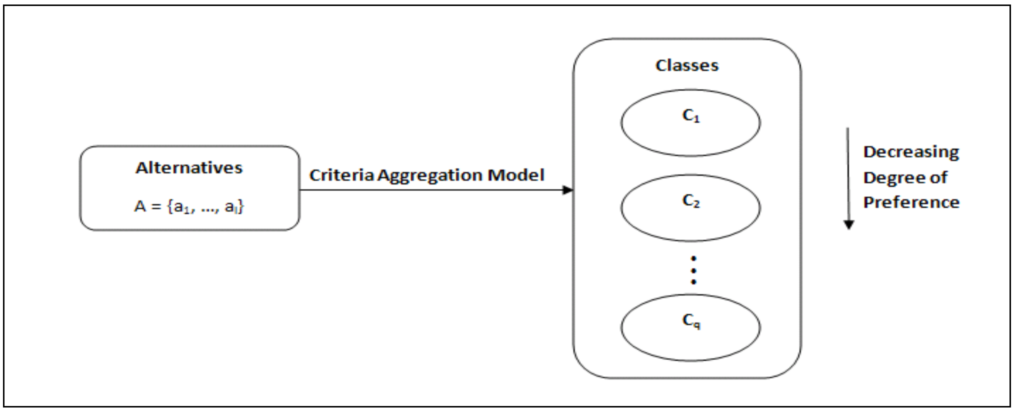

Figure 7: General structure of UTADIS

The criteria aggregation model is assumed to be an additive utility function composed of piecewise linear marginal utilities of n criteria affecting the performance of the alternatives. The global utility of alternative j that is in the range of [0, 1] can be obtained as given below:

$$U[g(a_j)] = \sum_{i=1}^{n} u_i[g_i(a_j)] \tag{3.5}$$

where $U[g(a_j)]$ is the global utility of alternative j, $g(a_j) = [g_1(a_j), \ldots, g_n(a_j)]$ is the vector of evaluation criteria of alternative j and $u_i[g_i(a_j)]$ is the marginal utility function of alternative j on the criterion i.

The marginal utility function of each criterion is divided into $b_i - 1$ subintervals as shown below in Figure 8, $[g_i^p, g_i^{p+1}]$ for $p = 1, \ldots, b_i - 1$, and each subinterval p is assumed to have a utility value of $w_{ip} = u_i(g_i^{p+1}) - u_i(g_i^p) \geq 0$ for $1 \leq p \leq b_i - 1$ in criterion i. These subintervals are defined by using some heuristic approaches. Two different heuristic for this purpose, HEUR 1 and HEUR 2, are suggested by Doumpos and Zopounidis (2002). In HEUR 1, the range of each criterion is divided into a number of equal subintervals in a way that each subinterval includes at least an alternative. In HEUR 2, the number of basic variables of the model is taken into consideration while defining the subintervals in order to decrease the number of redundant utility values for each subinterval. In this approach, the number of alternatives in each subinterval is increased by one at each iteration if the total number of subintervals in not less than the total number of basic variables. The marginal utility of alternative j for the criterion i with $g_i^{r_{ji}} \leq g_i(a_j) < g_i^{r_{ji}+1}$ for $1 \leq r_{ji} \leq b_i$ is obtained by linear interpolation between $u_i[g_i^{r_{ji}}]$ and $u_i[g_i^{r_{ji}+1}]$ as given below.

$$u_i[g_i(a_j)] = \sum_{p=1}^{r_{ji}-1} w_{ip} + \frac{g_i(a_j) - g_i^{r_{ji}}}{g_i^{r_{ji}+1} - g_i^{r_{ji}}} w_{ir_{ji}} \tag{3.6}$$

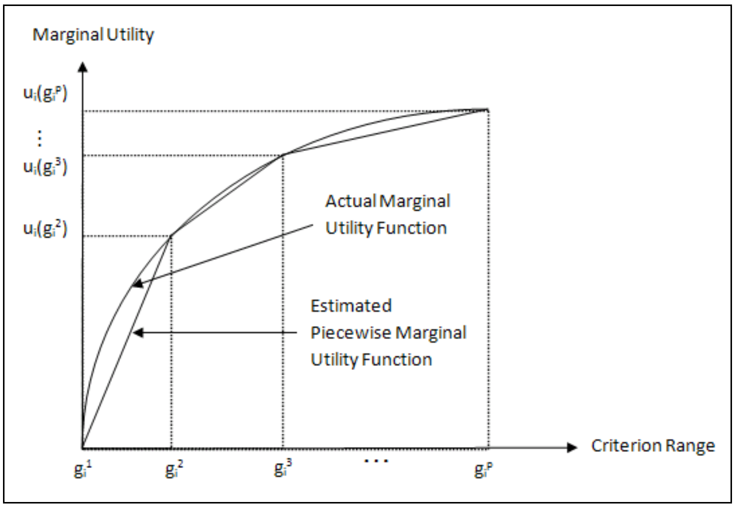

Figure 8: Piecewise linear marginal utility function of criterion i

The model estimates the piecewise linear marginal utility functions and utility thresholds that are the lower bounds separating the preference related q classes in which C_1 and C_q represent the group including the alternatives with best and worst performances, respectively, based on a reference set containing m_k number of alternatives that are already assigned to class k by the decision maker. The classification of the alternatives is accomplished via comparing the global utilities with the estimated thresholds as follows.

$$\begin{aligned} &U[g(a_j)] \geq u_1 \quad \Rightarrow \quad a_j \in C_1 \\ &u_k \leq U[g(a_j)] < u_{k-1} \quad \Rightarrow \quad a_j \in C_k \quad k = 2, \ldots, q-1 \\ &U[g(a_j)] < u_{q-1} \quad \Rightarrow \quad a_j \in C_q \end{aligned} \tag{3.7}$$

The objective of the model is to minimize the weighted sum of classification errors of the reference set. The classification error is defined as below.

$$\begin{aligned} &\sigma_j^+ = \max\{0, u_k - U[g(a_j)]\} \quad \forall a_j \in C_k \\ &\sigma_j^- = \max\{0, U[g(a_j)] - u_{k-1}\} \quad \forall a_j \in C_k \end{aligned} \tag{3.8}$$

The linear model estimating the utility functions and thresholds is presented below:

$$\text{Minimize} \quad \sum_{k=1}^{q} \left[\frac{\sum_{\forall a_j \in C_k} (\sigma_j^+ + \sigma_j^-)}{m_k} \right]$$

s.to

$$U[g(a_j)] - u_1 + \sigma_j^+ \geq \delta_1, \quad \forall a_j \in C_1$$

$$\left. \begin{array}{l} U[g(a_j)] - u_k + \sigma_j^+ \geq \delta_1 \\ U[g(a_j)] - u_{k-1} - \sigma_j^- \leq -\delta_2 \end{array} \right\}, \quad \forall a_j \in C_k \quad k = 2, \ldots, q-1$$

$$U[g(a_j)] - u_{q-1} - \sigma_j^- \leq -\delta_2, \quad \forall a_j \in C_q$$

$$\sum_{i=1}^{n} \sum_{p=1}^{b_i - 1} w_{ip} = 1$$

$$u_k - u_{k+1} \geq s, \quad \forall k = 1, \ldots, q-2$$

$$w_{ip}, \sigma_j^+, \sigma_j^- \geq 0, \quad \forall i = 1, \ldots, n, \quad p = 1, \ldots, b_i - 1, \quad j = 1, \ldots, m$$

where δ_1, δ_2 and s are user defined small positive constants with the property of $s > \delta_1, \delta_2 \geq 0$. Due to the fact that this linear program has multiple optimal solutions in most of the cases, a post optimality analysis is required to check the degeneracy and stability of the optimal solution. Two different post optimality approaches based on the distances between the global utilities of the alternatives and estimated utility thresholds are presented below (Doumpos and Zopounidis, 2002).

In the first post optimality method, POST OPT 1, the aim is to maximize the minimum difference between the global utilities of the correctly classified alternatives from the utility thresholds. The minimum difference is defined as follows:

$$d = \min \left\{ \begin{array}{l} \min\limits_{\forall a_j \in C_1 \cap COR} \{U[g(a_j)] - u_1\} \\ \min\limits_{\forall a_j \in C_k \cap COR} \{u_{k-1} - U[g(a_j)], U[g(a_j)] - u_k\} \\ \min\limits_{\forall a_j \in C_q \cap COR} \{u_{q-1} - U[g(a_j)]\} \end{array} \right\} \quad k = 2, \ldots, q-1 \qquad (3.9)$$

where COR is the set of alternatives classified correctly according to UTADIS model. Then, POST OPT 1 is given below:

$$
\begin{aligned}
&\textit{Maximize } d \\
&s.to \\
&U[g(a_j)] - u_1 - d \geq \delta_1 \quad \forall a_j \in C_1 \cap COR \\
&\left.\begin{aligned} &U[g(a_j)] - u_k - d \geq \delta_1 \\ &U[g(a_j)] - u_{k-1} + d \leq -\delta_2 \end{aligned}\right\} \quad \forall a_j \in C_k \cap COR,\ k = 2, \ldots, q-1 \\
&U[g(a_j)] - u_{q-1} + d \leq -\delta_2 \quad \forall a_j \in C_q \cap COR \\
&U[g(a_j)] - u_1 + \sigma_j^+ \geq \delta_1 \quad \forall a_j \in C_1 \cap MIS \\
&\left.\begin{aligned} &U[g(a_j)] - u_k + \sigma_j^+ \geq \delta_1 \\ &U[g(a_j)] - u_{k-1} - \sigma_j^- \leq -\delta_2 \end{aligned}\right\} \quad \forall a_j \in C_k \cap MIS,\ k = 2, \ldots, q-1 \\
&U[g(a_j)] - u_{q-1} - \sigma_j^- \leq -\delta_2 \quad \forall a_j \in C_q \cap MIS \\
&\sum_{i=1}^{n} \sum_{p=1}^{b_i - 1} w_{ip} = 1 \\
&u_k - u_{k+1} \geq s \quad k = 1, \ldots, q-2 \\
&\sum_{k=1}^{q} \left[\frac{\sum_{\forall a_j \in C_k \cap MIS} (\sigma_j^+ + \sigma_j^-)}{m_k} \right] \leq (1+z) f^* \\
&\sigma_j^+, \sigma_j^- \geq 0 \quad \forall a_j \in MIS \\
&d \geq 0 \\
&w_{ip} \geq 0 \quad \forall i = 1, \ldots, n, \forall p = 1, \ldots, b_i - 1
\end{aligned}
$$

where MIS is the set of misclassified alternatives according to UTADIS model, f^* is the optimal value of the UTADIS model and z is a small portion of f^* considered in order to investigate the near optimal solutions.

The other post optimality approach, POST OPT 2, is based on the maximization of the total differences between the correctly classified alternatives from the utility thresholds. The differences used in this method are found from the equations given below.

$$
\begin{aligned}
&d_j^+ = \max\{0, U[g(a_j)] - u_k\} \quad \forall a_j \in C_k, k = 1, \ldots, q-1 \\
&d_j^- = \max\{0, u_{k-1} - U[g(a_j)]\} \quad \forall a_j \in C_k, k = 2, \ldots, q
\end{aligned} \tag{3.10}
$$

This second post optimality model, POST OPT 2, is presented below.

$$Maximize \sum_{k=1}^{q} \left(\frac{\sum_{\forall a_j \in C_k \cap COR} (d_j^+ + d_j^-)}{m_k} \right)$$

s.to

$$U[g(a_j)] - u_1 - d_j^+ = \delta_1 \quad \forall a_j \in C_1 \cap COR$$

$$\left. \begin{array}{l} U[g(a_j)] - u_k - d_j^+ = \delta_1 \\ U[g(a_j)] - u_{k-1} + d_j^- = -\delta_2 \end{array} \right\} \forall a_j \in C_k \cap COR, k = 2, \ldots, q-1$$

$$U[g(a_j)] - u_{q-1} + d_j^- = -\delta_2 \quad \forall a_j \in C_q \cap COR$$

$$U[g(a_j)] - u_1 + \sigma_j^+ \geq \delta_1 \quad \forall a_j \in C_1 \cap MIS$$

$$\left. \begin{array}{l} U[g(a_j)] - u_k + \sigma_j^+ \geq \delta_1 \\ U[g(a_j)] - u_{k-1} - \sigma_j^- \leq -\delta_2 \end{array} \right\} \forall a_j \in C_k \cap MIS, k = 2, \ldots, q-1$$

$$U[g(a_j)] - u_{q-1} - \sigma_j^- \leq -\delta_2 \quad \forall a_j \in C_q \cap MIS$$

$$\sum_{i=1}^{n} \sum_{p=1}^{b_i - 1} w_{ip} = 1$$

$$u_k - u_{k+1} \geq s \quad k = 1, \ldots, q-2$$

$$\left. \begin{array}{l} d_j^+ \leq u_{k-1} - u_k \\ d_j^- \leq u_{k-1} - u_k \end{array} \right\} \forall a_j \in C_k \cap COR, k = 2, \ldots, q-1$$

$$\sum_{k=1}^{q} \left[\frac{\sum_{\forall a_j \in C_k \cap MIS} (\sigma_j^+ + \sigma_j^-)}{m_k} \right] \leq (1+z) f^*$$

$$\sigma_j^+, \sigma_j^- \geq 0 \quad \forall a_j \in MIS, \quad d_j^+, d_j^- \geq 0 \quad \forall a_j \in COR$$

$$w_{ip} \geq 0 \quad \forall i = 1, \ldots, n, \forall p = 1, \ldots, b_i - 1$$

CHAPTER 4

R&D PROJECT SELECTION CRITERIA

In this chapter, the R&D project selection criteria composed for Industrial R&D Grant Program of TEYDEB is described and hierarchical structure and independence of the criteria are explained in detail.

4.1 Determination of the R&D Project Selection Criteria and Their Explanations

In order to determine the R&D project selection criteria appropriate for Industrial R&D Projects Grant Program of TEYDEB, firstly a detailed literature survey is performed on this topic as explained in Chapter 2. In the review, it is realized that the criteria used in the previous researches can not be used directly since the purposes and the expected influences of the Grant Programs are quite different from the purposes of R&D activities carried out in companies which are mentioned in most of the previous studies.

Completing the review on the subject, purposes and aimed influences of the Grant Programs are studied because they have a high impact on the project selection criteria of the program. The principal aims and expected influences of Industrial R&D Projects Grant Program are;

- Increasing the technical competence and state of knowledge at the national level,
- Formation of R&D culture and structure in more firms,
- Acquiring project and resource management skills,
- Providing the permanency and continuity of obtained knowledge by the way of documentation,
- Constituting cooperation between universities and national industrial institutions,

- Increasing the qualified employment,
- Decreasing inter-regional differences in terms of development,
- Getting financial success,
- Obtaining new domestic and foreign cooperation and expansion opportunities.

Later, Project Proposal Evaluation Report which is prepared by the independent referees after visiting the company is examined extensively due to the fact that this report identifies the viewpoint of TEYDEB during proposal evaluation. As explained before in Chapter 1, the report contains some phrases and the referees select the ones that they think the proposal suits. During the study, it is seen that the report contains some repetitions measuring the same criterion. Therefore, the evaluation criteria mentioned in this study are obtained by analyzing what the phrases ask for and why it is asked one by one. In that way, repetitions are tried to be eliminated. Furthermore, the criteria obtained in this study are classified into three groups in order to keep the structure of the evaluation criteria considered in the study close to "three dimensions" of the currently used TEYDEB criteria.

After obtaining the project selection criteria as described above, they are discussed in a meeting with 11 TEYDEB experts including the author of this thesis. The experts with different and high level educational backgrounds, especially more experienced in TEYDEB and in international support programs in which TÜBİTAK is a participant are chosen from all 5 different technology groups. The criteria revised by the suggestions of the TEYDEB experts are than analyzed by five TEYDEB managers in another meeting. Each of the three managers are the members of one of the five technology group committees, one manager is the member of two technology group committees and the other one is the vice-president of TEYDEB. The managers belong to the decision makers of TEYDEB because they have a vote in the technology group committee meetings in which the decision of acceptance or rejection is made. Finally, project selection criteria represented in Figure 9 are formed by taking the advices of managers into account. As it can be seen, the criteria are structured as a five level hierarchy with the goal at the top level.

An important property of the developed criteria hierarchy is that the criteria determined for selecting R&D projects are qualitative rather than quantitative. The reason of this property is the fact that projects proposed to TEYDEB are not started during the application and evaluation phase and that is why quantitative data related with the projects are not available at that phase. In order to convert the qualitative criteria into quantitative criteria, a ten-point scale is developed for each criterion including the definition of that criterion and guiding the point allocation. The criteria with the corresponding ten-point scale are provided in Table 4.

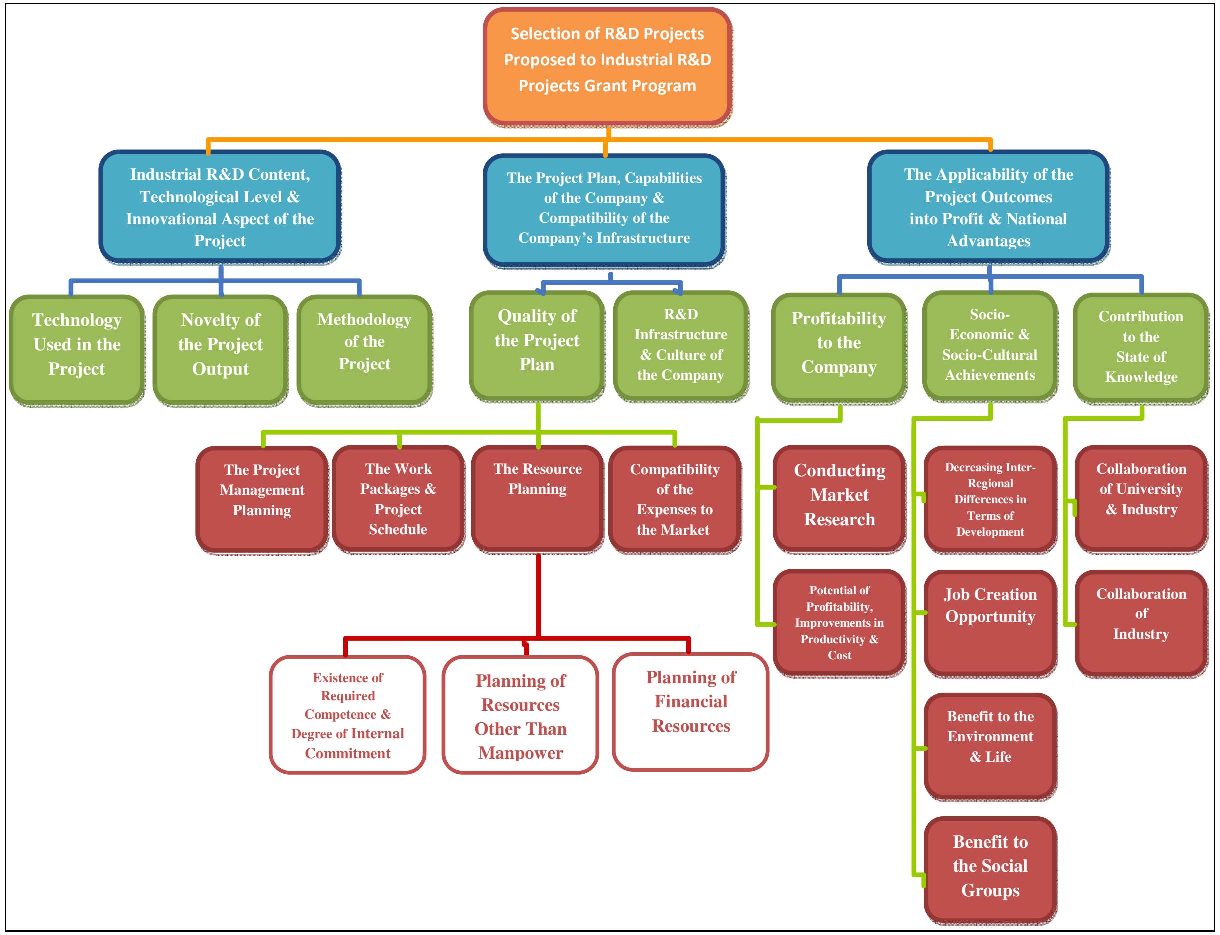

Figure 9: The project selection criteria hierarchy of the study

Table 4: The project selection criteria and corresponding point allocation guide

EVALUATION CRITERIA	POINT ALLOCATION GUIDE
1. Industrial R&D Content , Technological Level & Innovational Aspect of the Project	
1.1 Technology Used in the Project	10 – Today's headmost technology or a critical technology for the development of a(n) industry/product/process that includes many problems which are not solved yet is utilized. 7.5 – A contemporary technology presently finding acceptance and widespread usage is utilized to design and integrate many inputs and modules within a multidisciplinary approach. 5 – A contemporary technology presently finding acceptance and widespread usage with known solutions to the problems from the studies carried out so far but also including problems that need to be solved during application is utilized. 0 – An old technology that does not require research, having known solutions to the problems from the studies and applications carried out so far and having a widespread usage is utilized.
1.2 Novelty of the Project Output	10 – A new product/process for the international market is developed in the project. Or, an improved product/process that has advantages over the similar ones available in the international market is developed in the project. 5 –A new product/process for the national market is developed in the project. Or, an improved product/process that has advantages over the similar ones available in the national market is developed in the project. 2.5 – A product/process that has no advantages over the similar ones available in the national market but new for the company is developed. Or, a product/process that has no advantages over the similar ones available in the national market but ones available in the company is developed. 0 – The project output has no advantages over the similar ones available in the market.

Table 4 Continued: The project selection criteria and corresponding point allocation guide

EVALUATION CRITERIA	POINT ALLOCATION GUIDE
1.3 Methodology of the Project	10 – A systematic method appropriate to the target of the project and a work plan adequate to the method is defined. Technically risky works and planning for these risks (such as alternative solution ways) are determined. 5 – A systematic method appropriate to the target of the project and a work plan adequate to the method is defined. However, there is no planning for technical risks. 0 – A method appropriate to the target of the project is not defined. The work plan is not adequate to the project and there is no planning for technical risks.
2. The Project Plan, Capabilities of the Company & Compatibility of the Company's Infrastructure	
2.1 Quality of the Project Plan	
2.1.1 The Project Management Planning	10 – A comprehensive and adequate project management plan including project coordination, data flow and decision making processes are prepared. 5 – An adequate project management plan is prepared but it has some minor deficiencies. 0 – A project management plan is not prepared.
2.1.2 The Work Packages & Project Schedule	10 – Activities are allocated to the work packages according to their connections adequately and project schedule is prepared appropriately to the work packages. 5 – Activities are allocated to the work packages according to their connections adequately; however project schedule includes some inappropriateness. 0 – Work packages are not prepared adequately and project schedule is not realistic.

Table 4 Continued: The project selection criteria and corresponding point allocation guide

EVALUATION CRITERIA	POINT ALLOCATION GUIDE
2.1.3 The Resource Planning	
2.1.3.1 Existence of Required Competence & Degree of Internal Commitment	10 – Work sharing and manpower planning are done adequately according to the characteristics of the project team. The quality and the quantity of the project team are sufficient to carry out the project. All or near all R&D activities of the project are performed by the project team. 5 – Work sharing and manpower planning are done adequately according to the characteristics of the project team. The quality or quantity of the project team is not sufficient to carry out all fields of the project, however this need is planned to be filled appropriately (by employment or service procurement). The substantial part of the project is performed by the project team. 2.5 – The quality and the quantity of the project team is sufficient to carry out the project, however work sharing and manpower planning are not done adequately. A part of the R&D activities is not assigned to project staff. 0 – The quality of the project team is not sufficient to carry out the project and this need is not planned to be filled. Or, the project team does not contribute, alternatively, has a very limited contribution to the R&D activities of the project.
2.1.3.2 Planning of Resources Other Than Manpower	10 – All resources other than manpower (like equipment, publication and material) required for R&D activities are planned to be supplied. Their quality and quantity are adequate to carry out the project. 5 – All resources other than manpower required for R&D activities are planned to be supplied, however the quality and/or quantity of some of them are not adequate. 0 – Planning of the resources other than manpower required for R&D activities has significant deficiencies (such as inadequacy in quality or quantity).

Table 4 Continued: The project selection criteria and corresponding point allocation guide

EVALUATION CRITERIA	POINT ALLOCATION GUIDE
2.1.3.3 Planning of Financial Resources	10 – The company makes an adequate plan for the required financial resources. 5 – The company makes a plan for the required financial resources to execute the project; however the plan has some deficiencies. 0 – The company does not make a plan for the required financial resources to execute the project. Project can not be performed as it is planned due to the deficiencies in financial planning.
2.1.4 Compatibility of the Expenses to the Market	10 – All the expense items are compatible with the current market values. 5 – Some of the expense items are not compatible with the current market values. 0 – The expense items are not compatible with the current market values.
2.2 R&D Infrastructure and Culture of the Company	10 – R&D activities are mentioned in the strategy of the company. The company has R&D department with staff and hardware only belonging to this department. Monitoring, evaluation and development of R&D and innovation processes are performed systematically. The organization providing permanence and continuity of knowledge and experience is available in the company. R&D activities are supported by the management. 5 – A company strategy for R&D and innovation activities and R&D department are not available; however adequate staff and hardware to carry out R&D activities are present in the company. Monitoring, evaluating and development of R&D and innovation processes are performed and knowledge and experience acquired become permanent but not systematically. R&D activities are supported by the management. 0 – A company strategy for R&D and innovation activities and R&D staff and hardware are not present in the company. Monitoring, evaluating and development of R&D and innovation processes are not performed and R&D activities are not supported by the management.

Table 4 Continued: The project selection criteria and corresponding point allocation guide

EVALUATION CRITERIA	POINT ALLOCATION GUIDE
3. The Applicability of the Project Outcomes into Economical Profit & National Advantages	
3.1 Profitability to the Company	
3.1.1 Conducting Market Research	10 – A detailed research and plan for the target market and finding a market for the project output are made. The project output has the potential to find a new market or an international market. 5 – A research and plan for the target market and finding a market for the project output are made. The project output has the potential to find a national market. 0 – A market research and planning to find a market is not made.
3.1.2 Potential of Profitability, Improvements in Productivity and Cost	10 – The project output is expected to provide high profitability with respect to the current position of the company. Or, the project output is expected to provide high improvements in productivity or costs with respect to the current position of the company. 5 – The project output is expected to provide the profitability as the same as the current position of the company. Or, the project output is expected to provide improvements in productivity or costs. 0 – The project output is not expected to provide profitability. Or, the project output is not expected to provide improvements in productivity or costs.

Table 4 Continued: The project selection criteria and corresponding point allocation guide

EVALUATION CRITERIA	POINT ALLOCATION GUIDE
3.2 Socio-Economic & Socio-Cultural Achievements	
3.2.1 Decreasing Inter-Regional Differences in Terms of Development	10 – The project causes a decrease in inter-regional differences in terms of development and this is one of the aims of the project. 5 – The project can cause a decrease in inter-regional differences in terms of development. 0 – The project does not have an impact on decreasing inter-regional differences in terms of development.
3.2.2 Job Creation Opportunity	10 – The project creates job opportunities by providing new avenues for industry. 5 – The project has the probability of job creation. 0 – The project does not have an impact on job creation.
3.2.3 Benefit to Environment & Life	10 – The project provides the sustainability of the natural and limited resources by using them effectively. Or, the project or project output has a direct and positive impact on environment and life. 5 – The project or project output can have a positive impact on environment and life, however a plan related with this is not made. 0 – The project or project output has a negative impact on environment and life.
3.2.4. Benefit to Social Groups	10 – The project output has a positive impact on socio-cultural life. 5 – The project output can have a positive impact on socio-cultural life. 0 – The project output has a negative impact on socio-cultural life.

Table 4 Continued: The project selection criteria and corresponding point allocation guide

EVALUATION CRITERIA	POINT ALLOCATION GUIDE
3.3 Contribution to the State of Knowledge	
3.3.1 Collaboration of University and Industry	10 – During the collaboration of university and industry, flow of information takes place inter partes (such as post graduate studies of the project team members related with the project subject, contributions of the project to the academic/scientific researches, undergoing technical training from universities) and the knowledge and capabilities are planned to be internalized. The project has the potential to provide the continuity of university and industry collaboration. 5 – During the collaboration of university and industry, flow of information takes place unidirectional (from university to industry or from industry to university) and the knowledge and capabilities are planned to be internalized. 0 – The project does not have an impact on university and industry collaboration. Or, the flow of information does not take place during the university and industry collaboration.
3.3.2 Collaboration of Industry	10 – During the collaboration of industry, flow of information takes place inter partes (such as the potential of building up technology based companies, conveying information to supplier companies, undergoing technical training from industries) and the knowledge and capabilities are planned to be internalized. The project has the potential to provide the continuity of industry collaboration. 5 – During the collaboration of industry, flow of information takes place unidirectional (from a company to the other one) and the knowledge and capabilities are planned to be internalized. Or, the project causes an improvement in the knowledge and capability of the company and has a triggering effect for new R&D projects. 0 – The project does not have an impact on industry collaboration. Or, the flow of information does not take place during the industry collaboration.

The basic structure of the R&D project selection criteria used throughout the study is tried to be kept similar to the one currently used in TEYDEB. In order to satisfy this, the three dimensions of project evaluation criteria considered in TEYDEB are selected as the three main criteria of the study.

The first main criterion is the industrial R&D content, technological level and innovational aspect of the project which focuses on three sub-criteria, technology to be used in the project, novelty of the project output and methodology to be employed during the project work. The first sub-criterion under this main criterion considers state-of-the-art, competitiveness, ambiguity and complexity of the technology to be used in the project. Innovation level of the product or process that will be developed is examined in the second sub-criterion. Lastly; systematic design of the phases of the project including appropriateness of the method and work plan, technical risks and evidence of scientific feasibility are mentioned in the third sub-criterion.

The second main criterion is related to the project plan, capabilities of the company and adequacy of the company's infrastructure which is divided into two sub-criteria; the quality of the project plan and R&D infrastructure and culture of the company. The quality of the project plan is investigated in four parts in detail that are the project management planning, the work packages and project schedule, the resource planning and closeness of the proposed costs to actual prices. The planning of project leadership and coordination, flow of information and decision making processes, legal considerations, management risks such as alternative courses of action are among the basic considerations of the project management planning. The work packages and project schedule identifies if the operations are grouped into work packages according to their relations and dependencies together with their durations and timing. In the resource planning; adequacy of the project team, contributions of the team to the R&D activities of the project and work sharing according to the qualifications of the team members are analyzed in the sub-criterion of existence of required competence and degree of internal commitment. The sub-criterion of planning of resources other than manpower examines the planning of the resources except manpower required for the activities and their quality and quantity adequacy; while the sub-criterion of planning of financial resources checks the arrangement of the financial resources necessary to execute the project. In the final part of the quality of the project plan, making market research to obtain the prices of the resources is viewed in the compatibility of the expenses to the market sub-criterion. Besides, R&D infrastructure and culture of the company deals with the R&D strategy of the company, R&D approach of the management, availability of the R&D staff and hardware and knowledge institutionalization within the company.

The third main criterion which is the possibility of transformation of the project output into economic and social benefits is analyzed in three parts, profitability to the company, socio-economic and socio-cultural achievements and contribution to the state of knowledge. Profitability to the company considers two aspects; making market research and the potential of finding a market in the sub-criterion of conducting market research and the possible economic advantages of the project to the company in the sub-criterion of the potential of profitability, improvements in productivity and cost. Socio-economic and socio-cultural achievements are the decreases in inter-regional differences in terms of development, job creation opportunity, benefit to environment and life and benefit to social groups such as elderly or handicapped people. In the sub-criterion of contribution to the state of knowledge, continuity of collaboration of university and/or industry, flow of information between parties taking place in the collaboration and internalization of the knowledge and capabilities are examined.

Independence of the obtained criteria are tried to be clarified by going through some examples in the next part.

4.2 Independence of the R&D Project Selection Criteria

It should be noted that there are some directly correlated criteria in the currently used Project Proposal Evaluation Report. They are eliminated for this study in order to have a set of independent R&D project selection criteria. The indirect dependencies are not taken into account since it is thought unusual to have completely independent criteria and it is also complicated to identify indirect dependencies. As an example of direct dependency in the currently used evaluation criteria set, the correlation between the two questions, namely what novelty level the project output can have and which innovation category the project study falls into, can be indicated. Novelty level can be one or more of the following four types; internationally innovative, nationally innovative, innovative only for the company and a routine project without innovation. Likewise, innovation category is divided into three groups; a new product/process, an improved product/process and a product/process without any advantages over the existing ones, which is analyzed separately from the novelty level. On the other hand, it has to be clear that if a product/process is innovative for the international market, then it must be a completely new or an improved product/process. Additionally, if the product/process is a routine matter without innovation, then it could not have any advantages over the existing ones. Therefore, these two properties are associated in the criteria of novelty of the project output.

Another example for these associations is that the factors of work sharing, quality of the project team and degree of internal commitment of the project team to the project are evaluated separately in the Project Proposal Evaluation Report. However; the quality of the project team greatly affects the degree of internal commitment since a team that does not have the required qualifications to carry out the project is not expected to have sufficient commitment. Important R&D activities have to be assigned to the qualified organizations out of the company in order to accomplish the project which results in a decrease in internal commitment of the project team. In addition to these, work sharing should be done according to the quality of the team. As a conclusion, these factors are evaluated together in the criteria of existence of required competence and degree of internal commitment.

Furthermore; having a company strategy to carry out R&D activities, having staff and hardware adequate to perform R&D activities and institutionalization of knowledge and capabilities obtained during R&D activities are considered individually in the evaluation criteria of the current Project Proposal Evaluation Report. However; it is expected that if the company has a strategy related with R&D activities, than institutionalization of knowledge and capabilities obtained during R&D activities is done systematically and adequate staff and hardware is available in the company. Also; to institutionalize the knowledge and capabilities, adequate staff and hardware should be present in the company. As a result, the criterion of R&D infrastructure and culture of the company including all these three factors is defined.

As a last example, flow of information obtained during R&D activities and collaboration of university and/or industry are considered separately in the Project Proposal Evaluation Report. The collaboration of university and/or industry is evaluated due to the fact that flow of information and ultimate increase in the state of knowledge at the national level can be achieved by the way of collaboration. Because of this dependence, these factors are associated in the criteria of collaboration of university and industry and collaboration of industry.

Besides, some of the criteria presented in Table 4 and explained in the previous part may still seem to be dependent on each other. For example, methodology of the project and the work packages and project schedule can be thought to dependent on each other. In the first criterion, the method planned to be used in the project and compatibility of the work plan to the method are evaluated while allocation of work packages considering their connections and the schedule of the work packages are investigated in the second one. Selection of the method appropriately cannot make sure that the work packages are formed and scheduled properly. Similarly, planning and scheduling the work packages by taking their connections into account cannot point out the appropriateness of the methodology and consideration of technical risks. These criteria and their independence can be seen in Figure 10.

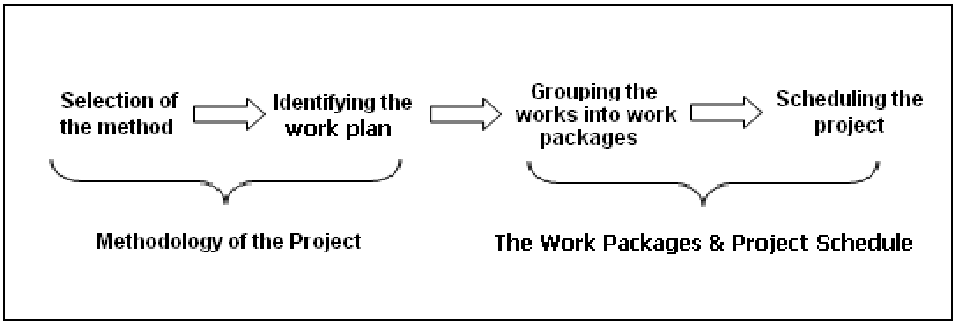

Figure 10: The independence of the criteria of methodology of the project and the work packages and project schedule

The criteria of technology used in the project and novelty of the project output can also seem to be interrelated. However, using today's headmost technology does not mean that a new or improved product/process is developed in the project. A basic research project with the aim of attaining knowledge can be planned to be performed using the headmost technology without any tangible results. Alternatively, a new product/process can be enhanced by utilizing an existing technology in a different way.

Furthermore; novelty of the project output and conducting market research are also independent from each other. A product that is new for the international/national market does not surely find an international/national market. In order to find an international/national market, many studies have to be performed; such as a detailed market research, analysis of customer expectations and a price policy suitable to the target market. Similarly, the company may not know about the novelty of the project but the referee evaluating the project can know the market and can decide about the novelty of the product. Therefore, the company may not conduct a market research but the project outcome can be innovative for the market.

Novelty of the project output and potential of profitability, improvements in productivity and cost can be realized to be dependent. Although the innovation can be made to enhance the competitive power of the company, it can not ensure the profitability of productivity and cost improvements. Profitability depends highly on the products of the competitors. Also, the novelty of the output can be a safer operation condition or removal of some dangerous or harmful inputs which has nothing related with the profitability or can result in cost increases in direct contradiction. Similarly, profitability of the company can be increased with a product that has no advanced technical properties over the existing ones in the market but with a price advantage. Therefore, these two criteria are not dependent directly.

Existence of required competence and degree of internal commitment, and R&D infrastructure and culture of the company may seem to be interrelated. It should be emphasized that the criterion of R&D infrastructure and culture of the company considers the R&D capability and structuring of the company generally. However, the criterion of existence of required competence and degree of internal commitment focuses on the staff capability and commitment in terms of project extent. The company can have an R&D culture, infrastructure, staff and hardware generally, but the project team may not have the required competence to perform the project. Also, the technical quality and the quantity of the team can be adequate for the project but the team may not able to plan R&D activities systematically.

Lastly, conducting market research and potential of profitability, improvements in productivity and cost also do not have direct dependence. Making a research about the market and finding a market do not mean that the project output is expected to provide high profitability. In addition to that, having a potential to find an international/national market is not enough to have an economic profit. Factors such as pricing, production costs and sales volumes are quite important to provide profitability. Also, it cannot be said that it is not possible to obtain profitability without investigating the market. The company proposing the project may not search the market but the referee can realize the profitability potential of the project.

CHAPTER 5

THE PROPOSED MODELS

In this chapter, the methods that are proposed in this thesis are explained extensively. In the first sub-section, the interval AHP approaches applied to evaluate the interval weights of the R&D project selection criteria mentioned in Chapter 4 are analyzed. In the next sub-section, the models which are based on DEA approach and proposed for solving sorting problems are proposed.

5.1 The AHP Model

As mentioned in the previous chapter, the criteria of the problem are constructed as a detailed five level linear hierarchy with the goal of R&D project selection at the top level as represented in Figure 9. Additionally, independence of the criteria is taken into consideration while identifying the project selection criteria. Because of eliminating the direct dependence between the developed criteria, AHP is chosen to be used to obtain the priorities of the criteria in the study.

It should be noted that the AHP is applied to figure out the relative priorities of the criteria rather than finding out the priorities of the proposed projects.

Selecting R&D projects that involve high risks and uncertainties, project proposals from different technology areas, group decision making environment, qualitative and subjective criteria due to fact that proposals are not started during the application and evaluation phase cause the utilization of interval priorities more realistic rather than crisp judgments in AHP. Therefore, an interval priority weight generation method from interval comparison matrices is decided to be used in the study. Moreover, due to the subjectivity of judgments and impracticability of proposing a consistent comparison matrix, a method that is suitable for inconsistent comparison matrices is judged to be applied. Another point that should be mentioned is the preference of mathematical modeling approaches because of their simple and fast solutions as required in real life problems.

During the literature review on the subject of interval judgments as explained in the second chapter, it is seen that only four methods meet these requirements simultaneously. These are the upper approximation method of Sugihara et al. (2004), goal programming method of Wang and Elhag (2007), two stage goal programming method of Wang et al. (2005b) and the methods proposed by Öztürk (2009). While the first two models consider additive normalization of interval priorities, the remaining approaches are based on multiplicative normalization. In the study of Öztürk (2009), the performances of their methods are compared with these three approaches and it is found out that the first variation of the proposed methods is the best performer. Based on this conclusion, the first variation of the method developed by Öztürk (2009) is decided as an appropriate approach for this problem. In addition, goal programming method of Wang and Elhag (2007) is chosen as the second approach in order to analyze the solutions of multiplicatively and additively normalized methods. Furthermore, goal programming method (Wang and Elhag, 2007) mostly presents better results than the upper approximation method (Sugihara et al., 2004).

As a result, two different interval priority weight generation methods are used in the study; goal programming method proposed by Wang and Elhag (2007) and the first variation of the methods proposed by Öztürk (2009). The main reasons for this choice are the determination of interval weights from interval comparison matrices, applicability of the methods for both consistent and inconsistent comparison matrices, practicability of both methods which requires the solution of a single or two linear models for the first and the second one respectively. The basic difference between two methods is that, additive normalization of the weights is performed in the first one while the second one requires multiplicative normalization as mentioned before. The results obtained from these methods are compared to each other and then the one with a better performance according to the considered measures is chosen as the final result. Moreover, a complete ranking of the priorities of the criteria is carried out for the best result in order to realize the relative importance of the criteria.

5.1.1 Construction of the Pairwise Comparison Matrices

The linear hierarchy of R&D project selection criteria is obtained after the meetings with 11 TEYDEB experts and 5 TEYDEB managers sequentially in order to determine the criteria that are in accordance with the viewpoint of TEYDEB. After that, a questionnaire that is given in Appendix B is conducted to the 5 managers of TEYDEB, who are the decision makers, in order to acquire the all pairwise comparison matrices required for establishing the relative weights of the criteria. 9 point scale of Saaty (1980) without intermediate values as presented in Table 3 is used in the questionnaire to facilitate the judgments of the decision makers.

These comparison matrices represent the importance of one element over another one which is in the same level with respect to a common attribute. For example, the first question of the questionnaire asks which sub-criterion is more important for selecting R&D projects, the right or the left one, and how much more important than the other one. If the decision maker decides that the left one is more important, then he/she chooses a box from the set of boxes whose numbering increases from right to left with the number that indicates the level of importance and vice versa for the right one. The questionnaire includes the same type of questions for all pairs of criteria at the same level of the hierarchy on the basis of one level higher hierarch elements. Each pair of criteria is considered once in the questionnaire and reciprocal of the value is used for the reverse comparison of the same pair in order to reduce the number of questions by eliminating the ones whose answers are already known.

All managers answer the questions separately to avoid influencing each other by the guidance of the author of the thesis. At the end, the highest and the lowest crisp judgments provided by the managers are taken as the interval judgments of the pairwise comparison matrices. Finally, nine interval comparison matrices corresponding to nine set of questions in the questionnaire respectively are obtained as presented in Appendix C.

5.1.2 Determination of the Criteria and Sub-Criteria Priority Weight Intervals

After obtaining the interval pairwise comparison matrices, interval priority weights of the criteria and sub-criteria are calculated by using two different methods as explained in the next sub-sections in detail.

5.1.2.1 Goal Programming Method Proposed by Wang and Elhag (2007)

As explained before, exact judgments and crisp comparison matrices are handled in the conventional AHP. However, utilization of interval judgments and interval comparison matrices become easier and more realistic when the uncertainty and complexity of the decision problem enhance as in the real life problems. A normalized interval priority weight generation method from a consistent or inconsistent interval comparison matrix is the goal programming method presented by Wang and Elhag (2007). The advantage of the goal programming method is the determination of interval priority weights by solving a single linear model for each matrix.

The interval comparison matrix provided by the decision maker can be represented as follows.

$$A = \begin{bmatrix} 1 & [l_{12}, u_{12}] & \cdots & [l_{1n}, u_{1n}] \\ [l_{21}, u_{21}] & 1 & \cdots & [l_{2n}, u_{2n}] \\ \vdots & \vdots & \vdots & \vdots \\ [l_{n1}, u_{n1}] & [l_{n2}, u_{n2}] & \cdots & 1 \end{bmatrix}$$

This matrix can be read as criterion i is at least as important as l_{ij} times and at most as important as u_{ij} times of criterion j where lower and upper bounds, l_{ij} and u_{ij}, are non-negative real numbers with the properties of $l_{ij} \le u_{ij}$, $l_{ij} = 1/u_{ji}$ and $u_{ij} = 1/l_{ji}$ for all $i, j = 1, ..., n; i \neq j$. This matrix is separated into two crisp comparison matrices of A_L and A_U as shown below, where $A_L \le A \le A_U$.

$$A_L = \begin{bmatrix} 1 & l_{12} & \cdots & l_{1n} \\ l_{21} & 1 & \cdots & l_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ l_{n1} & l_{n2} & \cdots & 1 \end{bmatrix} \qquad A_U = \begin{bmatrix} 1 & u_{12} & \cdots & u_{1n} \\ u_{21} & 1 & \cdots & u_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ u_{n1} & u_{n2} & \cdots & 1 \end{bmatrix}$$

An interval weight vector, $W = \left([w_1^L, w_1^U], \ldots, [w_n^L, w_n^U] \right)^T$, satisfying $a_{ij} = [l_{ij}, u_{ij}] \approx [w_i^L, w_i^U]/[w_j^L, w_j^U]$ for all $i, j = 1, ..., n; i \neq j$ is normalized according to equations proposed by Sugihara and Tanaka (2001) as given below.

$$\begin{aligned} &\sum_i w_i^U - \max_j (w_j^U - w_j^L) \ge 1 \\ &\sum_i w_i^L + \max_j (w_j^U - w_j^L) \le 1 \end{aligned} \qquad (5.1)$$

These additive normalization equations are equal to the ones given below.

$$\begin{aligned} &w_i^L + \sum_{j=1, j\neq i}^{n} w_j^U \ge 1, \; i = 1, \ldots, n \\ &w_i^U + \sum_{j=1, j\neq i}^{n} w_j^L \le 1, \; i = 1, \ldots, n \end{aligned} \qquad (5.2)$$

Then, the interval comparison matrix can be written in terms of interval weight vector $W = \left([w_1^L, w_1^U], \ldots, [w_n^L, w_n^U] \right)^T$ as follows.

$$A = \begin{bmatrix} 1 & \frac{[w_1^L, w_1^U]}{[w_2^L, w_2^U]} & \cdots & \frac{[w_1^L, w_1^U]}{[w_n^L, w_n^U]} \\ \frac{[w_2^L, w_2^U]}{[w_1^L, w_1^U]} & 1 & \cdots & \frac{[w_2^L, w_2^U]}{[w_n^L, w_n^U]} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{[w_n^L, w_n^U]}{[w_1^L, w_1^U]} & \frac{[w_n^L, w_n^U]}{[w_2^L, w_2^U]} & \cdots & 1 \end{bmatrix}$$

The division operation rule on interval numbers is given below.

$$\frac{[b_L, b_U]}{[d_L, d_U]} = [b_L / d_U, b_U / d_L] \tag{5.3}$$

The interval comparison matrix A can be defined by using the division operation rule as follows.

$$A = \begin{bmatrix} 1 & \left[\frac{w_1^L}{w_2^U}, \frac{w_1^U}{w_2^L}\right] & \cdots & \left[\frac{w_1^L}{w_n^U}, \frac{w_1^U}{w_n^L}\right] \\ \left[\frac{w_2^L}{w_1^U}, \frac{w_2^U}{w_1^L}\right] & 1 & \cdots & \left[\frac{w_2^L}{w_n^U}, \frac{w_2^U}{w_n^L}\right] \\ \vdots & \vdots & \vdots & \vdots \\ \left[\frac{w_n^L}{w_1^U}, \frac{w_n^U}{w_1^L}\right] & \left[\frac{w_n^L}{w_2^U}, \frac{w_n^U}{w_2^L}\right] & \cdots & 1 \end{bmatrix}$$

This A matrix can be split into non-negative A_L and A_U matrices as given below.

$$A_L = \begin{bmatrix} 1 & \frac{w_1^L}{w_2^U} & \cdots & \frac{w_1^L}{w_n^U} \\ \frac{w_2^L}{w_1^U} & 1 & \cdots & \frac{w_2^L}{w_n^U} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_n^L}{w_1^U} & \frac{w_n^L}{w_2^U} & \cdots & 1 \end{bmatrix} \qquad A_U = \begin{bmatrix} 1 & \frac{w_1^U}{w_2^L} & \cdots & \frac{w_1^U}{w_n^L} \\ \frac{w_2^U}{w_1^L} & 1 & \cdots & \frac{w_2^U}{w_n^L} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_n^U}{w_1^L} & \frac{w_n^U}{w_2^L} & \cdots & 1 \end{bmatrix}$$

The equations expressed below can be obtained from A_L and A_U matrices.

$$\begin{aligned} A_L W_U &= W_U + (n-1)\, W_L \\ A_U W_L &= W_L + (n-1)\, W_U \end{aligned} \tag{5.4}$$

where $W_L = (w_1^L, \ldots, w_n^L)^T$ and $W_U = (w_1^U, \ldots, w_n^U)^T$ are the lower and upper priority weight vectors respectively.

Since the judgments of the decision maker are subjective and uncertain, the deviation vectors, $\mathrm{E} = (\varepsilon_1, \ldots, \varepsilon_n)^T$ and $\Gamma = (\gamma_1, \ldots, \gamma_n)^T$, are defined as follows.

$$\begin{aligned} \mathrm{E} &= (A_L - I)\, W_U - (n-1)\, W_L \\ \Gamma &= (A_U - I)\, W_L - (n-1)\, W_U \end{aligned} \tag{5.5}$$

The optimization model (OPT 1) aiming at keeping the deviation variables as small as possible is given below.

$$\begin{aligned} &\textit{Minimize} \quad J = \sum_{i=1}^{n} (|\varepsilon_i| + |\gamma_i|) \\ &s.to \\ &(A_L - I)\, W_U - (n-1)\, W_L - \mathrm{E} = 0, \\ &(A_U - I)\, W_L - (n-1)\, W_U - \Gamma = 0, \\ &w_i^L + \sum_{j=1, j\neq i}^{n} w_j^U \geq 1, \qquad i = 1, \ldots, n, \\ &w_i^U + \sum_{j=1, j\neq i}^{n} w_j^L \leq 1, \qquad i = 1, \ldots, n, \\ &W_U - W_L \geq 0, \\ &W_L, W_U \geq 0. \end{aligned}$$

Let,

$$\varepsilon_i^+ = \frac{\varepsilon_i + |\varepsilon_i|}{2} \text{ and } \varepsilon_i^- = \frac{-\varepsilon_i + |\varepsilon_i|}{2}, i = 1, \ldots, n,$$

$$\gamma^+ = \frac{\gamma_i + |\gamma_i|}{2} \text{ and } \gamma^- = \frac{-\gamma_i + |\gamma_i|}{2}, i = 1, \ldots, n.$$

Based on these definitions, deviation terms can be written as:

$$\begin{aligned}
&\varepsilon_i = \varepsilon_i^+ - \varepsilon_i^-, \ i = 1, \ldots, n, \\
&|\varepsilon_i| = \varepsilon_i^+ + \varepsilon_i^-, \ i = 1, \ldots, n, \\
&\gamma_i = \gamma_i^+ - \gamma_i^-, \ i = 1, \ldots, n, \\
&|\gamma_i| = \gamma_i^+ + \gamma_i^-, \ i = 1, \ldots, n,
\end{aligned} \tag{5.6}$$

where $\varepsilon_i^+ \varepsilon_i^- = 0, \ \gamma_i^+ \gamma_i^- = 0 \ for \ i = 1, \ldots, n.$

Then the optimization model (OPT 2) can be represented as below.

$$\begin{aligned}
&Minimize \quad J = \sum_{i=1}^{n} (\varepsilon_i^+ + \varepsilon_i^- + \gamma_i^+ + \gamma_i^-) \\
&s.to \\
&(A_L - I)\, W_U - (n-1)\, W_L - \mathrm{E}^+ + \mathrm{E}^- = 0, \\
&(A_U - I)\, W_L - (n-1)\, W_U - \Gamma^+ + \Gamma^- = 0, \\
&w_i^L + \sum_{j=1,\, j \neq i}^{n} w_j^U \geq 1, \qquad i = 1, \ldots, n, \\
&w_i^U + \sum_{j=1,\, j \neq i}^{n} w_j^L \leq 1, \qquad i = 1, \ldots, n, \\
&W_U - W_L \geq 0, \\
&W_L, W_U, \mathrm{E}^+, \mathrm{E}^-, \Gamma^+, \Gamma^- \geq 0
\end{aligned}$$

Determination of Interval Global Priority Weights

After obtaining the local priority weights of the criteria and alternatives satisfying the additive normalization constraints by using the optimization model (OPT 2), the global or composite priority weights are found by the synthesis of the interval priorities. Assume that there are m criteria and n alternatives represented hierarchically as in Figure 5 with priority weights as shown in Table 5.

Table 5: The set of priority weights

Alternatives	Criterion 1	Criterion 2	…	Criterion m	Composite weights
	$[w_1^L, w_1^U]$	$[w_2^L, w_2^U]$	$\cdots$	$[w_m^L, w_m^U]$	
A_1	$[w_{11}^L, w_{11}^U]$	$[w_{12}^L, w_{12}^U]$	$\cdots$	$[w_{1m}^L, w_{1m}^U]$	$[w_{A_1}^L, w_{A_1}^U]$
A_2	$[w_{21}^L, w_{21}^U]$	$[w_{22}^L, w_{22}^U]$	$\cdots$	$[w_{2m}^L, w_{2m}^U]$	$[w_{A_2}^L, w_{A2}^U]$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
A_n	$[w_{n1}^L, w_{n1}^U]$	$[w_{n2}^L, w_{n2}^U]$	$\cdots$	$[w_{nm}^L, w_{nm}^U]$	$[w_{A_n}^L, w_{A_n}^U]$

In order to determine the composite weights, two linear programs, (OPT 3) and (OPT 4), proposed by Bryson and Mobolurin (1997) aiming at determining the lower and upper bounds of the alternatives' composite weights by considering the weights of the criteria as decision variables, are solved for each alternative:

$$\textit{Minimize} \quad w_{A_i}^L = \sum_{j=1}^{m} w_{ij}^L w_j$$

s.to

$$W \in \Omega_w$$

$$\textit{Maximize} \quad w_{A_i}^U = \sum_{j=1}^{m} w_{ij}^U w_j$$

s.to

$$W \in \Omega_w$$

where $W = (w_1, ...w_m)$ is the criteria weight vector and $\Omega_w = \left\{ W = (w_1, \ldots, w_m)^T \middle| w_j^L \le w_j \le w_j^U, \sum_{j=1}^{m} w_j = 1,\ j = 1, \ldots, m \right\}$ is the feasible region of criteria weight vector.

5.1.2.2 Interval Priority Weight Generation Method Proposed by Öztürk (2009)

Another interval priority weight generation method from interval comparison matrices determined from the decision maker is proposed by Öztürk (2009).

In this method, if the alternative has the priority weight interval of $[w_i^L, w_i^U]$, then the equations given below are valid for a consistent comparison matrix.

$$\begin{aligned} \frac{w_i^L}{w_j^U} &= l_{ij} \quad i,\ j = 1, \ldots, n \\ \frac{w_i^U}{w_j^L} &= u_{ij} \quad i,\ j = 1, \ldots, n \end{aligned} \tag{5.7}$$

Due to the inconsistency of the comparison matrices obtained from the decision makers, error parameters of $\in_{ij}$ and α_{ij} are introduced to the equations as below.

$$\begin{aligned} \frac{w_i^L}{w_j^U} &= l_{ij} \in_{ij} \quad i,\ j = 1, \ldots, n \\ \frac{w_i^U}{w_j^L} &= u_{ij}\, \alpha_{ij} \quad i,\ j = 1, \ldots, n \end{aligned} \tag{5.8}$$

These non-linear equations can be converted to linear equations by taking the natural logarithms of both sides as shown below.

$$\begin{aligned} \ln(w_i^L) - \ln(w_j^U) - \ln(\in_{ij}) &= \ln(l_{ij}) \quad i,\ j = 1, \ldots, n \\ \ln(w_i^U) - \ln(w_j^L) - \ln(\alpha_{ij}) &= \ln(u_{ij}) \quad i,\ j = 1, \ldots, n \end{aligned} \tag{5.9}$$

To simplify the equations, $\ln(w_i^L), \ln(w_i^U), \ln(w_j^L), \ln(w_j^U), \ln(\in_{ij})$ and $\ln(\alpha_{ij})$ are replaced with $x_i^L, x_i^U, x_j^L, x_j^U, y_{ij}$ and ω_{ij} respectively and the equations become.

$$\begin{aligned} x_i^L - x_j^U - y_{ij} &= \ln(l_{ij}) \quad i,\ j = 1, \ldots, n \\ x_i^U - x_j^L - \omega_{ij} &= \ln(u_{ij}) \quad i,\ j = 1, \ldots, n \end{aligned} \tag{5.10}$$

The objective function of the model aiming at minimizing the sum of errors is presented below.

$$Minimize \quad \sum_{i=1} \sum_{j=i+1} (z_{ij} + t_{ij})$$

During the error calculation, both the upper triangular matrix measuring the error of i vs. j and the lower triangular matrix measuring the error of j vs. i are considered. However, while summing the errors only the largest error of the triangular matrices for each pair of errors is taken into consideration as given below.

$$\begin{aligned}
& z_{ij} \geq y_{ij} \quad i,\ j = 1, \ldots, n; i < j \\
& z_{ij} \geq y_{ji} \quad i,\ j = 1, \ldots, n; i < j \\
& t_{ij} \geq \omega_{ij} \quad i,\ j = 1, \ldots, n; i < j \\
& t_{ij} \geq \omega_{ji} \quad i, j = 1, \ldots, n; i < j
\end{aligned} \tag{5.11}$$

Since the multiplicative constraint is used in this model, corresponding normalization constraint of the model is provided below.

$$\begin{aligned}
& \prod_{j=1,\ j\neq i} w_j^U \times w_i^L \geq 1, \\
& \prod_{j=1,\ j\neq i} w_j^L \times w_i^U \leq 1.
\end{aligned} \tag{5.12}$$

These non-linear equations are converted to linear equations by taking the natural logarithms of both sides as given below.

$$\begin{aligned}
& \sum_{j=1,\ j\neq i} \ln w_j^U + \ln w_i^L \geq 0 \\
& \sum_{j=1,\ j\neq i} \ln w_j^L + \ln w_i^U \leq 0
\end{aligned} \tag{5.13}$$

The first optimization model (OPT 5) minimizing the sum of errors is as follows.

$$Minimize \quad \sum_{i=1} \sum_{j=i+1} (z_{ij} + t_{ij})$$

s.to

$$x_i^L - x_j^U - y_{ij} = \ln(l_{ij}) \qquad i, j = 1, \ldots, n$$

$$x_i^U - x_j^L - \omega_{ij} = \ln(u_{ij}) \qquad i, j = 1, \ldots, n$$

$$z_{ij} \geq y_{ij} \qquad i, j = 1, \ldots, n, i < j$$

$$z_{ij} \geq y_{ji} \qquad i, j = 1, \ldots, n, i < j$$

$$t_{ij} \geq \omega_{ij} \qquad i, j = 1, \ldots, n, i < j$$

$$t_{ij} \geq \omega_{ji} \qquad i, j = 1, \ldots, n, i < j$$

$$\sum_{j=1,\ j \neq i} x_j^U + x_i^L \geq 0 \qquad i = 1, \ldots, n$$

$$\sum_{j=1,\ j \neq i} x_j^L + x_i^U \leq 0 \qquad i = 1, \ldots, n$$

$$x_i^L \leq x_i^U \qquad i = 1, \ldots, n$$

$$x_i^L, x_i^U \ URS \qquad i = 1, \ldots, n$$

$$y_{ij}, \omega_{ij} \ URS \qquad i = 1, \ldots, n$$

$$z_{ij}, t_{ij} \geq 0 \qquad i, j = 1, \ldots, n.$$

After solving the model above and getting the minimum value of the total inconsistency, the second model minimizing the maximum error of the system by keeping the total inconsistency as the same as the one obtained from the first optimization model is solved. This model (OPT 6) is given below:

$$Minimize \quad g_{\max}$$

s.to

$$x_i^L - x_j^U - y_{ij} = \ln(l_{ij}) \qquad i, j = 1, \ldots, n,$$

$$x_i^U - x_j^L - \omega_{ij} = \ln(u_{ij}) \qquad i, j = 1, \ldots, n,$$

$$z_{ij} \geq y_{ij} \qquad i, j = 1, \ldots, n, i < j,$$

$$z_{ij} \geq y_{ji} \qquad i, j = 1, \ldots, n, i < j,$$

$$t_{ij} \geq \omega_{ij} \qquad i, j = 1, \ldots, n, i < j,$$

$$t_{ij} \geq \omega_{ji} \qquad i, j = 1, \ldots, n, i < j,$$

$$\sum_{i=1} \sum_{j=i+1} (z_{ij} + t_{ij}) = z_{opt},$$

$$\sum_{j=1,\ j \neq i} x_j^U + x_i^L \geq 0 \qquad i = 1, \ldots, n,$$

$$\sum_{j=1,\ j\neq i} x_j^L + x_i^U \leq 0 \qquad i = 1, \ldots, n,$$

$$g_{\max} \geq z_{ij} \qquad i,\ j = 1, \ldots, n, i < j,$$

$$g_{\max} \geq t_{ij} \qquad i,\ j = 1, \ldots, n, i < j,$$

$$x_i^L \leq x_i^U \qquad i = 1, \ldots, n$$

$$x_i^L,\ x_i^U\ URS \qquad i = 1, \ldots, n$$

$$y_{ij},\ \omega_{ij},\ g_{\max}\ URS \qquad i,\ j = 1, \ldots, n$$

$$z_{ij},\ t_{ij} \geq 0 \qquad i, j = 1, \ldots, n.$$

where $g_{\max}$ is the maximum error value and z_{opt} is the optimal value of the first optimization model.

Determination of Interval Global Priority Weights

Suppose also that there are m criteria and n alternatives represented hierarchically as in Figure 5 with priority weights as shown in Table 5. Wang et al. (2005) proposed two non-linear programming models (OPT 7 and OPT 8) for obtaining lower and upper bounds of the global interval weights for the case of multiplicatively normalized weights:

$$Minimize \quad w_{A_i}^L = \prod_{j=1}^{m} (w_{ij}^L)^{w_j}$$

$$s.to$$

$$W \in \Omega_w$$

$$Maximize \quad w_{A_i}^U = \prod_{j=1}^{m} (w_{ij}^U)^{w_j}$$

$$s.to$$

$$W \in \Omega_w$$

where $W = (w_1, \ldots w_m)$ is the criteria weight vector and $\Omega_w = \left\{ W = (w_1, \ldots, w_m)\ \middle|\ w_j^L \leq w_j \leq w_j^U,\ \prod_{j=1}^{m} w_j = 1 \right\}$ is the feasible region of criteria weight vector.

Öztürk (2009) propose an alternative heuristic method to determine the global priority weights without solving non-linear models for the same case. The "effective weight" of an alternative is defined as the weight of the alternative for a criterion to the power of that criterion weight:

$$w_{eff_{ij}} = (w_{ij})^{w_j} \tag{5.14}$$

where w_{ij} is the weight of the alternative i for the criterion j and w_j is the weight of the criterion j.

The minimum and the maximum global weights of an alternative are calculated by multiplying all the minimum and maximum "effective weights" of that alternative for each criterion correspondingly.

It is shown that four possibilities of the maximum and minimum effective weights of an alternative with the interval weight of $w_{ij} = [w_{ij}^L, w_{ij}^U]$ for a criterion with the interval weight of $w_j = [w_j^L, w_j^U]$ are $(w_{ij}^L)^{w_j^L}$, $(w_{ij}^L)^{w_j^U}$, $(w_{ij}^U)^{w_j^L}$ and $(w_{ij}^U)^{w_j^U}$. For 9 point scale as used in AHP, all possible priority weights of the alternatives and criteria are investigated to find out the minimum and maximum effective weights. Finally, these three relations are obtained:

- If $w_{ij}^L, w_{ij}^U \geq 0$, $w_{ij}^L, w_{ij}^U \leq 1$, then the minimum and maximum effective weights are $w_{eff_{ij}} = (w_{ij}^L)^{w_j^U}$ and $w_{eff_{ij}} = (w_{ij}^U)^{w_j^L}$ respectively,
- If $w_{ij}^L, w_{ij}^U \geq 1$, then the minimum and maximum effective weights are $w_{eff_{ij}} = (w_{ij}^L)^{w_j^L}$ and $w_{eff_{ij}} = (w_{ij}^U)^{w_j^U}$ respectively,
- If $0 \leq w_{ij}^L \leq 1$, $w_{ij}^U \geq 1$, then the minimum and maximum effective weights are $w_{eff_{ij}} = (w_{ij}^L)^{w_j^U}$ and $w_{eff_{ij}} = (w_{ij}^U)^{w_j^U}$ respectively.

Lastly, the minimum and the maximum global weights of the alternatives are obtained by multiplying the corresponding effective weights of the alternative for all criteria.

5.1.3 Comparison of the Performances of the Methods

For comparing the interval global weights found from the two methods, two measures of performance are used. These are the fitted error proposed by Wang and Elhag (2007) and the absolute error proposed by Öztürk (2009).

Assume that $W^L = (w_1^L, \ldots, w_n^L)$ and $W^U = (w_1^U, \ldots, w_n^U)$ are the lower and upper priority weights found by using an interval priority weight generation method. The comparison matrix of $\tilde{A}$ with the lower and upper interval comparison elements of $\tilde{l}_{ij} = w_i^L / w_j^U$ and $\tilde{u}_{ij} = w_i^U / w_j^L$ respectively is given below.

$$\tilde{A} = \begin{bmatrix} 1 & \left[\frac{w_1^L}{w_2^U}, \frac{w_1^U}{w_2^L}\right] & \cdots & \left[\frac{w_1^L}{w_n^U}, \frac{w_1^U}{w_n^L}\right] \\ \left[\frac{w_2^L}{w_1^U}, \frac{w_2^U}{w_1^L}\right] & 1 & \cdots & \left[\frac{w_2^L}{w_n^U}, \frac{w_2^U}{w_n^L}\right] \\ \vdots & \vdots & \vdots & \vdots \\ \left[\frac{w_n^L}{w_1^U}, \frac{w_n^U}{w_1^L}\right] & \left[\frac{w_n^L}{w_2^U}, \frac{w_n^U}{w_2^L}\right] & \cdots & 1 \end{bmatrix}.$$

The difference between the calculated comparison matrix, $\tilde{A}$, and the one provided by the decision maker, A, is considered as the error of the method. The fitted error (Wang and Elhag, 2007) is defined as.

$$Fitted\ Error = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[\left(l_{ij} - \tilde{l}_{ij}\right)^2 + \left(u_{ij} - \tilde{u}_{ij}\right)^2\right] \tag{5.15}$$

Due to taking the square of the errors, this measure penalizes large errors.

The absolute error (Öztürk, 2009), in which absolute values of the errors are summed, is defined as.

$$Absolute\ Error = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[\left|l_{ij} - \tilde{l}_{ij}\right| + \left|u_{ij} - \tilde{u}_{ij}\right|\right] \quad (5.16)$$

Since the dimensions of the comparison matrices are different from each other, averages of these measures as given below are considered to make a comparison between them (Öztürk, 2009):

$$Fitted\ Error = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[\left(l_{ij} - \tilde{l}_{ij}\right)^2 + \left(u_{ij} - \tilde{u}_{ij}\right)^2\right]}{2n} \quad (5.17)$$

$$Absolute\ Error = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[\left|l_{ij} - \tilde{l}_{ij}\right| + \left|u_{ij} - \tilde{u}_{ij}\right|\right]}{2n} \quad (5.18)$$

where n is the dimension of the comparison matrix.

5.1.4 Comparison and Ranking of the Criteria and Sub-criteria Priority Weight Intervals

In the comparison method proposed by Wang et al. (2005b), the degrees of preference along with preference relations among the alternatives with interval weights are obtained.

Assume that $a = [a_1, a_2]$ and $b = [b_1, b_2]$ are two interval weights with the all possible relationship between them represented in Figure 11.

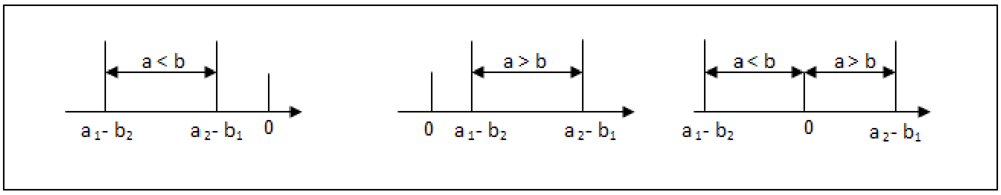

Figure 11: All possible relationships between two interval weights of a and b

The degree of preference of a over b (a>b) and b over a (b>a) are defined as below.

$$P(a > b) = \frac{\max(0, a_2 - b_1) - \max(0, a_1 - b_2)}{(a_2 - a_1) + (b_2 - b_1)} \tag{5.19}$$

$$P(b > a) = \frac{\max(0, b_2 - a_1) - \max(0, b_1 - a_2)}{(a_2 - a_1) + (b_2 - b_1)} \tag{5.20}$$

Because of the fact that maximum and minimum value of $a - b$ are $a_2 - b_1$ and $a_1 - b_2$ respectively, the equations (5.19) and (5.20) can be alternatively written as follows.

$$P(a > b) = \frac{\max(0, \max(a - b)) - \max(0, \min(a - b))}{\max(a - b) - \min(a - b)} \tag{5.21}$$

$$P(b > a) = \frac{\max(0, \max(b - a)) - \max(0, \min(b - a))}{\max(b - a) - \min(b - a)} \tag{5.22}$$

It can be realized that $P(a > b) + P(b > a) = 1$. Moreover, $P(a > b) = P(b > a) = 0.5$ when $a = b$ which means $a_1 = b_1$ and $a_2 = b_2$.

In case of $P(a > b) > P(b > a)$, it is said that a is superior to b to the degree of $P(a > b)$ that is represented as $a \overset{P(a>b)}{\succ} b$. When $P(a > b) = P(b > a)$, it is said that a is indifferent to b that is represented as $a \sim b$. When $P(b > a) > P(a > b)$, it is said that a is inferior to b to the degree of $P(b > a)$ that is represented as $a \overset{P(b>a)}{\prec} b$.

The properties of the comparison method given below facilitate the ranking of the interval priority weights:

- $P(a > b) = 1$ if and only if $a_1 \geq b_2$,
- If $a_1 \geq b_1$ and $a_2 \geq b_2$, then $P(a > b) \geq 0.5$ and $P(b > a) \leq 0.5$,

- If $a_1 \leq b_1$ and $a_2 \geq b_2$, that means b is nested in a, then $P(a > b) \geq 0.5$ if and only if $\frac{a_1 + a_2}{2} \geq \frac{b_1 + b_2}{2}$,

- If $P(a > b) \geq 0.5$ and $P(b > c) \geq 0.5$, then $P(a > c) \geq 0.5$.

Complete implement process can be accomplished by following the steps given below.

Step 1: The matrix of degrees of preference is calculated:

$$P_D = \begin{array}{c} \\ w_1 \\ w_2 \\ \vdots \\ w_n \end{array} \begin{array}{c} \begin{array}{cccc} w_1 & w_2 & \cdots & w_n \end{array} \\ \begin{bmatrix} - & p_{12} & \cdots & p_{1n} \\ p_{21} & - & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & - \end{bmatrix} \end{array}$$

where p_{ij} represents the degree of preference of w_i over w_j when $i \neq j$.

Step 2: A directed diagram, an arc from node i to node j, is drawn for the all preference relations in which $p_{ij} \geq 0.5$ as shown in Figure 12.

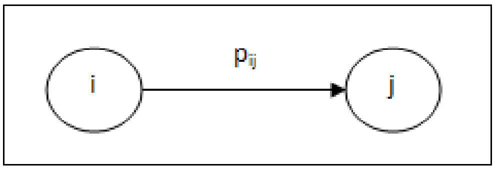

Figure 12: A directed diagram showing that the interval weight w_i is preferred to w_j with a preference degree of p_{ij}

Step 3: A complete preference ranking order is determined from the directed diagrams by using the fourth property of the comparison method or the row-column elimination method in which the rows and columns of the most preferred elements of the matrix are eliminated iteratively.

5.2 The DEA Based Sorting Methods with Assurance Region

In this part, the models developed for sorting purpose based on the methodology of DEA are presented. First of all, the proposed threshold estimation models considering only the reference set alternatives are explained in detail. Then, their corresponding assignment models classifying the alternatives which are not judged yet by comparing their performances with the reference set alternatives' are given.

The problem statement for which the models are proposed can be defined as follows: There are l number of discrete set of alternatives, represented as a_f. Alternatives need to be allocated to q number of ordinal classes, denoted by C_k, according to their efficiencies, θ_f. Notation to be used is as follows.

Indices:

$i: inputs\ of\ the\ \mathrm{mod}el\ (i = 1, \ldots, n)$
$r: outputs\ of\ the\ \mathrm{mod}el\ (r = 1, \ldots, o)$
$f: alternatives\ (f = 1, \ldots, l)$
$k: classes\ (k = 1, \ldots, q)$

Parameters:

x_{if} : *value of input i for alternative f*
y_{rf} : *value of output r for alternative f*
LB_{ij} : *lower bound on the ratio of the weight of input i to the weight of input j*
LB_{rp} : *lower bound on the ratio of the weight of output r to the weight of output p*
LB_{ir} : *lower bound on the ratio of the weight of input i to the weight of output r*
UB_{ij} : *upper bound on the ratio of the weight of input i to the weight of input j*
UB_{rp} : *upper bound on the ratio of the weight of output r to the weight of output p*
UB_{ir} : *upper bound on the ratio of the weight of input i to the weight of output r*
$\delta_1, \delta_2, s: user\ defined\ small\ positive\ cons\tan ts\ (s > \delta_1, \delta_2 \geq 0)$

Decision Variables:

v_{if} : *weight of input i for alternative f*
u_{rf} : *weight of output r for alternative f*

z_k : *threshold separating the classes of* C_k *and* C_{k+1}

$\sigma_f^{\ +}, \sigma_f^{\ -}$: *classification errors of alternative* f

$dev1_{ifg}$: *the difference between the weights of input* i *for alternatives* f *and* g

$dev2_{rfg}$: *the difference between the weights of output* r *for alternatives* f *and* g

5.2.1 The DEA Based Sorting Method

<u>*5.2.1.1 The Threshold Estimation Model (PM1)*</u>

The methodology of this model is similar to DEA in a way that the evaluated alternatives are considered as the DMUs of DEA that are consuming inputs to obtain outputs. In this model; rather than estimating piecewise linear marginal utility functions as in UTADIS, the efficiency of the alternative, which is the ratio of the weighted sum of outputs to the weighted sum of inputs as in DEA, is considered. Instead of assessing the alternatives with common set of weights like UTADIS, each alternative is evaluated according to the set of weights that ensures the best efficiency value. Then, the efficiency of each alternative can be obtained from the equation given below.

$$\theta_f = \frac{\sum_r u_{rf}\, y_{rf}}{\sum_i v_{if}\, x_{if}} \quad \forall a_f \tag{5.23}$$

In order to have a linear model, the sum of weighted outputs are constrained by the sum of weighted inputs and the sum of weighted inputs of each alternative is equalized to 1, as in DEA. Then, the equation (5.23) is expressed as given below.

$$\left.\begin{aligned} &\theta_f = \sum_r u_{rf}\, y_{rf} \\ &\sum_i v_{if}\, x_{if} = 1 \\ &\sum_r u_{rf}\, y_{rf} - \sum_i v_{if}\, x_{if} \le 0 \end{aligned}\right\} \quad \forall a_f \tag{5.24}$$

In (5.24), the efficiency of each alternative is equal to its sum of weighted outputs and it is scaled in the range of 0 and 1.

However, in order to eliminate the weight sets that are not possible or undesirable by the decision makers, the weights are restricted by applying the assurance region approach to the ratio of input weights, outputs weights and input to output weights.

$$
\begin{aligned}
& LB_{ij} \leq \frac{v_{if}}{v_{jf}} \leq UB_{ij} \quad \forall i \neq j, f \\
& LB_{rp} \leq \frac{u_{rf}}{u_{pf}} \leq UB_{rp} \quad \forall r \neq p, f \\
& LB_{ir} \leq \frac{v_{if}}{u_{rf}} \leq UB_{ir} \quad \forall i, r, f
\end{aligned}
\tag{5.25}
$$

The assignment of the alternatives into the classes is based on the comparisons of the efficiencies and the thresholds estimated from the model, as in UTADIS.

$$
\begin{aligned}
& \theta_f \geq z_1 \Rightarrow a_f \in C_1 \\
& z_k \leq \theta_f < z_{k-1} \Rightarrow a_f \in C_k \quad k = 2, \ldots, q-1 \\
& \theta_f < z_{q-1} \Rightarrow a_f \in C_q
\end{aligned}
\tag{5.26}
$$

The classification errors of the reference set alternatives are obtained as follows:

$$
\begin{aligned}
& \sum_r u_{rf} y_{rf} - z_1 + \sigma_f^{+} \geq \delta_1 \quad \forall a_f \in C_1 \\
& \left.
\begin{aligned}
& \sum_r u_{rf} y_{rf} - z_k + \sigma_f^{+} \geq \delta_1 \\
& \sum_r u_{rf} y_{rf} - z_{k-1} - \sigma_f^{-} \leq -\delta_2
\end{aligned}
\right\} \forall a_f \in C_k \quad k = 2, \ldots, q-1 \\
& \sum_r u_{rf} y_{rf} - z_{q-1} - \sigma_f^{-} \leq -\delta_2 \quad \forall a_f \in C_q
\end{aligned}
\tag{5.27}
$$

where σ_f^{+} and σ_f^{-} are the classification errors of alternative f, as defined in UTADIS.

The relation between the thresholds should satisfy the order of the classes, such as the threshold separating the classes C_k and C_{k+1}, z_k, should be greater than the one separating the classes C_{k+1} and C_{k+2}, z_{k+1}. This relation can be defined as given below.

$$z_k - z_{k+1} \geq s \quad k = 1, \ldots, q-2 \tag{5.28}$$

The proposed model aims to determine the thresholds sorting the reference set alternatives into the ordinal classes by minimizing the classification errors and evaluating the alternatives with the most promising weight sets. Then, the objectives of the model are to maximize the efficiency of each alternative:

$$\textit{Objective } 1: \textit{Maximize} \quad \sum_f \sum_r u_{rf}\, y_{rf} \tag{5.29}$$

and to minimize the total misclassification errors:

$$\textit{Objective } 2: \textit{Minimize} \quad \sum_k \left(\frac{\sum_{\forall a_f \in C_k} (\sigma_f^{\,+} + \sigma_f^{\,-})}{m_k} \right). \tag{5.30}$$

Then, the objective function can be presented as given below:

$$\textit{Maximize} \quad \alpha_1 \sum_f \sum_r u_{rf}\, y_{rf} - \alpha_2 \sum_k \left(\frac{\sum_{\forall a_f \in C_k} (\sigma_f^{\,+} + \sigma_f^{\,-})}{m_k} \right) \tag{5.31}$$

where α_1 and α_2 are the user defined constants representing the importance of each objective. It should be noted that the second objective, minimizing misclassification errors, is much more important than the first one, maximizing the total efficiencies. Therefore; preemptive priority weights, $\alpha_2 >>> \alpha_1$, are applied in order not to sacrifice from the more significant objective while maximizing the other objective (Charnes and Cooper, 1961).

Finally, the proposed model (PM1) is presented below:

$$Maximize\ \alpha_1 \sum_f \sum_r u_{rf} y_{rf} - \alpha_2 \sum_k \left(\frac{\sum_{\forall a_f \in C_k} (\sigma_f^{\ +} + \sigma_f^{\ -})}{m_k} \right)$$

s.to

$$\sum_i v_{if} x_{if} = 1 \quad \forall a_f \in R$$

$$\sum_r u_{rf} y_{rf} - \sum_i v_{if} x_{if} \le 0 \quad \forall a_f \in R$$

$$LB_{ij} \le \frac{v_{if}}{v_{jf}} \le UB_{ij} \quad \forall i \ne j, f$$

$$LB_{rp} \le \frac{u_{rf}}{u_{pf}} \le UB_{rp} \quad \forall r \ne p, f$$

$$LB_{ir} \le \frac{v_{if}}{u_{rf}} \le UB_{ir} \quad \forall i, r, f$$

$$\sum_r u_{rf} y_{rf} - z_1 + \sigma_f^{\ +} \ge \delta_1 \quad \forall a_f \in C_1 \cap R$$

$$\left.\begin{aligned} &\sum_r u_{rf} y_{rf} - z_k + \sigma_f^{\ +} \ge \delta_1 \\ &\sum_r u_{rf} y_{rf} - z_{k-1} - \sigma_f^{\ -} \le -\delta_2 \end{aligned}\right\} \quad \forall a_f \in C_k \cap R \quad k = 2, \ldots, q-1$$

$$\sum_r u_{rf} y_{rf} - z_{q-1} - \sigma_f^{\ -} \le -\delta_2 \quad \forall a_f \in C_q \cap R$$

$$z_k - z_{k+1} \ge s \quad k = 1, \ldots, q-2$$

$$v_{if}, u_{rf}, \sigma_f^{\ +}, \sigma_f^{\ -} \ge 0 \quad \forall i, r, f$$

where R is the set of reference set alternatives.

This model estimates the weight sets maximizing the efficiency of each alternative in the reference set and the thresholds that are the bounds separating the classes while minimizing the misclassification errors of the alternatives.

5.2.1.2 The Assignment Model of PM1 (APM1)

After PM1 is solved for the reference set alternatives and the thresholds are obtained, the alternatives that are not classified by the decision makers are analyzed to find out their corresponding classes. This assignment is accomplished by comparing the efficiencies of the evaluated alternatives with the thresholds estimated from PM1 as given in (5.26).

The assignment model for the unevaluated alternative a_e in accordance with PM1, APM1, is given below:

$$\begin{aligned}
&Maximize \sum_r u_r y_{re} \\
&s.to \\
&\quad \sum_i v_i x_{ie} = 1 \\
&\quad \sum_r u_r y_{rf} - \sum_i v_i x_{if} \le 0 \quad \forall a_f \in R \cup a_e \\
&\quad LB_{ij} \le \frac{v_i}{v_j} \le UB_{ij} \quad \forall i \ne j \\
&\quad LB_{rp} \le \frac{u_r}{u_p} \le UB_{rp} \quad \forall r \ne p \\
&\quad LB_{ir} \le \frac{v_i}{u_r} \le UB_{ir} \quad \forall i, r \\
&\quad v_i, u_r \ge 0 \quad \forall i, r
\end{aligned}$$

where v_i and u_r are the weights of input i and output r respectively and f includes the reference set alternatives and unevaluated alternative a_e. The main difference of this model is the fact that all alternatives considered in the model are evaluated by the best set of weights for the alternative a_e.

APM1 is the same as the original DEA assurance region model. The objective is to maximize the efficiency of the alternative a_e while restricting the efficiencies of the reference set elements and this alternative to be less than or equal to the sum of weighted inputs. The corresponding classes of each alternative can be determined by solving APM1 for each unevaluated alternative separately.

5.2.2 The Weight Restricted DEA Based Sorting Method

5.2.2.1 The Threshold Estimation Model (PM2)

PM1 illustrated in the previous part is modified by implementing additional restrictions on the weights based on the approaches of cross-efficiency and common set of weights in DEA. The logic of this modification is that; the efficiencies of the alternatives determined by assessing them with the most promising weight sets cannot provide a fair evaluation between the alternatives. Instead, in this new method each alternative in the reference set is analyzed with a promising weight set that is close to the other alternatives'. In order to accomplish this, the range of the promising input and output weights for all alternatives in the reference set are defined as follows:

$$\left.\begin{array}{l} dev1_{ifg} \geq v_{if} - v_{ig} \\ dev1_{ifg} \geq v_{ig} - v_{if} \end{array}\right\} \quad \forall i,\ f \neq g$$
$$\left.\begin{array}{l} dev2_{rfg} \geq u_{rf} - u_{rg} \\ dev2_{rfg} \geq u_{rg} - u_{rf} \end{array}\right\} \quad \forall r,\ f \neq g \qquad (5.32)$$

where f and g are different alternatives belonging to the reference set.

Then, the third objective minimizing the sum of input and output weight ranges of the alternatives is given below.

$$Objective\ 3: Minimize \quad \sum_{i}\sum_{f\neq g}\sum_{g} dev1_{ifg} + \sum_{r}\sum_{f\neq g}\sum_{g} dev2_{rfg} \qquad (5.33)$$

Finally, PM2 is provided below:

$$Maximize \quad \alpha_1 \sum_f \sum_r u_{rf} y_{rf} - \alpha_2 \sum_k \left(\frac{\sum_{\forall a_f \in C_k} (\sigma_f^{\ +} + \sigma_f^{\ -})}{m_k} \right)$$
$$- \alpha_3 \left(\sum_i \sum_{f \neq g} \sum_g dev1_{ifg} + \sum_r \sum_{f \neq g} \sum_g dev2_{rfg} \right)$$

s.to

$$\sum_i v_{if} x_{if} = 1 \quad \forall a_f \in R$$

$$\sum_r u_{rf} y_{rf} - \sum_i v_{if} x_{if} \leq 0 \quad \forall a_f \in R$$

$$LB_{ij} \leq \frac{v_{if}}{v_{jf}} \leq UB_{ij} \quad \forall i \neq j, f$$

$$LB_{rp} \leq \frac{u_{rf}}{u_{pf}} \leq UB_{rp} \quad \forall r \neq p, f$$

$$LB_{ir} \leq \frac{v_{if}}{u_{rf}} \leq UB_{ir} \quad \forall i, r, f$$

$$\sum_r u_{rf} y_{rf} - z_1 + \sigma_f^{\ +} \geq \delta_1 \quad \forall a_f \in C_1 \cap R$$

$$\left.\begin{array}{l} \sum_r u_{rf} y_{rf} - z_k + \sigma_f^{\ +} \geq \delta_1 \\ \sum_r u_{rf} y_{rf} - z_{k-1} - \sigma_f^{\ -} \leq -\delta_2 \end{array}\right\} \quad \forall a_f \in C_k \cap R \quad k = 2, \ldots, q-1$$

$$\sum_r u_{rf} y_{rf} - z_{q-1} - \sigma_f^{\ -} \leq -\delta_2 \quad \forall a_f \in C_q \cap R$$

$$z_k - z_{k+1} \geq s \quad k = 1, \ldots, q-2$$

$$\left.\begin{array}{l} dev1_{ifg} \geq v_{if} - v_{ig} \\ dev1_{ifg} \geq v_{ig} - v_{if} \end{array}\right\} \quad \forall i, f \neq g$$

$$\left.\begin{array}{l} dev2_{rfg} \geq u_{rf} - u_{rg} \\ dev2_{rfg} \geq u_{rg} - u_{rf} \end{array}\right\} \quad \forall r, f \neq g$$

$$v_{if}, u_{rf}, \sigma_f^{\ +}, \sigma_f^{\ -}, dev1_{ifg}, dev2_{rfg} \geq 0 \quad \forall i, r, f \neq g$$

where α_1, α_2 and α_3 are the preemptive priority weights, with the relative importance of $\alpha_2 >>> \alpha_3 >>> \alpha_1$. This model estimates the thresholds by minimizing the sum of the misclassification errors of the alternatives in the reference set that are evaluated by the most promising input and output weights within the minimum range.

5.2.2.2 The Assignment Models of PM2 (APM2, APM3, APM4 and APM5)

In this part, four different models providing the efficiencies of the alternatives that are not judged by the decision makers are presented. The assignment of the alternatives into the classes is performed by comparing their efficiency values and the thresholds obtained from PM2, as in APM1.

One of the assignment models derived to determine the efficiency of the unevaluated alternative e in accordance with PM2, APM2, is given below:

$$Maximize\ \alpha_1 \sum_f \sum_r u_{rf} y_{rf} - \alpha_3 \left(\sum_i \sum_{f \neq g} \sum_g dev1_{ifg} + \sum_r \sum_{f \neq g} \sum_g dev2_{rfg} \right)$$

s.to

$$\sum_i v_{if} x_{if} = 1 \quad \forall a_f \in R \cup a_e$$

$$\sum_r u_{rf} y_{rf} - \sum_i v_{if} x_{if} \leq 0 \quad \forall a_f \in R \cup a_e$$

$$LB_{ij} \leq \frac{v_{if}}{v_{jf}} \leq UB_{ij} \quad \forall i \neq j, f$$

$$LB_{rp} \leq \frac{u_{rf}}{u_{pf}} \leq UB_{rp} \quad \forall r \neq p, f$$

$$LB_{ir} \leq \frac{v_{if}}{u_{rf}} \leq UB_{ir} \quad \forall i, r, f$$

$$\left.\begin{aligned} dev1_{ifg} &\geq v_{if} - v_{ig} \\ dev1_{ifg} &\geq v_{ig} - v_{if} \end{aligned}\right\} \quad \forall i, f \neq g$$

$$\left.\begin{array}{l} dev2_{rfg} \geq u_{rf} - u_{rg} \\ dev2_{rfg} \geq u_{rg} - u_{rf} \end{array}\right\} \quad \forall r,\ f \neq g$$

$$v_{if},\ u_{rf},\ dev1_{ifg},\ dev2_{rfg} \geq 0 \quad \forall i,\ r,\ f \neq g$$

where α_1 and α_3 are the preemptive priority weights, with the relative importance of $\alpha_3 >>> \alpha_1$. This model is solved for each unevaluated alternative separately by considering only the reference set elements and that alternative under evaluation. Finally, the assignment is performed based on the best efficiency values of the alternatives assessed by the most promising input and output weights within the minimum range.

The second assignment model, APM3, is the same as APM2 but this model analyzes all the alternatives that are not allocated to the classes by the decision maker in one step by taking into account all of the unevaluated alternatives and the reference set elements in the model.

The third assignment model, APM4, apply additional restrictions to the input and output weights indirectly by constraining the efficiencies of the alternatives in the reference set. In APM4, the efficiencies of the reference set alternatives are ensured to be consistent with the judgments of the decision maker and with the results of the threshold estimation model of PM2 as given below:

$$\begin{array}{l} \sum_r u_{rf}\, y_{rf} \geq z_1 + \delta_1 \quad \forall a_f \in C_1 \cap R \\ z_k + \delta_1 \leq \sum_r u_{rf}\, y_{rf} \leq z_{k-1} - \delta_2 \quad \forall a_f \in C_k \cap R \quad k = 2, \ldots, q-1 \\ \sum_r u_{rf}\, y_{rf} \leq z_{q-1} - \delta_2 \quad \forall a_f \in C_q \cap R \end{array} \tag{5.34}$$

where the values of the thresholds are determined from PM2.

It should be mentioned that the inequalities of (5.34) are defined only for the reference set alternatives that are classified correctly in PM2.

This assignment model, APM4, determining the efficiency of the unevaluated alternative e is as follows:

$$Maximize\ \alpha_1 \sum_f \sum_r u_{rf} y_{rf} - \alpha_3 \left(\sum_i \sum_{f \neq g} \sum_g dev1_{ifg} + \sum_r \sum_{f \neq g} \sum_g dev2_{rfg} \right)$$

s.to

$$\sum_i v_{if} x_{if} = 1 \quad \forall a_f \in R \cup a_e$$

$$\sum_r u_{rf} y_{rf} - \sum_i v_{if} x_{if} \leq 0 \quad \forall a_f \in R \cup a_e$$

$$LB_{ij} \leq \frac{v_{if}}{v_{jf}} \leq UB_{ij} \quad \forall i \neq j, f$$

$$LB_{rp} \leq \frac{u_{rf}}{u_{pf}} \leq UB_{rp} \quad \forall r \neq p, f$$

$$LB_{ir} \leq \frac{v_{if}}{u_{rf}} \leq UB_{ir} \quad \forall i, r, f$$

$$\sum_r u_{rf} y_{rf} \geq z_1 + \delta_1 \quad \forall a_f \in C_1 \cap R \cap COR$$

$$z_k + \delta_1 \leq \sum_r u_{rf} y_{rf} \leq z_{k-1} - \delta_2 \quad \forall a_f \in C_k \cap R \cap COR \quad k = 2, \ldots, q-1$$

$$\sum_r u_{rf} y_{rf} \leq z_{q-1} - \delta_2 \quad \forall a_f \in C_q \cap R \cap COR \quad \forall a_f \in C_q$$

$$\left. \begin{array}{l} dev1_{ifg} \geq v_{if} - v_{ig} \\ dev1_{ifg} \geq v_{ig} - v_{if} \end{array} \right\} \quad \forall i, f \neq g$$

$$\left. \begin{array}{l} dev2_{rfg} \geq u_{rf} - u_{rg} \\ dev2_{rfg} \geq u_{rg} - u_{rf} \end{array} \right\} \quad \forall r, f \neq g$$

$$v_{if}, u_{rf}, dev1_{ifg}, dev2_{rfg} \geq 0 \quad \forall i, r, f \neq g$$

where COR is the set of alternatives in the reference set that are correctly assigned to the groups by PM2.

This model is also solved for each unevaluated alternative separately by dealing with this alternative and the reference set alternatives only.

In the last assignment model, APM5, APM4 is solved in a single step to evaluate all the unevaluated alternatives at the same time by considering all alternatives and the reference set elements in the model.

The general approach of the sorting methods proposed in this part is illustrated in Figure 13.

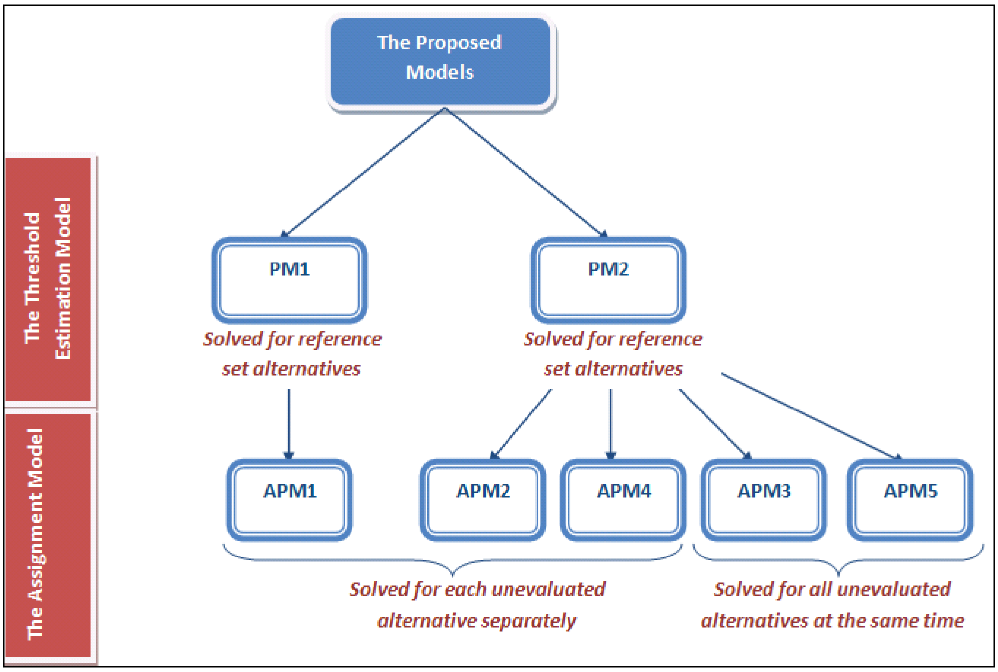

Figure 13: The proposed sorting methods

It should be noted that after solving PM1 or PM2, a post-optimality analysis, as explained in chapter 3.3 for UTADIS, can be further applied by adding the optimal value of the objective of PM1 or PM2 as a constraint in order to check the stability of the estimated thresholds.

The general structure of the proposed methodology for the problem of sorting the Industrial R&D projects proposed to TEYDEB is given in Figure 14.

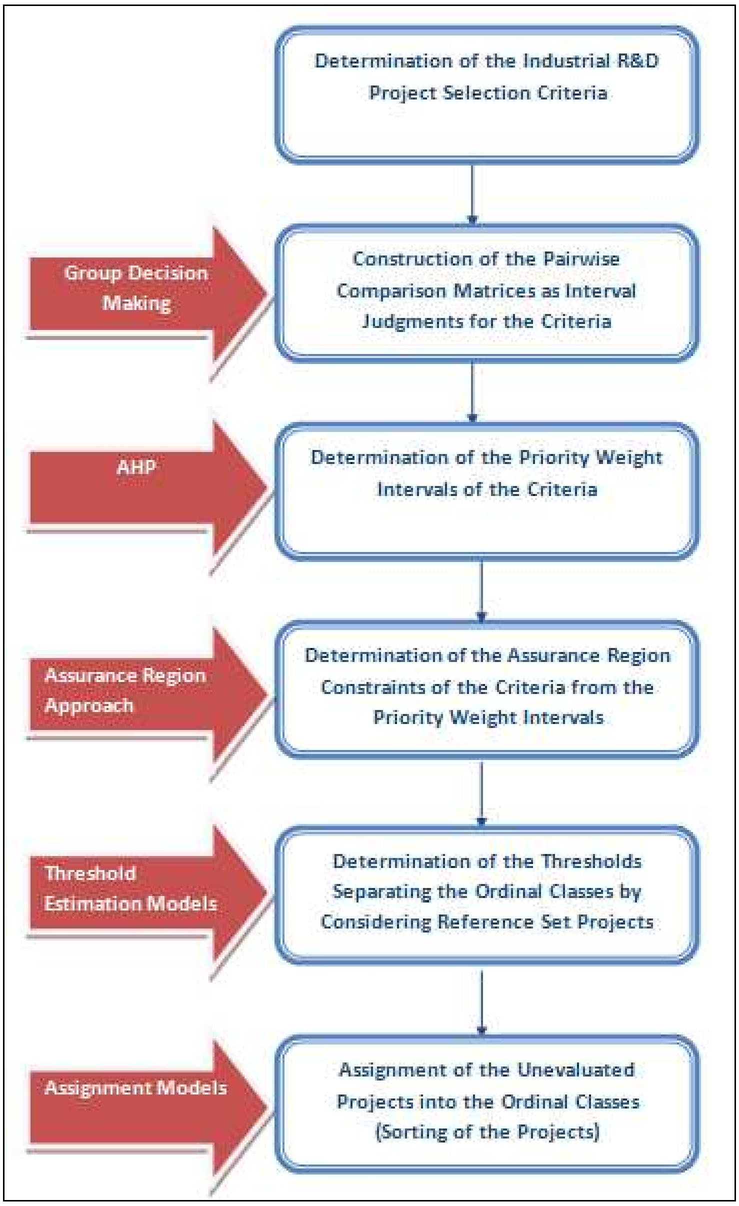

Figure 14: The general structure of the proposed methodology

CHAPTER 6

IMPLEMENTATION OF THE MODEL

In this chapter, the methods proposed in the previous chapter are applied to a real case study. First of all, the results of the AHP models utilized to obtain the priorities of the evaluation criteria and their comparisons are provided. Then, the solutions of the proposed threshold estimation models and assignment models are given. Finally, the discussions of the results are presented.

It should be noted that the results of the methods are determined by using the CPLEX solver of GAMS (v.23.0) software.

6.1 Results of the AHP Model

6.1.1 The Criteria and Sub-Criteria Priority Weight Intervals

Two different methods that are explained in the previous chapter are used to obtain the interval priority weights of the criteria and sub-criteria of the problem.

Firstly, the optimization model (OPT 2) of the goal programming method proposed by Wang and Elhag (2007) is solved and local priority weights of the criteria and sub-criteria are determined as given in Appendix D. Then, the interval global priority weights are found by solving the two linear models of (OPT 3) and (OPT 4) presented by Bryson and Mobolurin (1997) from the top of the hierarchy to the bottom of it. For this criteria structure, the models (OPT 3) and (OPT 4) are reduced to the equations (6.1) and (6.2) as given below since there is only one element which is on the one level upper hierarchy affecting the element in consideration and therefore there is no need for the summation term.

$$w_{A_i}^L = w_{ij}^L w_j^L \quad (6.1)$$

$$w_{A_i}^U = w_{ij}^U w_j^U \quad (6.2)$$

The interval global priorities obtained from the equations (6.1) and (6.2) are presented in Table 6.

Table 6: The interval global weights of the criteria and subcriteria obtained from Goal Programming Method (Wang and Elhag, 2007)

(Sub) Criteria	Lower weight	Upper weight
w_1	0.472	0.778
w_2	0.171	0.207
w_3	0.051	0.321
$w_{1.1}$	0.038	0.312
$w_{1.2}$	0.043	0.534
$w_{1.3}$	0.055	0.395
$w_{2.1}$	0.043	0.172
$w_{2.2}$	0.029	0.155
$w_{3.1}$	0.004	0.129
$w_{3.2}$	0.006	0.163
$w_{3.3}$	0.005	0.157
$w_{2.1.1}$	0.002	0.084
$w_{2.1.2}$	0.004	0.077
$w_{2.1.3}$	0.005	0.058
$w_{2.1.4}$	0.003	0.030
$w_{3.1.1}$	0.0005	0.107
$w_{3.1.2}$	0.0007	0.113

Table 6 Continued: The interval global weights of the criteria and subcriteria obtained from Goal Programming Method (Wang and Elhag, 2007)

(Sub) Criteria	Lower weight	Upper weight
$w_{3.2.1}$	0.0004	0.041
$w_{3.2.2}$	0.0009	0.053
$w_{3.2.3}$	0.0005	0.068
$w_{3.2.4}$	0.0003	0.057
$w_{3.3.1}$	0.004	0.141
$w_{3.3.2}$	0.0005	0.039
$w_{2.1.3.1}$	0.002	0.045
$w_{2.1.3.2}$	0.0009	0.012
$w_{2.1.3.3}$	0.0003	0.019

Moreover, the interval priority weight generation method of Öztürk (2009) is used for the second solution to the same linear hierarchy. By solving the optimization models of (OPT 5) and (OPT 6) in sequentially for each comparison matrix, local priority weights of the criteria and sub-criteria are determined as given in Appendix D. Later, in order to find the global weights the heuristic method of Öztürk (2009) is used instead of non-linear programming models of (OPT 7) and (OPT 8) proposed by Wang et al. (2005) due to the fact that this heuristic method is the exact solution of the non-linear models for this criteria structure. The interval global weights obtained from the method of Öztürk (2009) are given in Table 7.

Table 7: The interval global weights of the criteria and subcriteria obtained from the method proposed by Öztürk (2009)

(Sub) Criteria	Lower weight	Upper weight
w_1	1.661	3.555
w_2	0.602	0.920
w_3	0.306	1.000
$w_{1.1}$	0.010	3.540
$w_{1.2}$	0.022	19.890
$w_{1.3}$	0.037	12.809
$w_{2.1}$	0.603	2.097
$w_{2.2}$	0.477	1.657
$w_{3.1}$	0.324	1.485
$w_{3.2}$	0.430	1.969
$w_{3.3}$	0.342	1.866
$w_{2.1.1}$	0.073	4.323
$w_{2.1.2}$	0.148	4.323
$w_{2.1.3}$	0.148	4.323
$w_{2.1.4}$	0.073	0.914
$w_{3.1.1}$	0.236	3.303
$w_{3.1.2}$	0.302	4.242
$w_{3.2.1}$	0.093	2.207
$w_{3.2.2}$	0.254	2.207
$w_{3.2.3}$	0.093	2.207
$w_{3.2.4}$	0.093	2.207
$w_{3.3.1}$	1.207	7.768
$w_{3.3.2}$	0.128	0.829

Table 7 Continued: The interval global weights of the criteria and subcriteria obtained from the method proposed by Öztürk (2009)

(Sub) Criteria	**Lower weight**	**Upper weight**
$w_{2.1.3.1}$	1.078	240.591
$w_{2.1.3.2}$	0.111	0.988
$w_{2.1.3.3}$	0.006	1

6.1.2 The Comparison of the Performances of the Methods

In order to compare the performances of the two interval priority weight generation methods, the equations of (5.17) and (5.18) are used to calculate the errors of each matrix.

It should be noted that since the matrices provided by the decision makers giving the relative importance of the criteria at the same level of the hierarchy are used in the performance comparison, the local weights obtained by the two methods are utilized instead of the global weights presenting the overall importance of the whole criteria.

The fitted errors and absolute errors of each matrix and the total errors of the two methods are given in Table 8. Since both the total fitted error and absolute error of the method proposed by Öztürk (2009) are smaller, the interval priority weights of the criteria and sub-criteria obtained from this method are decided to be used in the study.

Table 8: The fitted and absolute errors of the methods proposed by Wang and Elhag (2007) and Öztürk (2009)

	Wang and Elhag (2007)		**Öztürk (2009)**	
	Fitted Error	Absolute Error	Fitted Error	Absolute Error
Matrix 1	12.815	2.468	4.865	1.909
Matrix 2	0.831	0.850	0.902	0.922
Matrix 3	0	0.003	0	0.001
Matrix 4	0.533	0.727	0.514	0.731
Matrix 5	2.224	1.623	0.795	0.602
Matrix 6	0	0.003	0	0.001
Matrix 7	7.583	2.489	2.062	1.134
Matrix 8	0	0	0	0.003
Matrix 9	12.814	2.468	4.865	1.909
Total	***36.800***	***10.631***	***14.003***	***7.212***

6.1.3 Comparison and Ranking of the Criteria and Sub-criteria Priority Weight Intervals

The priority weight intervals of criteria and sub-criteria found from the method proposed by Öztürk (2009) are compared to each other by using the equations (5.21) and (5.22). At the end, the rankings given below are obtained.

- In Matrix 1, $w_1 \overset{100\%}{\succ} w_2 \overset{61\%}{\succ} w_3$
- In Matrix 2, $w_{1.2} \overset{61\%}{\succ} w_{1.3} \overset{78\%}{\succ} w_{1.1}$
- In Matrix 3, $w_{2.1} \overset{61\%}{\succ} w_{2.2}$

- In Matrix 4, $w_{3.2} \overset{53\%}{\succ} w_{3.3} \overset{57\%}{\succ} w_{3.1}$

- In Matrix 5, $w_{2.1.2} = w_{2.1.3} \overset{50.4\%}{\succ} w_{2.1.1} \overset{83\%}{\succ} w_{2.1.4}$

- In Matrix 6, $w_{3.1.2} \overset{57\%}{\succ} w_{3.1.1}$

- In Matrix 7, $w_{3.2.2} \overset{52\%}{\succ} w_{3.2.1} = w_{3.2.3} = w_{3.2.4}$

- In Matrix 8, $w_{3.3.1} \overset{100\%}{\succ} w_{3.3.2}$

- In Matrix 9, $w_{2.1.3.1} \overset{100\%}{\succ} w_{2.1.3.2} \overset{52\%}{\succ} w_{2.1.3.3}$

- In the second level of the hierarchy, $w_{1.2} \overset{61\%}{\succ} w_{1.3} \overset{78\%}{\succ} w_{1.1} \overset{58\%}{\succ} w_{2.1} \overset{55\%}{\succ} w_{3.2} \overset{53\%}{\succ} w_{3.3} \overset{51\%}{\succ} w_{2.2} \overset{57\%}{\succ} w_{3.1}$

- In the third level of the hierarchy, $w_{3.3.1} \overset{71\%}{\succ} w_{3.1.2} \overset{50.4\%}{\succ} w_{2.1.2} = w_{2.1.3} \overset{50.4\%}{\succ} w_{2.1.1} \overset{56\%}{\succ} w_{3.1.1} \overset{61\%}{\succ} w_{3.2.2} \overset{52\%}{\succ} w_{3.2.1}$ $= w_{3.2.3} = w_{3.2.4} \overset{72\%}{\succ} w_{2.1.4} \overset{51\%}{\succ} w_{3.3.2}$

6.2 A Case Study Implementation of the Proposed Models

In this part of the study, the models developed in the previous chapter are implemented to the industrial R&D projects proposed to TEYDEB. For this purpose, 106 projects proposed to Industrial R&D Projects Grant Program in the year 2009 are selected. The reference set is also derived from these projects. The reason to select the projects from the proposals of the year 2009 is to identify the final decisions, namely global judgments, of the technology group committees and to form a more realistic reference set by considering the previously decided projects.

The first objective of this analysis is to identify the thresholds that separate the reference set projects into four groups in a way that the groups are ordered from one to four as decreasing degree of preference. The first group includes the projects that have very high performances. It is thought that these projects can be accepted directly without discussing in the technology group committee meetings. The fourth group contains the projects that have very poor performances. Therefore, they can be directly rejected without handling in the committee. The second and third groups are composed of good to intermediate and intermediate to poor level projects respectively which need further evaluation before the final decision.

After estimating the thresholds, the next aim is to evaluate the unevaluated projects in order to find out their corresponding groups by comparing their performances with the thresholds.

Before the application of the proposed models, the appropriate points of the R&D project selection criteria for each project is needed to be acquired from the referee reports. Since these criteria are developed for this study; the current referee reports, given in Appendix A, should be investigated in detail to convert the referee judgments into the criterion values according to the point allocation guide in Table 4. When the project is assessed by more than one referee, the average of all points is regarded as the final value of that criterion. Analyzing all the referee reports, corresponding criteria values of the 60 unevaluated projects, denoted by P, are obtained as presented in Appendix E.

In this case study; two reference sets, namely Reference Set 1 and Reference Set 2, which are composed of 20 and 46 representative projects respectively, are developed to examine the effect of reference set size on the proposed models. The second reference set includes all the projects of the first one and 26 additional projects. Therefore, the second one counts more judgments of the decision makers compared to the first one. The R&D project selection criterion values for each project of these reference sets, denoted by R, are given in Appendix F. The names of the projects are colored to indicate the groups that they belong to. The projects colored in orange are the ones in the first priority group, Group 1, while the ones in blue, green and red represent the second, third and fourth priority groups, Group 2, 3 and 4 respectively. The first five projects in each color belong to Reference Set 1 and all of the projects presented in Table 20 are the elements of Reference Set 2. For example; the first 10 projects colored in orange are the representatives of Group 1 for Reference Set 2 while the first 5 of them also belong to Reference Set 1 as the members of Group 1.

It should be mentioned that the reference set projects in the upper priority groups should not be dominated by the lower priority group projects. Moreover, the projects in the same priority group do not dominate each other in order to elicit new knowledge to the models. These properties are taken into consideration while composing the reference sets.

As explained in detail in the fifth chapter, the evaluation criteria of the projects should be analyzed to obtain the inputs and the outputs of the proposed models. In this analysis, only the lowest level elements of the criteria hierarchy given in Figure 9 are considered. Finally, the criteria are grouped into two as inputs and outputs with corresponding indices as given below in Table 9.

As can be seen from Table 9, all the subcriteria of the second main criterion, the project plan, capabilities of the company and compatibility of the company's infrastructure, are the inputs of the model since they are the basic requirements and plans of an R&D project. Moreover, all the subcriteria of the third main criterion, the applicability of the project outcomes into profit and national advantages, are the outputs of the model because of the fact that they are the results of the R&D project. The two subcriteria of the first main criterion which are technology used in the project and methodology of the project are the inputs while the remaining subcriterion of this criterion, novelty of the project output, is the output of the model.

Table 9: The inputs and the outputs of the proposed models

INPUTS		OUTPUTS	
Criteria	**Index i**	**Criteria**	**Index r**
1.1	1	1.2	1
1.3	2	3.1.1	2
2.1.1	3	3.1.2	3
2.1.2	4	3.2.1	4
2.1.3.1	5	3.2.2	5
2.1.3.2	6	3.2.3	6
2.1.3.3	7	3.2.4	7
2.1.4	8	3.3.1	8
2.2	9	3.3.2	9

While the qualitative criteria formed in the fourth section are quantified by providing a ten-point scale, ten points was defined as the best possible score and zero point as the worst score. Therefore, the higher point is given to a criterion, the better its performance. This situation is applicable to the outputs since they are tried to be maximized in the proposed models. However, the inputs are desired to be minimized. In order to match with the proposed models; the points of input criteria are subtracted from ten, that is the top point, before inserting them to the models as the input values of the projects.

Completing the pre-requirements of the models, obtaining the input and output values of the projects and forming the reference sets, the next step is to develop the assurance region constraints for the input and output weights. These constraints are acquired by utilizing the interval global weights determined from the method of Öztürk (2009) as given below.

$$LB_{ij} = \frac{\text{Lower weight of input criterion } i}{\text{Upper weight of input criterion } j} \le \frac{v_{if}}{v_{jf}}$$

$$\frac{v_{if}}{v_{jf}} \le \frac{\text{Upper weight of input criterion } i}{\text{Lower weight of input criterion } j} = UB_{ij}$$

$$LB_{rp} = \frac{\text{Lower weight of output criterion } r}{\text{Upper weight of output criterion } p} \le \frac{u_{rf}}{u_{pf}}$$

$$\frac{u_{rf}}{u_{pf}} \le \frac{\text{Upper weight of output criterion } r}{\text{Lower weight of output criterion } p} = UB_{rp}$$

$$LB_{ir} = \frac{\text{Lower weight of input criterion } i}{\text{Upper weight of output criterion } r} \le \frac{v_{if}}{u_{rf}}$$

$$\frac{v_{if}}{u_{rf}} \le \frac{\text{Upper weight of input criterion } i}{\text{Lower weight of output criterion } r} = UB_{ir}$$

An important point that should be considered in the assurance region approach is the hierarchical structure of the R&D project selection criteria. The interval priority weight generation method of Öztürk (2009) is based on multiplicative normalization of weights; therefore upper weights of the criteria can increase dramatically at the lower levels of the hierarchy. Due to this property, the assurance region constraints are defined only for the criteria that are placed at the same hierarch level. For instance; first two elements of the inputs and the first element of the outputs given in Table 9 belong to the same hierarchy level. As a result, the ratios of the weights of these three criteria form the assurance region constraints of this hierarchy level. The complete list of assurance region constraints used in the models is provided in Appendix G.

After constructing the assurance region constraints, the threshold estimation models of PM1 and PM2 are solved for each reference set. The influence of the model parameters on the results is also investigated. Moreover, the stability of the thresholds is also checked by applying POST OPT 1 and POST OPT 2 after the implementation of the proposed models. The results of the models and discussions of them are provided in the next sub-section.

Besides the models proposed in this thesis, UTADIS is also applied to the same problem for comparing the results of the methods. In UTADIS, there is no discrimination of the criteria as inputs and outputs and all of the criteria are regarded as the maximization criteria. Therefore, the points that each project receives from the criteria are directly used in UTADIS. Moreover, HEUR 2 suggested by Doumpos and Zopounidis (2002) is applied to model each piecewise linear marginal utility. The reason to choose this heuristic is the fact that the number of subintervals are determined by considering the number of basic variables of the model in order to eliminate the redundancy of the subinterval utility values, w, and the instability of the model. The criteria subintervals determined by HEUR 2 for Reference Set 1 and Reference Set 2 is given in Appendix H.

Finally, the unevaluated projects are assessed by the proposed assignment models, APM1, APM2, APM3, APM4 and APM5. Besides these models, the applicability of the average weights of the reference set projects obtained from PM1 and PM2 for the evaluation of projects that are not judged by the decision makers is also analyzed. In this analysis, the efficiency of the unevaluated project a_e is estimated by the equation given below:

$$\theta_e = \frac{\sum_r u_{r,ave} y_{re}}{\sum_i v_{i,ave} x_{ie}} \tag{6.3}$$

where $v_{i,ave}$ and $u_{r,ave}$ are the average weight of input i and average weight of output r for the reference set projects respectively. The results and discussions about the assignments are given in the next sub-section.

6.3 Discussion of the Results

6.3.1 Discussion of the Priorities of the R&D Project Selection Criteria

As expressed previously, the three dimensions of the Project Proposal Evaluation Report are considered while forming the evaluation criteria of this study. It is emphasized that the three dimensions are equally weighted in TEYDEB. Even if the second and third dimensions can be regarded to be equally significant, it is realized from the section 6.1.3 that the first dimension is in great consideration compared to the others. This result is also expected since the unsatisfactory performance in the first dimension reduces the acceptance probability of the projects immensely. Moreover, the novelty of the project output (1.2) is the most and the technology used in the project (1.1) is the least important sub-criteria of this dimension.

The second dimension, that measures the feasibility of the project, is obtained to be slightly more crucial than the third dimension, possible outcomes of the project. The importance of the sub-criteria in the third and fourth level of the second dimension is quite close to each other, except the compatibility of the expenses to the market (2.1.4). The compatibility of the expenses to the market (2.1.4) is the least significant sub-criterion in the second dimension as expected, because the granting is accomplished after the company makes the expenses and these expenses have been examined and approved by independent financial auditors. In the fifth level, existence of required competence and degree of internal commitment (2.1.3.1) is the most critical sub-criterion since it is a direct measure of company competence in terms of R&D capabilities.

In the third dimension, nearly all of the sub-criteria in the third and fourth level of the hierarchy have equal importance. However, it should be noticed that collaboration of university and industry (3.3.1) is definitely more essential than the collaboration of industry. It is also an anticipated result since the cooperation with universities is also an expected influence of the grant program.

On the other hand; while the performances of the projects used in the case study are derived, it is seen that the referees may not mark any of the phrases related with an important measure and do not provide their judgments about it in the reports. Therefore, although the currently utilized Project Proposal Evaluation Report facilitates the evaluation of the referees by presenting phrases and guiding about the criteria, some important criteria may not be assessed in this approach. However, evaluations through the point allocation guide developed in this study provide the assessment of all important points.

6.3.2 Discussion of the Threshold Estimation Models

The two threshold estimation models, PM1 and PM2, are analyzed by considering both of the reference sets.

First of all; the effect of model parameters, s, δ_1 and δ_2, and the coefficients of the objectives on the decision variables of the models are investigated. For the sake of simplicity, it is assumed that;

$$\delta_1 = \delta_2 = \delta \qquad (6.4)$$

The results of the proposed threshold estimation models with respect to the changes of these parameter values are provided in Appendix I.

Firstly; the appropriate objective function coefficients that satisfy the preemptive characteristic of the priority weights are determined while keeping the values of the parameters s and δ constant at 0.01 and 0.001. In order to facilitate this analysis, the coefficient of the least important objective, that is the first one, is fixed to 1 throughout the case study. It is realized that the coefficient of the second objective should be at least 15 and 36 when PM1 is solved for Reference Set 1 and 2, respectively. Therefore, these values are taken into consideration as the coefficients of the objectives for PM1 in the remaining part of the analysis. When PM2 is solved for Reference Set 1, the decision variables of the model are firstly stabilized at the values of 5,000,000 and 10,000 for the second and third coefficients, respectively. If the Reference Set 2 is utilized in PM2, the values of 1,000,000 and 1000 for the second and third coefficients can be sufficient to stabilize the results. Since Reference Set 2 counts more judgments of the decision makers compared to Reference Set1, the decision variables are fixed at lower coefficients of the objectives. In order to use common set of coefficients for both of the reference sets in PM2, the values of 10,000,000 and 10,000 are selected to be set for the second and thirds objectives respectively.

The convenience of the objective function coefficients can be checked by solving these models sequentially by dealing with only one objective at a time. In this approach, only the most significant objective is considered at first and then its value is fixed at the optimal while solving the model for the next significant objective. In this way, the objective in consideration is maximized without sacrificing from a more important one.

Deciding on the objective function coefficients, the influence of the parameters s and δ on the results of the models is examined. It is seen that the results of PM1 depend on the values of these parameters significantly. To demonstrate this dependence, the thresholds and the efficiencies of the reference set alternatives obtained from PM1 for Reference Set 1 are shown in Figure 15. As it can be seen from Figure 15, all the projects belonging to a particular group have the same efficiency values. Moreover; all of the first five projects, which are the elements of Group 1, acquire the best possible efficiency value. The distance between these efficiencies and the first threshold is exactly equal to the value of parameter δ. In addition, the distances between the thresholds are also completely defined by the value of parameter s. The projects are assigned to the best efficiencies according to the group that they belong to by keeping the distance between the efficiencies and the thresholds at the value of δ. When Reference Set 2 is utilized in PM1 by using the same values of s and δ, the same efficiencies and the thresholds are obtained again. Even if POST OPT

1 and POST OPT 2 are solved after PM1, the results do not change. Therefore, it is concluded that the reason for this excessive dependence of PM1 on the parameters of s and δ is because of the loose constraints of the model and existence of many alternative solutions, not due to the reference set size or instability of the model.

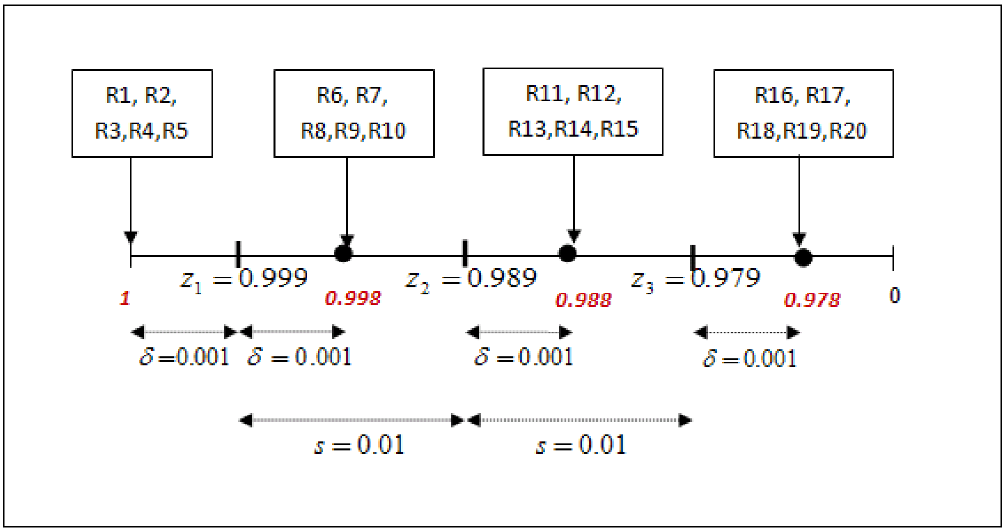

Figure 15: The estimated thresholds and efficiencies for Reference Set 1 by PM1 when $\alpha_1 = 1, \alpha_2 = 15, s = 0.01$ *and* $\delta = 0.001$

When PM2 is solved for different values of the parameters s and δ, it is found out that these parameters are not so determinative as in PM1. Figure 16 represents the results obtained from PM2 for Reference Set 1 with the same parameters used in PM1 in Figure 15. For this case, the distances between the thresholds are farther than the value of the parameter s. Furthermore, the projects belonging to same groups can have different efficiencies. However, the effect of parameter δ is more significant for PM2. For instance, the project that posses the lowest efficiency value is R6 and R8 in Group 2. The distance between these efficiencies and the threshold separating Group 2 and Group 3 is equal to the value of δ. The highest efficiency value for the same group is

0.878 which is δ amount far from the threshold dividing Group 1 and Group 2. The same discussion can be made for the projects in Group 3 and Group 4, but not for Group 1.

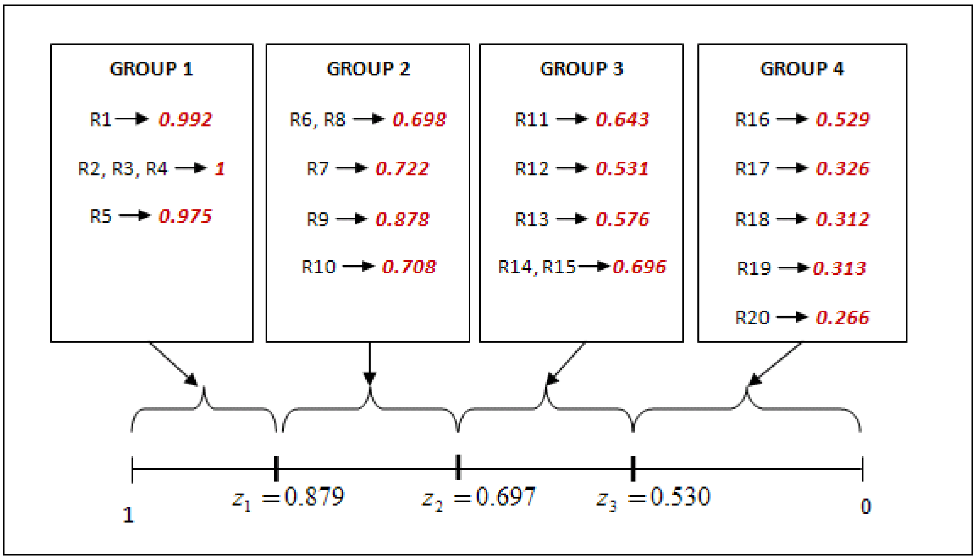

Figure 16: The estimated thresholds and efficiencies for Reference Set 1 by PM2 when $\alpha_1 = 1, \alpha_2 = 10{,}000{,}000$, $\alpha_3 = 10{,}000$, $s = 0.01$ *and* $\delta = 0.001$

Completing the analysis about the effect of parameters on the model results, the stability of the thresholds estimated from PM1 and PM2 for Reference Set 1 and Reference Set 2 are examined by applying post optimality analysis as in UTADIS. Moreover, UTADIS is also implemented on the same problem for both of the reference sets. All of the models are solved for the parameters of $s = 0.01$ and $\delta = 0.001$ and finally the thresholds provided in Table 10 are obtained. It is clear that thresholds estimated from PM1 and PM2 are quite stable for both of the reference sets. In addition, the thresholds of PM1 are not affected by the change in reference set and the thresholds slightly change when the reference set size increases in PM2. However, implementing a post optimality analysis causes dramatic changes in the thresholds of UTADIS for both of the reference sets. Furthermore, the type of the post optimality analysis is also an important matter since the estimated thresholds are highly dependent on the secondary objective of UTADIS. Additionally, the impact of reference set size on the thresholds is also notable in UTADIS. For instance; for Reference Set 1 the third threshold, z_3 is obtained as 0.029 from UTADIS without any post optimality analysis. When POST OPT 1 and POST OPT 2 are applied, this threshold is found as 0.529 and 0.259 respectively. Furthermore; in case of Reference Set 2, the same threshold is determined as 0.019, 0.350 and 0.098 when post optimality is not performed, POST OPT 1 and POST OPT 2 are implemented in sequence.

In conclusion, it is realized that the thresholds determined from the proposed models are much more stable than the ones obtained from UTADIS. However, the constraints of PM1 is assessed to be very loose and the decision variables of this model are influenced too much by the parameters of s and δ. On the contrary, PM2 is not only significantly affected by the model parameters as PM1, it also proposes realistic and stable the results compared to the other methods.

Table 10: The thresholds determined from the proposed models and UTADIS when $s = 0.01$ and $\delta = 0.001$

Models		**Estimated Thresholds**		
Threshold Estimation Model	**The Reference Set**	z_1	z_2	z_3
PM1	Reference Set 1	0.999	0.989	0.979
PM1 + POST OPT 1		0.999	0.989	0.979
PM1 + POST OPT 2		0.999	0.989	0.979
PM1	Reference Set 2	0.999	0.989	0.979
PM1 + POST OPT 1		0.999	0.989	0.979
PM1 + POST OPT 2		0.999	0.989	0.979
PM2	Reference Set 1	0.879	0.697	0.530
PM2 + POST OPT 1		0.879	0.697	0.530
PM2 + POST OPT 2		0.879	0.697	0.530
PM2	Reference Set 2	0.830	0.696	0.505
PM2 + POST OPT 1		0.830	0.696	0.505
PM2 + POST OPT 2		0.830	0.696	0.505
UTADIS	Reference Set 1	0.419	0.082	0.029
UTADIS + POST OPT 1		0.789	0.647	0.529
UTADIS + POST OPT 2		0.759	0.579	0.259
UTADIS	Reference Set 2	0.120	0.086	0.019
UTADIS + POST OPT 1		0.832	0.608	0.350
UTADIS + POST OPT 2		0.941	0.746	0.098

6.3.3 Discussion of the Assignment Models

In this part, the proposed assignment models are applied to evaluate 60 unevaluated projects given in Appendix E. Throughout the application, the model parameters of s and δ are kept at 0.01 and 0.001 respectively and the coefficients of the objective functions identified in the previous section are utilized for each model.

In addition to the models proposed in the fifth chapter, the average weights of the reference set projects determined from POST OPT 1 after solving PM1 and PM2 are also used for assigning the unevaluated projects, as stated before. The average weights obtained from this approach are presented in Appendix J. The reason of utilizing average weights is to examine the necessity of solving proposed linear models for assigning projects into the preference related groups rather than using average weights simply.

Furthermore, the assignments of the 60 projects are also analyzed for the case of UTADIS implementation in order to compare the results of the proposed models. These assignments are based on the subinterval utility values, w, and the thresholds obtained from POST OPT 1 after solving UTADIS. The optimal values of w determined by POST OPT 1 for both of the reference sets are available in Appendix K. It is seen from Appendix K, many subinterval utility values take the value of zero at optimality. This means that the criterion subinterval corresponding to zero valued utility value has no effect on the R&D project selection. This situation is not realistic, especially for the criteria of conducting market research (3.1.1), the work packages and project schedule (2.1.2), the project management planning (2.1.1), R&D infrastructure and culture of the company (2.2) and planning of resources other than manpower (2.1.3.2).

The assignments of the projects are accomplished by comparing their efficiency values, provided in Appendix L for all methods, with the estimated thresholds presented in Table 10, by the inequalities of (5.26). Finally, the results given in Table 11 are obtained.

Before analyzing the assignments of the projects in detail, some statistics of the results are examined. These statistics are derived based on these two performance measures.

$$Percentage\ of\ the\ relocated\ projects = \frac{Total\ number\ of\ replaced\ projects}{Total\ number\ of\ projects} \times 100$$

$$Percentage\ of\ the\ class\ changes = \frac{Total\ number\ of\ class\ changes}{Total\ number\ of\ projects} \times 100$$

These performance measures are based on the changes in the groups that the projects assigned to, the changes in the sorting of the alternatives proposed to DMs. In the first measure, the matter is the relocation of the evaluated project. If the class of a project changes in case of a modification in the model, then that project is counted as one. In the second measure, the number of class changes in case of a model modification becomes important. For example; if a project shifts to Group 3 from Group 1, this project is counted as two in this measure.

Firstly, the effect of reference set size on the performance of the assignment models is investigated. As mentioned before; the two reference sets, composed of 20 and 46 projects, are utilized to assess 60 unevaluated projects. Therefore, the ratio of the number of alternatives in the reference set to the number of alternatives in the validation sample is 33.3% and 76.7% while using Reference Set 1 and Reference Set 2, respectively.

Table 11: The groups of the 60 unevaluated projects determined from the proposed assignment models and UTADIS

Threshold Estimation Model	**Assignment Method**	**The Reference Set**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	**P14**	**P15**
PM1	Ave. Weights	Reference Set 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	APM1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
PM1	Ave. Weights	Reference Set 2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	APM1		1	1	1	1	1	4	1	-	4	1	1	1	1	1	1
PM2	Ave. Weights	Reference Set 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	APM2		1	1	2	1	1	1	1	1	1	2	1	2	1	1	2
	APM3		1	1	1	1	1	1	1	1	2	2	1	3	1	2	2
	APM4		2	1	1	1	1	1	1	1	1	1	1	2	1	1	1
	APM5		1	1	1	1	1	1	1	1	1	1	1	2	1	1	1
PM2	Ave. Weights	Reference Set 2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	APM2		1	1	1	1	1	1	1	1	1	2	1	3	1	2	1
	APM3		1	1	1	1	1	1	1	1	2	2	1	3	1	2	2
	APM4		2	1	2	1	1	1	1	1	1	1	1	2	1	1	1
	APM5		1	1	1	1	1	1	1	1	1	1	1	2	1	1	1
UTADIS - POST OPT 1		Reference Set 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
UTADIS - POST OPT 2			1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
UTADIS - POST OPT 1		Reference Set 2	2	2	2	2	2	1	1	1	1	1	1	2	1	1	2
UTADIS - POST OPT 2			3	1	3	1	3	1	1	1	1	1	1	1	1	2	1

Table 11 Continued: The groups of the 60 unevaluated projects determined from the proposed assignment models and UTADIS

Threshold Estimation Model	**Assignment Method**	**The Reference Set**	**P16**	**P17**	**P18**	**P19**	**P20**	**P21**	**P22**	**P23**	**P24**	**P25**	**P26**	**P27**	**P28**	**P29**	**P30**
PM1	Ave. Weights	Reference Set 1	1	1	1	1	1	2	4	1	4	1	4	4	4	4	1
	APM1		1	1	1	1	1	4	1	4	4	1	4	4	4	4	1
PM1	Ave. Weights	Reference Set 2	1	1	1	1	4	4	4	4	4	1	4	4	4	4	1
	APM1		1	1	1	1	4	4	4	4	4	4	4	4	4	4	4
PM2	Ave. Weights	Reference Set 1	1	1	1	1	2	3	3	3	3	1	4	4	4	4	1
	APM2		2	2	3	2	2	3	1	3	3	1	3	4	4	4	3
	APM3		3	2	4	2	3	3	1	4	4	1	3	4	4	4	4
	APM4		1	1	3	2	2	2	2	3	3	1	3	4	4	4	3
	APM5		2	2	2	2	2	2	1	3	3	1	3	4	4	4	3
PM2	Ave. Weights	Reference Set 2	1	1	1	1	3	3	3	3	3	2	4	4	4	4	1
	APM2		2	1	3	2	2	2	2	3	3	1	3	4	4	4	3
	APM3		2	2	3	2	3	3	1	3	3	1	3	4	4	4	3
	APM4		1	1	2	2	2	2	3	3	2	2	3	3	3	4	3
	APM5		1	2	2	2	2	2	2	3	3	1	3	4	4	4	3
UTADIS - POST OPT 1		Reference Set 1	1	1	1	2	2	3	2	3	2	2	3	3	4	4	3
UTADIS - POST OPT 2			1	1	1	2	1	3	2	3	2	2	3	3	4	3	3
UTADIS - POST OPT 1		Reference Set 2	1	1	2	2	3	2	2	3	3	2	3	3	4	3	2
UTADIS - POST OPT 2			1	1	3	2	2	3	3	3	3	2	3	4	3	4	3

Table 11 Continued: The groups of the 60 unevaluated projects determined from the proposed assignment models and UTADIS

Threshold Estimation Model	Assignment Method	The Reference Set	P31	P32	P33	P34	P35	P36	P37	P38	P39	P40	P41	P42	P43	P44	P45
PM1	Ave. Weights	Reference Set 1	4	4	4	1	4	4	1	4	4	4	4	1	4	4	4
	APM1		4	4	4	4	4	4	4	4	4	4	4	1	4	4	4
PM1	Ave. Weights	Reference Set 2	4	4	4	4	4	4	4	4	4	4	4	1	4	4	4
	APM1		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
PM2	Ave. Weights	Reference Set 1	4	3	3	3	4	4	2	3	4	4	4	1	4	4	4
	APM2		4	4	3	3	3	4	3	3	4	3	3	2	4	4	4
	APM3		4	4	4	4	3	4	4	3	4	4	2	3	4	4	4
	APM4		3	3	2	3	3	3	2	3	4	3	4	2	3	4	4
	APM5		4	3	3	3	3	4	3	3	4	3	3	3	3	4	4
PM2	Ave. Weights	Reference Set 2	4	4	4	4	4	4	3	3	4	4	4	3	4	4	4
	APM2		4	3	3	4	2	4	3	3	3	3	4	3	4	4	4
	APM3		4	4	3	4	3	4	3	3	4	3	3	3	4	4	4
	APM4		4	3	3	3	3	4	2	3	3	3	4	3	3	4	4
	APM5		4	3	3	3	2	4	3	3	3	3	4	3	3	4	4
UTADIS - POST OPT 1		Reference Set 1	4	3	2	4	4	3	3	3	4	4	4	3	4	4	4
UTADIS - POST OPT 2			4	3	2	3	3	3	3	3	3	3	4	3	3	4	4
UTADIS - POST OPT 1		Reference Set 2	4	2	2	3	3	3	3	3	4	3	4	2	3	4	3
UTADIS - POST OPT 2			4	4	3	3	4	4	3	4	4	3	3	3	4	4	4

Table 11 Continued: The groups of the 60 unevaluated projects determined from the proposed assignment models and UTADIS

Threshold Estimation Model	Assignment Method	The Reference Set	P46	P47	P48	P49	P50	P51	P52	P53	P54	P55	P56	P57	P58	P59	P60
PM1	Ave. Weights	Reference Set 1	4	4	4	1	4	4	4	4	4	4	4	1	4	4	4
	APM1		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
PM1	Ave. Weights	Reference Set 2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	APM1		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
PM2	Ave. Weights	Reference Set 1	4	4	4	2	4	4	4	4	4	4	4	3	3	4	4
	APM2		3	4	3	1	4	3	4	4	4	3	3	3	2	3	2
	APM3		3	4	3	3	4	4	4	4	4	3	4	3	2	3	3
	APM4		3	4	2	1	3	3	4	4	4	3	3	2	2	3	3
	APM5		3	4	2	2	4	3	4	4	4	3	3	2	3	3	3
PM2	Ave. Weights	Reference Set 2	4	4	4	3	4	4	4	4	4	4	4	3	4	4	4
	APM2		3	4	2	3	4	4	4	4	4	3	3	3	3	3	3
	APM3		3	4	2	3	4	4	4	4	4	3	3	3	3	3	3
	APM4		3	4	3	2	3	3	3	4	4	4	3	3	3	3	3
	APM5		3	4	2	3	3	3	3	4	4	3	3	3	3	3	3
UTADIS - POST OPT 1		Reference Set 1	4	4	4	2	4	3	4	4	4	4	3	2	3	3	3
UTADIS - POST OPT 2			3	4	3	3	3	3	3	4	4	4	3	3	3	3	3
UTADIS - POST OPT 1		Reference Set 2	3	4	3	2	4	3	3	4	4	4	3	3	3	3	3
UTADIS - POST OPT 2			3	4	4	2	4	3	3	4	4	4	4	2	2	4	3

As given in Table 12, the assignment models that are least sensitive to the reference set size are APM3 and APM5. These models consider all the unevaluated projects and the reference set projects together; therefore the total number of projects utilized is higher in these methods. Furthermore, when more information about the reference set projects is added to the model as in APM5, the sensitivity on the reference set size diminishes more. In addition; comparing the two performance measures, it is realized that only one class change takes place for the relocated projects in both of the models. As a result, APM3 and APM5 are regarded to be the most stable models in terms of reference set size.

Table 12: The effect of reference set size on the results of the assignment models

Models		**Performance Measures**	
The Threshold Estimation Model	**The Assignment Model**	**Percentage of the relocated projects**	**Percentage of the class changes**
PM1	APM1	11.7	35.0
PM2	APM2	30.0	31.7
PM2	APM3	20.0	20.0
PM2	APM4	30.0	30.0
PM2	APM5	15.0	15.0
UTADIS – POST OPT 1		40.0	40.0
UTADIS – POST OPT 2		45.0	51.7

The methods that are most sensitive to the reference set size are POST OPT 1 and POST OPT 2 applied UTADIS models. In these methods, nearly half of the projects are relocated when the reference set size changes. Moreover, more than one class change occurs for some of the projects when POST OPT 2 is implemented. In conclusion, UTADIS is considered as the least stable approach in terms of reference set size.

The impact of reference set size on the performance of UTADIS is also studied by Doumpos and Zopounidis (2002, 2004b). In 2002, they carry out experimental analysis by using the ratios of the reference set size to the validation sample size of 16.7%, 33.3% and 50%. They indicate that even if larger training samples provide more information, they also cause an increase in the complexity of the problem and a decrease in the classification accuracy of UTADIS. Besides; considering 20%, 30%, 40%, 50%, 60% and 70% as the ratios of the reference set size to the validation sample size, Doumpos and Zopounidis (2004b) state the lower error rates and higher instability in case of larger reference sets and warn about the trade-off between the error rates and instability for larger reference sets. The findings in this analysis also cohere with the results proposed by Doumpos and Zopounidis (2004b).

When the performance measures of APM1 are studied, it is seen that the number of projects that are relocated in case of a change in the reference set size is very limited in spite of the fact that the number of class changes is more significant. Analyzing Table 11 in detail, it is realized that APM1 assigns the projects into the Group 1 or Group 4 only. Thus; when a project is relocated, its class changes by three which causes a sharper increase in the second performance measure. In consequence, it is interpreted that APM1 can not provide meaningful classifications.

The performance measures of APM2 and APM4 are nearly the same except for a project whose class is changed by two in APM2. The impact of reference set size for these models is not as significant as UTADIS models. However, since the number of projects utilized in these models is less than the ones in APM3 and APM5, the reference set size is more important in APM2 and APM4.

Besides the impact of reference set size, the type of post-optimality analysis on the performance of UTADIS method is also investigated for both of the reference sets. The results provided in Table 13 are obtained in this analysis. Even if the same reference set with the identical subintervals determined from a particular heuristic approach are used by keeping the model parameters constant, the changes in the assignments of UTADIS for POST OPT 1 and POST OPT 2 are notable. The change is more drastic for the larger reference set size in which half of the projects are relocated. This study also shows the instability of UTADIS results in terms of different secondary objectives.

Table 13: The effect of the type of post optimality analysis on the assignments of UTADIS

Models		**Performance Measures**	
The Assignment Model	**The Reference Set**	**Percentage of the relocated projects**	**Percentage of the class changes**
UTADIS	Reference Set 1	23.3	23.3
	Reference Set 2	50.0	51.7

When the assignment models APM2 and APM4 are compared, the only difference between these models is the addition of decision makers judgments about the reference set projects and some information determined from the threshold estimation models to APM4. Therefore, APM4 includes more judgments of the decision makers. The performances of these models are also compared for both of the reference sets as presented in Table 14. It is seen that the differences between the results of APM2 and APM4 are slightly higher when the reference set size is larger.

Table 14: The effect of the assignment models APM2 and APM4 on the results

The Reference Set	Performance Measures	
	Percentage of the relocated projects	**Percentage of the class changes**
Reference Set 1	31.7	31.7
Reference Set 2	36.7	36.7

The similarity between the assignment models of APM3 and APM5 is the same as the relation between APM2 and APM4, but in the case of APM3 and APM5 all of the validation samples are evaluated in a single step. Comparing the results of APM3 and APM5 for both of the reference sets, as given in Table 15, the difference between the results is less when the references set size is larger.

Table 15: The effect of the assignment models APM3 and APM5 on the results

The Reference Set	Performance Measures	
	Percentage of the relocated projects	**Percentage of the class changes**
Reference Set 1	41.7	43.3
Reference Set 2	31.7	31.7

Investigating the statistical values of the assignment models, Table 11 is studied in detail to identify the placements of the unevaluated projects by each model. The discussions of the assignments are provided below for average weight approach, UTADIS and proposed models separately.

The Assignments of Average Weight Approaches

As mentioned previously, the applicability of the average weights of the reference set projects for the assignments of validation sample is also investigated. However, it is found out that this simple approach can not perceive the complexity of the problem and not able to provide satisfactory results.

For instance; the performance of the project P19 on the criteria of novelty of the project output (1.2), methodology of the project (1.3) and collaboration of university and industry (3.3.1) is not sufficient to assign the project to Group 1. However, using the average weights obtained from PM1 and PM2 for both of the reference sets cause the project to be placed in Group 1. All the other assignment models analyzed in this case study assign the project into Group 2, as expected.

Moreover, the project P22 is placed to Group 4 by the average weight approach of PM1 for both of the reference sets in spite of the fact that P22 dominates R34, the reference set project of Group 3. Therefore, the worst possible class of P22 is Group 3 and it is not possible to assign P22 into Group 4.

In addition; when the average weights determined from PM1 and PM2 for both of the reference sets are utilized, the projects P26 and P51 are assigned to Group 4. Nevertheless, both of the projects outperform R32, the reference set project belonging to Group 3, except for the criterion of benefit to the social groups (3.2.4). Since this criterion is not so significant, both of the projects should be at least placed to Group 3.

Furthermore; because of the insufficient performances of the two important criteria, novelty of the project output (1.2) and existence of required competence and degree of internal commitment (2.1.3.1), placement of project P30 into Group 1 is not expected. However, the average weight approaches for PM1 and PM2 considering both of the reference sets assign the project to Group 1.

Finally; comparing the performances of the projects P32 and R32, P32 is expected to be assigned to Group 3 in the worst case. But using the average weights obtained from PM1 for both of the reference sets and PM2 for Reference Set 2 cause the project to be assigned to Group 4.

<u>The Assignments of UTADIS Methods</u>

It is demonstrated previously that the results of UTADIS methods are greatly influenced by the reference set size and type of the post optimality analysis. In addition to these, the assignments of UTADIS are not thought to be adequate as explained below.

First of all; the weights of some criteria subintervals are obtained as zero from UTADIS methods, as mentioned previously. As a result of this unrealistic criteria weights for some subintervals, the project P54 recieves the global utility value of zero, which is regarded as meaningless.

When the projects P1 and P5 are analyzed, it is seen that they dominate five and two of the reference set projects out of thirteen belonging to Group 3, respectively. Investigating the performance of the project P3, it is also realized that P3 outperforms most of the reference set projects in Group 3. Furthermore, neither the reference set projects of Groups 1 and 2 dominate P1, P3 and P5 nor they dominate these reference set projects. Only the performance of the criterion of novelty of the project output (1.2), which is the most significant criterion, is slightly worse for the three projects compared to the projects belonging to Group 1 in reference sets. As a result, placement of these projects to the first two classes can be expected. But, assignment of the projects into Group 3 is not anticipated, as it is the case for UTADIS – POST OPT 2 with Reference Set 2.

The project P4 receives excellent points from the first two dimensions of the evaluation criteria, in parallel to the performances of the reference set projects belonging to Group 1. Moreover, the points of the third evaluation criteria are also sufficient for the project to be assigned to Group 1. However, it is placed to Group 2 by UTADIS - POST OPT 2 for Reference set 1 and UTADIS - POST OPT 1 for Reference set 2. The only criterion that the performance of the project is not satisfactory is the collaboration of university and industry (3.3.1). However, the placement of this project into Group 2 just because of this deficiency is not thought to be fair.

The projects P12 and P18 are very good in terms of second dimension of the evaluation criteria. Their achievements in the third dimension are also similar to the ones in the reference sets belonging to Group 1. However, the assessment of the most significant criterion, novelty of the project output (1.2), is not sufficient to place these projects in Group 1, as in the case of both post optimality analysis of UTADIS for Reference Set 1 and UTADIS – POST OPT 2 for Reference Set 2. Moreover, the performance of the project R18 which is the reference set project of Group 2 is comparable to the performances of the projects P12 and P18. Therefore, the assignment of these projects into Group 1 is not an expected result.

Additionally, the project P20 is placed into Group 1 by UTADIS – POST OPT 2 for Reference Set 1. However; the points of some important criteria, such as the novelty of the project output (1.2), methodology of the project (1.3) and the collaboration of university and industry (3.3.1), are not satisfactory for Group 1. Moreover; when the projects P20 and R27, the reference set project of Group 3, are compared, it is seen that their performances are close to each other. As a result, placing the project P20 into Group 1 is not regarded to be realistic.

Furthermore; as stated for average weight approach, the worst class of the project P32 is expected to be Group 3. However, it is assigned to Group 4 by UTADIS – POST OPT 2 for Reference Set 2. Besides, comparing the performances of the projects P38 and P56 with the third group reference set projects R38 and R33 respectively, both of the projects are anticipated to be placed to Group 3 rather that Group 4 as assigned by UTADIS – POST OPT 2 for Reference Set 2.

The Assignments of the Proposed Models

As stated before, the model APM1 can not distinguish between the classes satisfactorily and assigns the projects only to the first and fourth classes. Furthermore, the efficiency of the project P8 can not be obtained from APM1 for Reference Set 2. The reason of this situation is the low input criteria values preventing to satisfy the constraint equalizing sum of weighted inputs to one. Besides these handicaps, inadequacy of the assignments of APM1 is shown by some examples below.

The performance of project P6 is excellent and it is placed to Group 1 except for APM1 considering both of the reference sets. Although the project P9 is comparable with the reference set projects in Group 1, it is also assigned to Group 4 by APM1 application dealing with Reference Set 2. Moreover; the project P22 dominates R34, a reference set project of Group 3, and therefore it should not be assigned to Group 4, as in the case of AMP1 for Reference Set 2. The same project is placed to Group 1 when Reference Set 1 is utilized in APM1. This result is also not expected because of the insufficiencies in the performances of first dimension criteria and the criterion of collaboration of university and industry (3.3.1). In addition, it is realized that the achievements in the criteria of first and third dimensions of the project P24 are better than the ones of reference set project R32. In the second dimension, only the performance of the criterion of work packages and project schedule (2.1.2) is lower. Therefore, the expected worst class of this project is Group 3 whereas it is placed to Group 4 by AMP1 for both of the references. Finally, the worst class of the project P49 is also anticipated to be Group 3 compared to the reference set project R32. However, it is assigned to Group 4 by APM1 considering both of the reference sets.

Completing the discussions about APM1, the models of APM3 and AMP5 are analyzed in detail. An important characteristic of APM3 and APM5 are the stability of the results with respect to the reference set size changes compared to other methods. This property is due to the consideration of large number of projects, that is the total number of reference set and validation sample projects. However, dealing with all the projects simultaneously is also the shortcoming of the models from the perspective of TEYDEB evaluation approach. In AMP3 and APM5, the projects in the validation sample affect each other and can be determinative in terms of the efficiencies of the unevaluated projects. In these approaches, the best projects from the proposals are selected to be funded. However; each project is evaluated according to its achievements and its performance and it is not compared to the other proposed projects in TEYDEB. The reason of this evaluation methodology is the fact that projects are proposed and evaluated continuously in TEYDEB. Therefore, it is not possible to measure the performances of the all proposals at the same time and choose the bests from them. On the other hand, APM3 and APM5 can be applicable for the programs those accept the proposals by calls and evaluate all of them in the same time period, such as the funding programs of European Union.

It should also be notified that even if APM3 and APM5 are linear programs, the computation time of these models are longer compared to the other models due to larger number of evaluated projects. For example; APM2 and APM4 can be solved in a few seconds and in a few minutes respectively, but AMP3 and APM5 require nearly a day long computation for the case study in consideration. Nevertheless, this situation is not considered as a shortcoming since these models are solved once to assess all of the proposals.

Besides the methodological inconvenience of the models APM3 and APM5 for TEYDEB, the assignments obtained from these approaches may not meet the expectations. For example; the project P9 is placed to Group 2 by APM3 considering both of the reference sets. However, the performance of P9 is quite satisfying and it should be better if it is assigned to Group 1. Moreover, the project P17 dominates most of the reference set projects in Group 1 in terms of the first and second dimensions of the evaluation criteria. The only weakness of the project is the low score of the criterion collaboration of university and industry (3.3.1). In spite of this deficiency, this project should be placed into Group 1. But it is assigned to Group 2 by APM3 and APM5 for the both of the reference sets. Furthermore; since the project P18 dominates the reference set project R24 belonging to Group 3, its worst possible class can be Group 3. However, APM3 places the project to Group 4 for the Reference Set 1. In addition; comparing the project P25 with the reference set project R13 from Group 2, this project is expected to be assigned to Group 2. Even if the deficiency in the criterion of existence of required competence and degree of internal commitment (2.1.3.1) can be compensated by the criterion of collaboration of university and industry (3.3.1), this project is not anticipated to be in Group 1. But, P25 is placed to Group 1 by APM3 and APM5 for both of the reference sets. When the performance of the project P41 is investigated, it is realized that its scores especially in the criteria of novelty of the project output (1.2) and existence of required competence and degree of internal commitment (2.1.3.1) are not sufficient to assign the project to Group 2. As expected, all the models except for APM3 with Reference Set 1 place the project to the groups other than Group 2. Finally, although the project P51 outperforms the reference set project R32 in Group 3, it is assigned to Group 4 by APM3 considering both of the reference sets.

On the contrary; considering all the assignments of the project in validation sample by the models of AMP3 and APM5, it can be further stated that including more information about the judgments of the decision maker causes an improvement in the model performance in APM5.

The assignment models APM2 and APM4 deal with each project in the validation sample individually by comparing its performance only with the reference set projects. Therefore, these models are most suitable to the evaluation approach of TEYDEB.

When the performances of the models APM2 and APM4 are compared, it is realized that APM4 can meet the expectations better than APM2. This is due to the fact that the order of the reference set projects and the thresholds utilized to distinguish between the classes are regarded in APM4 based on the opinions of the decision makers. From Table 14, it can be stated that the improvement in the assignments is nearly 30% when APM4 is utilized rather that APM2. For instance; the project P10 should be placed to Group 1 since it outperforms the reference set project R8 in Group 1. The results of the model APM4 for both of the reference sets are in accordance with the expectation, but APM2 assigns the project to Group 2 for both of the reference sets. Additionally, the project P12 dominates the reference set project R14 belonging to Group 2 in terms of the first and second dimension criteria and anticipated to be in Group 2. This project is assigned to Group 2 by model APM4 for both references whereas APM2 assigns it to Group 3 for Reference Set 2. Furthermore; the project P17, expected to be placed to Group 1 as explained before, is assigned to Group 2 by APM2 for Reference Set 1. As a last example, the performance of P35 is regarded to be in parallel with the projects in Group 3, especially with R29. However, it is assigned to Group 2 by APM2 for Reference Set 2.

The effect of the reference set size on the performance of APM4 is analyzed in terms of statistics previously. When it is investigated in terms of assignments of the validation sample, it is realize that utilizing Reference Set 2 provides better results in most of the times compared to Reference Set 1 in APM4. For example; the performance of the project P22 in the first dimension is not sufficient to place it in Group 2. Moreover, comparing the achievements of the same project with the reference set project R29 in Group 3, it is realized that P22 can be assigned to Group 3 as it is the case for APM4 for Reference Set 2. Moreover, APM4 assigns the project P25 to Group 1 for Reference Set 1. However, the performance of P25 is not satisfactory enough to be in this group since it is not good especially in the criteria of methodology of the project (1.3), the existence of required competence and degree of internal commitment (2.1.3.1) and conducting market research (3.1.1). Furthermore, comparing the project with R13, a reference set project belonging to Group 2, the best possible class of P25 is regarded as Group 2. APM4 with Reference Set 2 meet this expectation for this project. In addition; in spite of the fact that the project

P48 is not good enough to be assigned to Group 2 in terms of the first and second dimension criteria, the model APM4 places it to Group 2 for Reference Set 1. On the contrary, the same model assigns the project to Group 3 for Reference Set 2 as expected when its performance is compared with the reference set projects in Group 3. The only project in which Reference Set 1 gives better assignment is P28. Due to the very low performances at the criteria of methodology of the project (1.3), novelty of the project output (1.2) and existence of required competence and degree of internal commitment (2.1.3.1), placement to Group 3 is not anticipated as in the case of APM4 application with Reference Set 2.

It should be noted that all these methods searches for the best possible efficiency values and assign the projects into the best classes. Even if the model APM4 that best corresponds to the evaluations in TEYDEB is utilized, the obtained results can be optimistic. For example; the projects P20, P21 and P37 are assigned to Group 2 by APM4 for both of the reference sets. However, the performances of these projects are similar to the reference set project R27 of Group 3. Furthermore; APM2 and APM5 also places the projects of P20 and P21 to Group 2.

In conclusion; besides the instability of estimated thresholds, the instability of the assignments of the UTADIS methods with respect to the type of post-optimality analysis and the reference set size are shown in this part. Furthermore; it is also noted that some important criteria subintervals receive the value of zero and this causes unrealistic assignments of the unevaluated projects in UTADIS. In addition; the need to solve the proposed linear programs for the placement of validation sample is emphasized by demonstrating the insufficiency of the reference set projects' average weights. Besides, it is mentioned that APM1 can not sort the unevaluated projects into the four classes but assigns them only to the first and fourth groups. Moreover, the inappropriateness of the methodologies of APM3 and APM5 to TEYDEB evaluation approach is explained. Declaring the most suitable assignment models as APM2 and APM4, after analyzing the results in detail it is concluded that APM4 with Reference Set 2 provides the best results due to the consideration of more judgments of the DMs compared to AMP2.

CHAPTER 7

CONCLUSIONS

In this study, the decision of choosing private sector conducted R&D projects in order to be funded by TEYDEB – TÜBİTAK is considered. For this purpose, DEA based sorting methods are proposed.

First of all, R&D project selection criteria in accordance with the aims and expected influences of TEYDEB are derived as a five level hierarchy. Due to the qualitative characteristics of the criteria, they are converted to quantitative measures with the assistance of the proposed point allocation guide. The independence of the criteria is also ensured.

In order to determine the importance of the evaluation criteria; from the AHP methods proposed by Wang and Elhag (2007) and Öztürk (2009), the method of Öztürk (2009) is utilized since its performance is better. By this method, interval priorities are obtained from interval comparison matrices considering the complexity of the criteria, uncertainties and risks of R&D projects, subjectivity of human judgments and group decision making approach of TEYDEB. As far as we know, the hierarchy developed for this study is the most complicated structure analyzed by AHP method in the literature.

Then, the interval priorities of the criteria are used as the assurance region constraints of the proposed DEA based sorting methods to introduce the managerial judgments and preferences into the models. By this way, the inappropriate weight assignment deficiency of DEA is also prevented. To our knowledge, integrating AHP method that determines interval priorities from interval comparison matrices and DEA is also the first attempt in the literature. Rather than using the pairwise comparison matrices directly to derive the assurance region constraints by assuming the matrices to be precise as in Zhu

(1996), the method proposed by Öztürk (2009) provides the advantage of accounting the inconsistencies of the judgments of the DMs.

The AHP method is only applied to obtain the importance of the criteria rather than assessing the proposals. This is due to the fact that the number of projects proposed to TEYDEB is quite large and constructing pairwise comparisons for all of them is impractical.

As also stated by Bouyssou (1999), Madlener et al. (2009) and Köksalan and Özpeynirci (2009); the classifying alternatives into preference related groups is more precise and provides more robust and confident results compared to the ranking of the alternatives. Therefore, it is decided to develop a sorting method for industrial R&D projects proposed to TEYDEB.

It is realized that evaluation criteria constitute the inputs and the outputs of the project proposals. Motivated by this property, DEA that assesses the efficiencies of the DMUs by the conversion rate of inputs into outputs is decided to be used for sorting the projects. The proposed two threshold estimation models, PM1 and PM2, and five assignment models, AMP1, APM2, AMP3, APM4 and APM5, based on DEA are the contributions to the literature as a first attempt of utilizing DEA for sorting.

The differences between the two threshold estimation models are the flexibility of the first model in terms of evaluating the projects by the most favorable weights and the restriction of the second model in terms of optimal weight dispersions of the projects. While PM1 estimates the thresholds with the most optimistic efficiencies, the projects are assessed more fairly by keeping the optimal weight sets of the projects close to each other in PM2.

Non-homogeneous dispersion of the input and output weights in DEA is also mentioned by Bal et al. (2008). They suggest introducing the minimization of the coefficient of variation of input and output weights as the second and third objectives to DEA model. However; this approach is proposed for ranking problems and the model is a non-linear optimization model that is harder to solve compared to the proposed linear programs.

The assignment model of PM1, APM1, is the DEA model with assurance regions. The remaining four assignment models are compatible with PM2. Both APM2 and APM4 evaluate the validation sample projects individually, therefore the unevaluated projects do not affect each other in these models. The difference between these models is the implementation of efficiency restrictions to the reference set projects based on the preferences of DMs and the results of PM2 in APM4. The APM3 and APM5 are the same as AM2 and APM4 models respectively; however they deal with the all validation sample in a single step. As a result, the projects in the validation sample affect each other in APM3 and APM5.

An important characteristic of the developed models is the consideration of preference disaggregation analysis by dealing with previously decided alternatives in order to identify the global judgments of DMs. This approach requires less time and cognitive effort from DMs compared to requiring the technical and preferential information directly from them.

Furthermore, the advantages of DEA are also valid for the proposed models such as handling multiple inputs and outputs and not demanding the explicit form of the input and output relationships. Besides, the problem of assigning weights in contradiction with the preferences of DMs in DEA is eliminated by the assurance region approach and preference disaggregation analysis.

The proposed models are applied to a case study to assess 60 unevaluated projects into four groups based on two reference sets including 20 and 46 projects respectively. The well-known sorting method UTADIS is also implemented to the same case study for two types of post-optimality analysis.

As explained in Köksalan and Özpeynirci (2009), there are many alternative solutions in UTADIS because of large number of decision varibles defining the parameters of the estimated utility function. As a remedy for alternative optimal solutions, applying post optimality analysis is proposed by Doumpos and Zopounidis (2002). However; as it is shown by two different post-optimality analysis, the estimated thresholds and the placements of the unevaluated projects are significantly depend on the type of the post optimality analysis and size of the reference set. Moreover, the weights of some important criteria subintervals are found as zero by UTADIS which means these criteria do not have an effect on the assessment of the projects. As a result of this deficiency, unrealistic assignments of unevaluated projects take place in UTADIS.

The constraints of the first threshold estimation model, PM1, is interpreted to be very loose that results in the thresholds determinative by the parameters of the model. In addition, APM1 is not satisfactory to distinguish between the four classes and it assigns all the unevaluated projects either the first or the fourth group. However, the thresholds estimated from PM2 are not significantly affected by the model parameters as PM1. Additionally, it also proposes realistic and stable results compared to PM1 and UTADIS. Moreover, the lack of discrimination in DEA is also improved by PM2 by constraining the weights.

An essential point of the proposed models is the determination of optimistic efficiency scores in the spirit of DEA. However, the most optimistic efficiencies of DEA are reduced to moderate optimism when PM2 and its compatible assignment models are used. Assessing the proposals that contain risk and uncertainty from a positive viewpoint is also appropriate in terms of TEYDEB approach.

Besides, the necessity of solving a linear model to place an unevaluated project into a group is also examined by considering the average weights of the reference set projects obtained from PM1 and PM2 as a constant set of evaluation weights. The unsatisfactory results of the average weight approach remark the need for a linear model compatible with the threshold estimation models.

The assignment models of APM3 and APM5 are the least sensitive models in terms of reference set size because of the larger number of projects assessed by these models. However, these models are not suitable to TEYDEB since receiving proposals and evaluating them are performed continuously and assessing all the proposals together is not possible in TEYDEB. On the other hand, these models are appropriate for the funding programs accepting proposals by calls.

APM2 and APM4 are the most suitable models for TEYDEB evaluation approach because of assessing each validation sample project separately. Comparing the performances of them, it is seen that APM4 is better than APM2 due to the consideration of more judgments of the DMs. In addition, increasing the reference set size the performance of APM4 is also increased.

Hence, integrated use of PM2 and APM4 for Reference Set 2 provides the best results in accordance with the viewpoints of TEYDEB. Furthermore, these models are quite stable compared to UTADIS.

It should be emphasized that the evaluations considered throughout the case study are based on the reports of the referees. The committee members other than TEYDEB managers are not included in this study. However, since the final decision of acceptance or rejection is made by the committee, an interactive approach based on the proposed methods can be developed as a future work.

REFERENCES

Adler, N., Friedman, L., Stern, Z. (2002). Review of Ranking Methods in the Data Enveleopment Analysis Context. *European Journal of Operations* Research, 140, 249-265.

Alidi, A.S. (1996). Use of the analytic hierarchy process to measure the initial viability of industrial projects. *International Journal of Project Management*, 14 (4), 205-208.

Andersen, P., Petersen, N. (1993). A Procedure for Ranking Efficient Units in Data Envelopment Analysis. *Management Science*, 39(10), 1261-1294.

Angulo-Meza, L., Lins, M. (2002). Review of Methods for Increasing Discrimination in Data Envelopment Analysis. *Annals of Opearations* Research, 116, 225-242.

Apostolou, B., Hassell, J. M. (1993). An Overview of the Analytic Hierarchy Process and Its Use in Accounting Research. *Journal of Accounting Literature*, 12 (1), 1-28.

Araz, C., Özkarahan, İ. (2007). Supplier Evaluation and Management System for Strategic Sourcing Based on a New Multicriteria Sorting Procedure. *International Journal of Production Economics*, 106(2), 585-606.

Arbel, A. (1989). Approximate Articulation of Preference and Priority Derivation. *European Journal of Operational Research*, 43, 317-326.

Arbel, A., Vargas, L.G. (1993). Preference Simulation and Preference Programming: Robustness Issues in Priority Deviation. *European Journal of Operation Research*, 69, 200-209.

Arbel, A., Vargas, L.G (2007). Interval Judgments and Euclidean Centers. *Mathematical and Computer Modelling*, 46, 976-984.

Azadeh, A., Ghaderi, S., Izadbakhsh, H. (2008). Integration of DEA and AHP with Computer Simulation for Railway System Improvement and Optimization. *Applied Mathematics and Computation*, 195, 775-785.

Bal, H., Örkcü, H., Çelebioğlu, S. (2008). A New Method Based on the Dispersion of Weights in Data Envelopment Analysis. *Computers & Industrial Engineering, 54, 502-512.*

Bal, H., Örkcü, H., Çelebioğlu, S. (2010). Improving the Discrimination Power and Weights Dispersion in the Data Envelopment Analysis. *Computers & Operations Research*, 37, 99-107.

Balachandra, R., Friar, J.H. (1997). Factors for success in R&D projects and new product innovation: A contextual framework. *IEEE Transactions on Engineering Management, 44 (3), 276-287.*

Bana e Costa, C., Vansnick, J.-C. (2008). A Critical Analysis of the Eigenvalue Method Used to Derive Prioritiesin AHP. *European Journal of Operational Research*, 187, 1422-1428.

Banker, R., Charnes, A., Cooper, W. (1984). Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis. *Management Science, 30(9), 1078-1092.*

Banuelas, R., Antony, J. (2004). Modified Analytic Hierarchy Process to Incorporate Uncertainty and Managerial Aspects. *International Journal of Production Research*, 42, 3851-3872.

Barzilai, J. (1997). Deriving Weights from Pairwise Comparison Matrices. *Journal of Operational Research Society, 48, 1226-1232.*

Barzilai, J., Golany, B. (1994). AHP Rank Reversal, Normalization and Aggregation Rules. *INFOR*, 32, 57-64.

Behzadian, M., Kazemzadeh, R., Albadvi, A., Aghdasi, M. (2010). PROMETHEE: A Comprehensive Literature Review on Methodologies and Applications. *European Journal of Operatinal Research*, 200(1), 198-215.

Belton, V., Gear, T. (1983). On a Shortcoming of Saaty's Method of Analytic Hierarchies. *Omega*, 11, 228-230.

Belton, V., Vickers, S. (1993). Demystifying DEA - A Visiual Interactive Approach Based on Multiple Criteria Analysis. *The Journal of the Operational Research* Society, 44(9), 883-896.

Bouyssou, D. (1999). Using DEA as a Tool for MCDM: Some Remarks. *The Journal of the Operational Research Society*, 50(9), 974-987.

Brans, J., Vincke, P. (1985). A Preference Ranking Organization Method: The PROMETHEE Method for Multiple Criteria Decision Making. *Management Science*, 31(6), 647-656.

Bryson, N., Mobourin, A. (1995). An Action Learning Evaluation Procedure for Multicriteria Decision Making Problems. *European Journal of Operational Research*, 96, 379-386.

Cai, Y., Wu, W. (2001). Synthetic Financial Evaluation by a Method of Combining DEA with AHP. *International Transactions in Operational Research*, 8, 603-609.

Cebeci, Ö.Z., Genç, S., Kerç, A., Karataş, H., Feyzioğlu, A., Coşkun, F., et al. (2006). Models of Evaluation for Research Proposals in Turkey. *NATO Advanced Research Workshop "Bulgarian Integration into European and NATO Policies-best practices".*

Chandran, B., Golden, B., Wasil, E. (2005). Linear Programming Models for Estimating Weights in the Analytic Hierarchy Process. *Computers & Operations Research* , 32, 2235-2254.

Charnes, A., Cooper, W. (1961). *Management Models and Industrial Applications of Linear Programming.* New York: John Wiley.

Charnes, A., Clark, C., Cooper, W., Golany, B. (1985). A Developmental Study of Data Envelopment Analysis in Measuring the Efficiency of Maintenance Units in the US Air Forces. *Annals of Operations Research*, 2, 95-112.

Charnes, C., Cooper, W., Rhodes, E. (1978). Measuring the Efficiency of Decision Making Units. *European Journal of Operational Research*, 2, 429-444.

Chen, Y., Hipel, K., Kilgour, D. (2008). A Multiple Criteria Sequential Sorting Procedure. *Journal of Industrial and Management Optimization*, 4(3),407-423.

Chiang, T.-A., Che, Z. (2010). A Fuzzy Robust Evaluation Model for Selecting and Ranking NDP Projects Using Bayesian Belief Network and Weight-Restricted DEA. *Expert Systems with Applications*, 37(11), 7408-7418.

Conde, E., Perez, M.D. (2010). A Linear Optimization Problem to Derive Relative Weights Using An Interval Judgement Matrix. *European Journal of Operational Research*, 201, 537-544.

Cook, W.D., Seiford, L.M. (1982). R&D project selection in a multidimensional environment: A practical approach. *The Journal of the Operational Research Society*, 33 (5), 397-405.

Cook, W.D., Seiford, L.M. (2009). Data Envelopment Analysis (DEA) - Thirty Years On. *European Journal of Operational Research*, 192, 1-7.

Cook, W., Kress, M., Seiford, L. (1992). Prioritization Models for Frontier Decision Making Units in DEA. *European Journal of Operational Research*, 59, 319-323.

Cook, W., Roll, Y., Kazakov, A. (1990). A DEA Model for Measuring the Relative Efficiency of Highway Maintenance Patrols. *INFOR*, 28(2), 113-124.

Cox, M.A. (2007). Examining Alternatives in the Analytic Hierarchy Process Using Complete Enumeration. *European Journal of Operational Research*, 180, 957-962.

Despotis, D. (2002). Improving the Discriminating Power of DEA: Focus on Globally Efficient Units. *Journal of the Operational Research Society*, 53, 314-323.

Dias, J., Figueira, J., Roy, B. (2010). Electre Tri-C: A Multiple Criteria Sorting Method Based on Characteristic Reference Actions. *European Journal of Operational Research*, 204(3), 565-580.

Dias, L., Mousseau, V., Figueira, J., Climaco, J. (2002). An Aggregation/Disaggregation Approach to Obtain Robust Conclusions with ELECTRE TRI. *European Journal of Operational Research*, 138(2), 332-348.

Doumpos, M., Zopounidis, C. (2002). *Multicriteria Decision Aid Classification Methods*. Boston: Kluwer Academic Publishers.

Doyle, J., Green, R. (1995). Cross-Evaluation in DEA: Improving Discrimination Among DMUs. *INFOR*, 33(3), 205-222.

Dyer, J.S. (1990). Remarks on the Analytic Hierarchy Process. *Management Science*, 36 (3), 249-258.

Dyson, R., Thannassoulis, E. (1988). Reducing Weight Flexibility in Data Envelopment Analysis. *The Journal of the Operational Research Society*, 39(6), 563-576.

Entani, T., Ichihashi, H., Tanaka, H. (2001). Optimistic Priority Weights with an Interval Comparison Matrix. *Proceedings of the Joint JSAI 2001 Workshop on New Frontiers,* 344-348.

Ertay, T., Ruan, D., Tuzkaya, U. (2006). Integrating Data Envelopment Analysis and Analytic Hierarchy for the Facility Layout Design in Manufacturing Systems. *Information Sciences*, 176, 237-262.

EUREKA. (n.d.). Retrieved June 17, 2010, from http://www.bicro.hr/docdokumenti/EUREKA%20PD013%20PAM%20manual%20130303.pdf.

Feng, Y., Lu, H., Bi, K. (2004). An AHP/DEA Methodology for Measurement of the Efficiency of R&D Management Activities in Universities. *International Transactions in Operational Research*, 11, 181-191.

Gattoufi, S., Oral, M., Reisman, A. (2004). Data Envelopment Analysis Literature: A Bibliography Update (1951-2001). *Socio-Economic Planning Sciences*, 38, 159-229.

Golany, B. (1988). An Interactive MOLP Procedure for the Extension of DEA to Effectiveness Analysis. *The Journal of the Operational Research Society*, 39(8), 725-734.

Haines, L.M. (1998). A Statistical Approach to the Analytic Hierarchy Process with Interval Judgments. (I). Distributions on Feasible Regions. *European Journal of Operational Research*, 110, 112-125.

Halme, M., Joro, T., Korhonen, P., Salo, S., Wallenius, J. (1999). A Value Efficiency Approach to Incorporating Preference Information in Data Envelopment Analysis. *Management Science*, 45(1), 103-115.

Henriksen, A. D., Trayner, A. J. (1999). A practical R&D project-selection scoring tool. *IEEE Transactions on Engineering Management*, 46 (2), 158-170.

Ho, W. (2008). Integrated Analytic Hierarchy Process and Its Applications. *European Journal of Operational Research*, 186, 211-228.

Hsu, Y.-G., Tzeng, G.-H., Shyu, J. Z. (2003). Fuzzy multiple criteria selection of government-sponsored frontier technology R&D projects. *R&D Management*, 33 (5), 539-551 .

Huang, C.C., Chu, P.Y., Chiang, Y.H. (2008). A fuzzy AHP application in government-sponsored R&D project selection. *Omega*, 36 (6), 1038-1052.

Islam, R., Biswal, M.P., Alam, S.S. (1997). Preference Programming and Inconsistent Interval Judgments. *European Journal of Operational Research*, 97, 53-62.

Johnson, S., Zhu, J. (2003). Identifying "Best" Aplicants in Recruiting Using Data Envelopment Analysis. *Socio-Economic Planning Sciences*, 37, 125-139.

Joro, T., Korhonen, P., Wallenius, J. (1998). Structural Comparison of Data Enveleopment Analysis and Multiple Objective Linear Programming. *Management Sciency*, 44(7), 962-970.

Joro, T., Korhonen, P., Zionts, S. (2003). An Interactive Approach to Improve Estimates of Value Efficiency in Data Envelopment Analysis. *European Journal of Operational Research*, 149, 688-699.

Keeney, R., Raiffa, H. (1993). *Decisions with Multiple Objectives: Preferences and Value Trade-Offs*. Cambridge: Cambridge University Press.

Köksalan, M., Tuncer, C. (2009). A DEA Based Approach to Ranking Multi-Criteria Alternatives. *International Journal of Information Technology & Decision Making*, 8(1), 29-54.

Köksalan, M., Mousseau, V., Özpeynirci, Ö., Özpeynirci, S. (2009). A New Outranking-Based Approach for Assigning Alternatives to Ordered Classes. *2008 Wiley Periodicals, Inc. Naval Research Logistics*, 56, 74-85.

Korhonen, P., Tainio, R., Wallenius, J. (2001). Value Efficiency Analysis of Academic Research. *European Journal of Operational Research*, 130, 121-132.

Korpela, J., Lehmusvaara, A., Nisonen, J. (2007). Warehouse Operator Selection by Combining AHP and DEA Methodologies. *International Journal of Production Economics*, 108, 135-142.

Kress, M. (1991). Approximate Articulation of Preference and Priority Derivation - A Comment. *European Journal of Operational Research*, 52, 382-383.

Lan, J., Lin, J., Cao, L. (2009). An Information Mining Method for Deriving Weights from an Interval Comparison Martix. *Mathematical and Computer Modelling*, 50, 393-400.

Lee, S., Mogi, G., Lee, S., Hui, K., Kim, J. (2010). Econometric Analysis of the R&D performance in the National Hydrogen Energy Technology Development for Measuring Relative Efficiency: The Fuzzy AHP/DEA Integrated Model. *International Journal of Hydrogen Energy*, 35, 2236-2246.

Levary, R.R., Wan, K. (1998). A Simulation Approach for Handling Uncertainty in the Analytic Hierarchy Process. *European Journal of Operational Research*, 106, 116-122.

Li, X.-B., Reeves, G. (1999). A Multiple Criteria Approach to Data Envelopment Analysis. *European Journal of Operational Research*, 115, 507-517.

Liberatore, M.J. (1987). An extension of the analytic hierarchy process for industrial R&D project selection and resource allocation. *IEEE Transactions on Engineering Management*, 34 (1), 12-18.

Liberatore, M.J., Nydick, R.L. (2008). The Analytic Hierarchy Process in Medical and Health Care Decision Making: A literature review. *European Journal of Operational Research*, 189, 194-207.

Linton, J.D., Walsh, S.T., Morabito, J. (2002). Analysis, ranking and selection of R&D projects in a portfolio. *R&D Management*, 32 (2), 139-148.

Liu, F. (2009). Acceptable Consistency Analysis of Interval Reciprocal Comparison Matrices. *Fuzzy Sets and Systems*, 160, 2686-2700.

Liu, F.-H., Peng, H. (2008). Ranking of Units on the DEA Frontier with Common Weights. *Computers & Operations Research*, 35, 1624-1637.

Lockett, G.B. (1986). Modelling a research portfolio using AHP: A group decision process. *R&D Management*, 16 (2), 151-160.

Lourenço, R., Costa, J. (2004). Using ELECTRE TRI Outranking Method to Sort MOMILP Nondominated Solutions. *European Journal of Operational Research*, 153(2), 271-289.

Lozano, S., Villa, G. (2009). Multiobjective Target Setting in Data Envelopment Analysis Using AHP. *Computers & Operations Research*, 36, 549-564.

Ma, L.-C., Li, H.-L. (2008). A Fuzzy Ranking Method with Range Reduction Techniques. *European Journal of Operational Research*, 184, 1032-2043.

Madlener, R., Antunes, C., Dias, L. (2009). Assessing the Performance of Biogas Plants with Multi-Criteria and Data Envelopment Analysis. *European Journal of Operational Research*, 197, 1084-1094.

Maidique, M., Zirger, B. (1984). A study of success and failure in product innovation: the case of the US electronics industry. *IEEE Transactions on Engineering Management*, 31 (4), 192-203.

Martino, J.P. (1995). *Research and development project selection.* New York: Wiley Interscience.

Mavrotas, G., Trifillis, P. (2006). Multicriteria Decision Analysis with Minimum Information: Combining DEA with MAVT. *Computers & Operations Research*, 33, 2083-2098.

Meade, L.M., Presley, A. (2002). R&D project selection using the analytic network process. *IEEE Transactions on Engineering Management*, 49 (1), 59-66.

Mohajeri, N., Amin, G. (2010). Railway Station Site Selection Using Analytical Hierarchy Process and Data Envelopment Analysis. *Computers and Industrial Engineering*, 59(1), 107-114.

Mohanty, R.P. (1992). Project selection by a multiple-criteria decision-making method: An example from a developing country. *International Journal of Project Management*, 10 (1), 31-38.

Mohanty, R.P., Agarwal, R., Choudhury, A.K., Tiwari, M.K. (2005). A fuzzy ANP based approach to R&D project selection: a case study. *International Journal of Production Research*, 43 (24), 5199-5216.

Morris, P.A., Olmsted Teisberg, E., Kolbe, A. (1991). When choosing R&D projects, go with long shots. *Research-Technology Management*, 34 (1), 35-40.

Öztürk, U. (2009). Interval priority weight generation from interval comparison matrices in Analytic Hierarchy Process. *MS Thesis*. Middle East Technical University.

Perez, J., Jimeno, J.L., Mokotoff, E. (2006). Another Potential Shortcoming of AHP. *An Official Journal of the Spanish Society of Statistics and Operations Research*, 14 (1), 99-111.

Pillai, A.S., Joshi, A., Rao, K.S. (2002). Performance measurement of R&D projects in a multi-project, concurrent engineering environment. *International Journal of Project Management*, 20, 165-177.

Podinovski, V.V. (2007). Interval Articulation of Superiority and Precise Elicitation of Priorities. *European Journal of Operational Research*, 180, 406-417.

Porter, J. (1978). Post audits and aid to research planning. *Research Management*, 11 (1), 28-30.

Pöyhönen, M.A., Hamalainen, R.P., Salo, A.A. (1997). An Experiment on the Numerical Modelling of Verbal Ratio Statements. *Journal of Multi-Criteria Decision Analysis*, 6, 1-10.

Ramanathan, R. (2006). Data Envelopment Analysis for Weight Derivation and Aggregation in the Analytic Hierarchy Process. *Computers & Operations Research*, 33, 1289-1307.

Ramanathan, R., Ramanathan, U. (2010). A Qualitative Perspective to Deriving Weights from Pairwise Comparison Matrices. *Omega*, 38, 228-232.

Saaty, T.L. (1980). *The Analytic Hierarchy Process*. New York: McGraw-Hill.

Saaty, T.L., Vargas, L. G. (1987). Uncertainty and Rank Order in the Analytic Hierarchy Process. *European Journal of Operational Research*, 32, 107-117.

Saaty, T.L., Vargas, L.G., Whitaker, R. (2009). Addressing with Brevity Criticism of the Analytic Hierarchy Process. *International Journal of the Analytic Hierarchy Process*, 1 (2), 121-134.

Saen, R., Memariani, A., Lotfi, F. (2005). Determining Relative Efficiency of Slightly Non-Homogeneous Decision Making Units by Data Envelopment Analysis: A Case Study in IROST. *Applied Mathematics and Computation*, 165, 313-328.

Salo, A.A., Hamalainen, R.P. (1997). On the Measurement of Preferences in the Analytic Hierarchy Process. *Journal of Multi-Criteria Decision Analysis*, 6 (6), 309-319.

Salo, A., Hamalainen, R.P. (1995). Preference Programming Through Approximate Ratio Comparisons. *European Journal of Operational Research*, 82, 458-475.

Salo, A., Hamalainen, R.P. (1992). Processing Interval Judgments in the Analytic Hierarchy Process. In: Goicoecha, A., Duckstein, L., Zionts, S. (Eds.), Multiple Criteria Decision Making. *Proceedings of the Ninth International Conference*, 359-372.

Schenkerman, S. (1997). Inducement of Nonexistent Order by the Analytic Hierarchy Process. *Decision Sciences*, 28 (2), 475-482.

Seiford, L. (1997). A Bibliography for Data Envelopment Analysis (1978-1996). *Annals of Operations Research*, 73, 393-438.

Seifort, L., Zhu, J. (1998). Identifying Excesses and Deficits in Chinese Industrial Productivity (1953-1990): A Weighted Data Envelopment Analysis Approach. *Omega*, 26(2), 279-296.

Sexton, T., Silkman, R., Hogan, A. (1986). Data Envelopment Analysis: Critique and Extensions. *In Measuring Efficiency: An Assesment of Data Envelopment Analysis*. San Francisco: Jossey-Bass.

Shang, J., Sueyoshi, T. (1995). A Unified Framework for the Selection of a Flexible Manufacturing System. *European Journal of Operational Research*, 85, 297-315.

Sinuany-Stern, Z., Mehrez, A., Hadad, Y. (2000). An AHP DEA Methodology for Ranking Decision Making Units. *International Transactions in Operational Research*, 7, 109-124.

Sipahi, S., Timor, M. (2010). The Analytic Hierarchy Process and Analytic Network Process: An Overview of Applications. *Management Decision*, 48 (5), 775-808.

Souder, W., Chakrabarti, A. (1978). The R&D marketing interface: Results from an emprical study of innovtion projects. *IEEE Transactions on Engineering Management*, 25 (4), 88-103.

Sowlati, T., Paradi, J., Suld, C. (2005). Information Systems Project Prioritization Using Data Envelopment Analysis. *Mathematical and Computer Modelling*, 41, 1279-1298.

Stam, A., Silva, A. P. (2003). On Multiplicative Priority Rating Methods for the AHP. *European Journal of Operational Research*, 145, 92-108.

Steuer, R. E., Na, P. (2003). Multiple Criteria Decision Making Combined with Finance: A Categorized Bibliographic Study. *European Journal of Operational Research*, 150, 496-515.

Stewart, T. (1996). Relationships Between Data Envelopment Analysis and Multicriteria Decision Analysis. *The Journal of the Operational Reserach Society*, 46, 654-665.

Sueyoshi, T., Shang, J., Chiang, W.-C. (2009). A Decision Support Framework forInternal Audit Prioritization in a Rental Car Company: A Combined Use Between DEA and AHP. *European Jorunal of Operational Research*, 199, 219-231.

Sugihara, K., Tanaka, H. (2001). Interval Evaluation in the Analytic Hierarchy Process by Possibility Analysis. *International Journal of Computational Intelligence*, 17, 567-579.

Sugihara, K., Ishii, H., Tanaka, H. (2004). Interval Priorities in AHP by Interval Regression Analysis. *European Journal of Operational Research*, 158, 745-754.

Takamura, Y., Tone, K. (2003). A Comperative Site Evaluation Study for Relocating Japanese Government Agencies Out of Tokyo. *Socio-Economic Planning Sciences*, 37, 85-102.

Tervonen, T., Figueira, J., Lahdelma, R., Dias, J., Salminen, P. (2009). A Stochastic Method for Robustness Analysis in Sorting Problems. *European Journal of Operational Research*, 192(1), 236-242.

Thompson, R., Singleton, F., Thrall, R., Smith, B. (1986). Comperative Site Evaluations for Locating a Highenergy Physics Lab in Texas. *Interfaces*, 16, 35-49.

Tohumcu, Z. (2007). R&D Project Performance Evaluation with Multiple and Interdependent Criteria. *MS Thesis*, Middle East Technical University.

Tone, K. (2001). A Slack-Based Measure of Efficiency in Data Envelopment Analysis. *Journal of Operational Research*, 130(3), 498-509.

Troutt, M. (1997). Derivation of the Maximin Efficiency Ratio Model from the Maximum Decisional Efficiency Principle. *Annals of Operations Research*, 73, 323-338.

Tseng, F.-M., Chiu, Y.-J., Chen, J.-S. (2009). Measuring Business Performance in the High-Tech Manufacturing Industry: A Case Study of Taiwan's Large-Sized TFT-LCD Panel Companies. *Omega*, 37, 686-697.

Tseng, Y.-F., Lee, T.-Z. (2009). Comparing Appropriate Decision Support of Human Resource Practices on Organizational Performance with DEA/AHP Model. *Expert Systems with Applications*, 36, 6548-6558.

TÜBİTAK Catalogue. (n.d). Retrieved September 18, 2010 from http://www.tubitak.gov.tr/tubitak_content_files/english/TUBITAKcatalogue.pdf.

TÜBİTAK-TEYDEB. (n.d.). Retrieved June 12, 2010, from www.teydeb.tubitak.gov.tr.

Ulucan, A., Atıcı, K. (2010). Efficiency Evaluatons with Context-Dependent and Measure-Specific Data Envelopment Approaches: An Application in a World Bank Supported Project. *Omega*, 38, 68-83.

Vaidya, O. S., Kumar, S. (2006). Analytic Hierarchy Process: An Overview of Applications. *European Journal of Operational Research*, 169, 1-29.

Wang, H., Che, Z., Chuang, C.-L. (2010). A Fuzzy AHP and DEA Approaches for Making Bank Loan Decisions for Small and Medium Enterprises in Taiwan. *Expert Systems with Applications*, 37(10), 7189-7199.

Wang, Y., Chin, K. (2009). A New Data Envelopment Analysis Method for Priority Determination and Group Decision Making in the Analytic Hierarchy Process. *European Journal of Operational Research*, 195, 239-250.

Wang, Y.-M. (2006). On Lexicographic Goal Programming Method for Generating Weights from Inconsistent Interval Comparison Matrices. *Applied Mathematics and Computation*, 173, 985-991.

Wang, Y.-M., Elhag, T. M. (2007). A Goal Programming Method for Obtaining Interval Weights from an Interval Comparison Matrix. *European Journal of Operational Research*, 177, 1, 458-471.

Wang, Y.-M., Chin, K.-S., Poon, G. (2008a). A Data Envelopment Analysis Method with Assurance Region for Weight Generation in the Analytic Hierarchy Process. *Decision Support Systems*, 45, 913-921.

Wang, Y.-M., Liu, J., Elhag, T. (2008c). An Integrated AHP DEA Methodology for Bridge Risk Assesment. *Computers & Industrial Engineering*, 54, 513-525.

Wang, Y.-M., Parkan, C., Luo, Y. (2008b). A Linear Programming Method for Generating the Most Favorable Weights from a Pairwise Comparison Matrix. *Computers & Operations Research*, 35, 3918-3930.

Wang, Y.-M., Yang, J.-B., Xu, D.-L. (2005b). A two-stage logarithmic goal programming method for generating weights from interval comparison matrices. *Fuzzy Sets and Systems*, 152, 475-498.

Wang, Y.-M., Yang, J.-B., Xu, D.-L. (2005a). Interval Weight Generation Approaches Based on Consistency Test and Interval Comparison Matrices. *Applied Mathematics and Computation*, 167, 252-273.

Wei, C.-P., Zhang, Y.-Z., Feng, X.-Q. (2007). Deriving Interval Weights from Interval Comparison Matrices Based on Consistency Test. *SETP*, 27 (10), 132-139.

Wong, Y.-H., Beasley, J. (1990). Restricting Weight Flexibility in Data Envelopment Analysis. *The Journal of the Operational Research Society*, 41(9), 829-835.

Yang, T., Kuo, C. (2003). A Hierarchical DEA/AHP Methodology for the Facilities Layout Design Problem. *European Journal of Operational Research Society*, 147, 128-136.

Yoo, H. (2003). A Study on the Efficiency Evaluation of Total Quality Management Activities in Korean Companies. *Total Quality Management*, 14(1), 119-128.

Yu, W. (1992). ELECTRE-TRI: Aspects Methodologiques Et Manuel D'Utilization. D*ocument du LAMSADE*, 74.

Zhu, J. (1996). DEA/AR Analysis of the 1988-1989 Performance of the Nanjing Textiles Corporation. *Annals of Operaions Research*, 66, 311-335.

Zopounidis, C., Doumpos, M. (1999). A Multicriteria Decision Aid Methodology for Sorting Decision Problems: The Case of Finanancial Stress. *Computational Economics*, 14, 197-218.

APPENDIX A

CURRENTLY USED PROJECT PROPOSAL EVALUATION REPORT

2. PROJENİN ENDÜSTRİYEL AR-GE İÇERİĞİ, TEKNOLOJİ DÜZEYİ VE YENİLİKÇİ YÖNÜ (I. BOYUT)

Uygun bulduğunuz kriterlere ait kutucukları işaretleyiniz.

ÇOK İYİ		
1	Günümüz teknoloji düzeyini ileri götüren bir projedir.	☐
2	Çalışma **uluslararası bazda** yenilik içermektedir.	☐
3	Proje sonuçları şartname, standart veya teknik regülasyonun geliştirilmesine yol açabilecek niteliktedir.	☐
4	Farklı teknoloji alanlarında yeni uygulamalara veya araştırma çalışmalarına yol açma potansiyeli vardır.	☐
5	Proje çıktısının tasarımı ve geliştirilmesi için gereken teknoloji proje sonunda ülkemize kazandırılarak teknolojik dışa bağımlılık azalmakta veya kalkmaktadır.	☐
6	Kendisinden yeni modellerin türetilebileceği temel bir ürünün (firmanın mevcut ürünlerinden farklı yeni bir ürün platformu) geliştirilmesi projesidir.	☐
	Konu başlığı ile ilgili varsa eklemek istediğiniz diğer kriterler:	

İYİ		
1	Çalışma ulusal bazda yenilik içermektedir.	☐
2	Çalışma ulusal teknolojik bilgi birikimine katkı sağlamaktadır.	☐
3	Projenin yeni Ar-Ge projeleri başlatma potansiyeli vardır.	☐
4	Proje çok sayıda alt sistem ve/veya modül içerdiğinden, farklı teknoloji alanlarında çalışılacaktır.	☐
5	Mevcut durumun (teknoloji, yöntem, ürün, süreç, teknik, sistem) iyileştirilmesi amaçlanmaktadır.	☐
6	Proje çıktısı, **firma için** yeni bir ürün/süreç niteliği taşımaktadır.	☐
7	Bilinen bir yöntemin, tekniğin veya teknolojinin yeni bir alana, sektöre, ürüne, ya da sürece uygulanmasını içermektedir.	☐
	Konu başlığı ile ilgili varsa eklemek istediğiniz diğer kriterler:	

İYİ DEĞİL/YETERSİZ		
1	Çalışmanın Ar-Ge sistematiği (analitik ve/veya deneysel yönden) yetersizdir.	☐
2	Projenin hedefi ve proje çıktılarının başarı ölçütleri tanımlanmamıştır.	☐
3	Proje çıktısının, teknolojik yapılabilme, kullanılabilme veya endüstriyel uygulamaya dönüşme olasılığı yoktur.	☐
4	Proje çıktısının benzerlerine göre karşılaştırmalı farklılığı/avantajı/üstünlüğü yoktur.	☐
5	Proje faaliyetleri ağırlıklı olarak teknoloji transferi niteliğindedir ve söz konusu teknoloji transferinin firmanın araştırma ve teknoloji geliştirme yeteneğine katkısı olmayacaktır.	☐
6	Proje çalışmaları rutin uygulamalardır.	☐
7	Proje üretime yönelik yatırım ağırlıklıdır.	☐
8	Kuruluşun bilgi birikimi, teknolojik altyapısı, beceri ve deneyimleri esas alındığında, proje firmanın Ar-Ge yeteneğini ve teknolojik bilgi birikimini artıracak nitelikte değildir.	☐
9	Proje çalışmaları firmanın desteklenen diğer Ar-Ge projelerinde kazandığı yeteneklerin tekrarı niteliğindedir.	☐
10	Firmanın Ar-Ge çalışmalarındaki özgün katkısı çok sınırlıdır, projedeki Ar-Ge çalışmaları hizmet alımı yapılan kurum/kuruluş tarafından yapılmaktadır ve kuruluşun bilgi birikimine katkısı olmayacaktır.	☐
	Konu başlığı ile ilgili varsa eklemek istediğiniz diğer kriterler	

BÖLÜMÜN GENEL DEĞERLENDİRMESİ

☐ ÇOK İYİ ☐ İYİ ☐ İYİ DEĞİL/YETERSİZ

3. PROJE PLANININ VE KURULUŞ ALTYAPISININ PROJE İÇİN UYGUNLUĞU (II. BOYUT)

Uygun bulduğunuz kriterlere ait kutucukları işaretleyiniz.

ÇOK İYİ		
1	Projede bilgi akışı ve karar alma süreçlerini gösteren kapsamlı bir yönetim planı yapılmıştır.	☐
2	Kuruluşta, projenin gerektirdiği tüm alanlarda bilgi birikimi vardır.	☐
3	Kuruluşta Ar-Ge birimi vardır ve bu birimde kuruluşun diğer faaliyetlerinde görev almayan/kullanılmayan, sadece Ar-Ge faaliyetlerine ayrılmış personel ve donanım bulunmaktadır.	☐
4	Kuruluş, Ar-Ge projelerinden elde ettiği bilgi ve deneyimin kalıcılığını sağlayacak yöntem ve mekanizmalara sahiptir.	☐
5	Kuruluşun, Ar-Ge sürecinde gözden geçirme ve iyileştirme sistemi vardır. Verilerin (zaman, kaynak, maliyet, hedefler v.b) izlenmesi, değerlendirilmesi ve sürecin geliştirilmesine yönelik adımlar bir sistematik içerisinde gerçekleştirilmektedir.	☐
6	Proje ekibinde bilimsel yetkinlikte araştırmacılar vardır.	☐
	Konu başlığı ile ilgili varsa eklemek istediğiniz diğer kriterler	

İYİ		
1	Kuruluşta Ar-Ge birimi vardır ancak bu birimde yer alan personel/donanım firmanın rutin faaliyetlerinde de kullanılmaktadır.	☐
2	Kuruluşun yeni ürün/süreç geliştirme ve tasarım yeteneği vardır.	☐
3	Proje çalışanlarının uzmanlık ve yetkinlikleri proje ile uyumlu ve yeterlidir.	☐
4	Proje yürütücüsünün veya ekibinin proje yürütme/gerçekleştirme tecrübesi vardır.	☐
5	Proje planı gerçekçi ve uygulanabilirdir. Iş paketleri ve alt iş paketleri bazında iş akış-zaman çizelgesi uygun bir şekilde hazırlanmıştır. İş paketleri arasındaki bağlantılar tanımlanmıştır.	☐
6	Proje gider kalemleri nicelik ve nitelik olarak yapılacak işle uyumludur.	☐
7	Proje süresi proje kapsamına göre çok iyi ayarlanmıştır.	☐
8	Proje çalışanlarının iş paketlerindeki görevleri belirlidir, adam/ay oranları ve toplam adam-ay değeri gerçekçidir.	☐
9	Kuruluşta projenin gerektirdiği bilgi birikimi olmakla birlikte yetersiz kalınan konular için danışmanlık veya hizmet alımları gerçekçi ve somut olarak planlanmıştır.	☐
	Konu başlığı ile ilgili varsa eklemek istediğiniz diğer kriterler.	

İYİ DEĞİL/YETERSİZ		
1	Proje ekibi proje önerisinin içerdiği teknolojik alanda sistematik bir Ar-Ge çalışması yürütülebilmesi için yeterli değildir.	☐
2	Kuruluşta, proje konusu ile ilgili en az lisans derecesine sahip herhangi bir proje personeli bulunmamaktadır.	☐
3	Kuruluşun Ar-Ge olanakları (laboratuvar, test ortamları, alet-teçhizat, yazılım araçları, bilgiye erişim olanakları, dokümantasyon sistematiği) projeyi yürütmek için uygun değildir.	☐
4	Firma proje sonucunda ortaya çıkacak bilgi birikimini ve yetenekleri içselleştirecek personel altyapısına sahip değildir.	☐
5	Projede kullanılması önerilen yöntem ve araçlar güncel teknolojiler ile uyumlu değildir.	☐
6	Proje Ar-Ge faaliyetlerinin gerektirdiği tüm alanlarda uzman personel mevcut değildir ve bu alanlardaki ihtiyaçların giderilmesine ilişkin planlama yapılmamıştır.	☐
7	Projenin teknik/teknolojik fizibilitesi yapılmamıştır.	☐
8	Proje çalışanlarının projeye katkısı belli değildir, görev paylaşımı yapılmamıştır.	☐
9	Proje faaliyetleri iş paketlerine doğru bir şekilde dağıtılmamıştır.	☐
10	Firma projedeki risk unsurlarını ve olası aksaklıkları yönetecek önlemleri planlamamıştır.	☐
11	Proje gider kalemlerinin proje faaliyetleriyle ilişkisi gerçekçi bir şekilde tanımlanmamıştır.	☐
12	Projenin bütçesini oluşturan kalemler için fiyat belirlemeye yönelik piyasa araştırması yapılmamıştır.	☐
13	Projenin izlenebilirliği açısından ara çıktıları ve başarı kriterleri tanımlanmamıştır.	☐
14	Proje önerisi ortak olarak sunulmuş ancak projenin iş planında ortaklar arasındaki iş dağılımı ve bütçe planlaması yetersizdir. (İlgili gerekçeyi 5. Bölümde ayrıntılı olarak açıklayınız.)	☐
15	Proje konusu Etik Kurul Onay Belgesi ve yasal/özel izin belgeleri gerektirmektedir ancak firmanın bu yönde herhangi bir başvurusu veya planlaması bulunmamaktadır.	☐
	Konu başlığı ile ilgili varsa eklemek istediğiniz diğer kriterler.	

4. PROJE ÇIKTILARININ EKONOMİK YARARA VE ULUSAL KAZANIMA DÖNÜŞEBİLİRLİĞİ (III. BOYUT)

Uygun bulduğunuz kriterlere ait kutucukları işaretleyiniz.

ÇOK İYİ		
1	Proje çıktısı firmanın küresel pazarda yer almasını sağlayacaktır.	☐
2	Proje çıktısı yeni bir pazar veya kullanım alanı oluşturmaktadır.	☐
3	Proje sonucunda ulusal güvenlik için gereken ve/veya tedarikinde güçlük çekilen ürün veya teknoloji geliştirilecektir.	☐
4	Doğal/sınırlı kaynakların değerlendirilmesi ve etkin kullanımı sağlanacaktır.	☐
5	Teknoloji tabanlı firmalar ortaya çıkarma potansiyeli bulunmaktadır.	☐
6	Projenin ve çıktılarının bölgeler arası gelişmişlik farklılığını azaltma etkisi olacaktır.	☐
7	Proje çıktısı yeni iş alanları yaratarak istihdamı arttıracaktır.	☐
8	Projenin bilimsel araştırmalara katkısı vardır.	☐
9	Projenin, Ar-Ge yeteneklerini geliştirerek Türkiye'nin küresel rekabet gücünü artırma potansiyeli vardır.	☐
10	Proje faaliyetleri ve çıktısının çevreye ve canlılara doğrudan olumlu etkileri vardır ve projenin temel hedeflerinden birisi budur.	☐
11	Proje faaliyetleri proje sonrasında firmaya uluslararası projelerde yer alma yeteneği ve olanağı kazandırabilecektir.	☐
	Konu başlığı ile ilgili varsa eklemek istediğiniz diğer kriterler	

İYİ		
1	Proje çıktısı ulusal ölçekte firmanın rekabet gücünü artırıcı niteliktedir.	☐
2	Proje çıktısı ithal edilen bir ürünün yerini alacaktır.	☐
3	Proje çıktısının ihraç potansiyeli vardır.	☐
4	Proje çıktısı patente konu olabilecektir.	☐
5	Proje, üniversite – sanayi işbirliği sürekliliğini sağlayacak niteliktedir.	☐
6	Projenin ve çıktılarının sosyo-kültürel hayata olumlu etkisi vardır.	☐
7	Proje faaliyetlerinin Ar-Ge işbirlikleri oluşturma etkisi vardır.	☐
8	Kuruluşa Ar-Ge projeleri yapabilme sürekliliği kazandıracak bir projedir.	☐
9	Projedeki işbirliklerinin yan sanayi geliştirme ve yan sanayiye bilgi aktarma etkisi vardır.	☐
10	Proje, konusuyla ilgili veya farklı sektörlerdeki araştırma çalışmalarına katkıda bulunmaktadır.	☐
11	Proje çıktılarının doğrudan ticarileşme potansiyeli ya da hedefi olmamakla birlikte aşağıdaki şartların hepsini sağlamaktadır. -Proje konusu uluslar arası düzeyde ticarileşmesi yaygın olarak gerçekleşmemiş ancak yakın gelecekte ticarileşeceği beklenen bir teknoloji alanındadır, -Projede yapılacak çalışmalar söz konusu teknoloji alanında bilgi birikimi oluşturmaya yöneliktir ve -Proje sonucunda elde edilecek bilgi birikimi ile uluslararası rekabetten kopulmayacaktır.	☐

İYİ DEĞİL/YETERSİZ		
1	Projenin ekonomik fizibilitesi yeterli düzeyde yapılmamış ve ekonomik katkısı incelenmemiştir.	☐
2	Müşteri beklentileri ve gereksinimleri dikkate alınarak pazar araştırması yapılmamıştır.	☐
3	Proje kapsamında mümkün olmasına rağmen, proje çıktısının firmada verimlilik, kalite veya standart artışı sağlaması veya maliyetleri azaltmasına yönelik planlama yapılmamıştır.	☐
4	Proje çıktısı ekonomik yarara dönüşebilir nitelikte değildir.	☐
5	Firmanın, proje sonuçlarını/çıktılarını uygulama iradesi ya da yetkisi yoktur.	☐
6	Proje faaliyetleri ve çıktısının çevreye ve canlılara olumsuz etkileri vardır ve bu konuda önleyici tedbir alınmamıştır.	☐
7	Firma, proje sonuçlarının ticarileşmesinin önündeki hukuki engeller konusunda bilgi sahibi değildir.	☐
	Konu başlığı ile ilgili varsa eklemek istediğiniz diğer kriterler	

BÖLÜMÜN GENEL DEĞERLENDİRMESİ

☐ ÇOK İYİ ☐ İYİ ☐ İYİ DEĞİL/YETERSİZ

APPENDIX B

THE QUESTIONNAIRE FOR OBTAINING THE IMPORTANCE OF R&D PROJECT SELECTION CRITERIA

The questionnaire that is composed of 9 set of questions conducted to the managers of TEYDEB in order to acquire the relative importance of the criteria is given in Table 16. The note instructing the managers is provided in Figure 17.

*** Soruları cevaplarken aşağıdaki ölçeği dikkate alınız.**
1- Eşit önemli
3- Biraz önemli
5- Fazla önemli
7- Çok fazla önemli
9- Son derece önemli

*** Soruları cevaplarken eğer sağdaki kriteri soldakine göre daha önemli buluyorsanız 3-5-7-9 sıralamasındaki kutucuklardan uygun olanını, soldaki kriteri sağdakine göre daha önemli buluyorsanız 9-7-5-3 sıralamasındaki kutucuklardan uygun olanını, iki kriteri eşit derecede önemli buluyorsanız 1 numaralı kutucuğu işaretleyiniz.**

***Her soru için yanlız bir kutucuğu işaretleyiniz.**

Figure 17: The instruction note of the questionnaire

Table 16: The questionnaire for acquiring the relative importance of the R&D project selection criteria

1) Desteklenmeye değer Ar-Ge projelerinin seçilmesi üzerindeki etkileri açısından değerlendirildiğinde aşağıda en sol ve en sağda belirtilen iki kriterden hangisi diğerine göre daha önemlidir ve kaç kat daha önemlidir?										
1. Projenin teknoloji, yenilik ve Ar-Ge düzeyi	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2. Proje planı ve kuruluşun Ar-Ge yapılanması/kültürü
1. Projenin teknoloji, yenilik ve Ar-Ge düzeyi	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3. Projenin sağlayacağı kazanımlar
2. Proje planı ve kuruluşun Ar-Ge yapılanması/kültürü	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3. Projenin sağlayacağı kazanımlar
2) Projenin teknoloji, yenilik ve Ar-Ge düzeyi üzerindeki etkileri açısından değerlendirildiğinde aşağıda en sol ve en sağda belirtilen iki kriterden hangisi diğerine göre daha önemlidir ve kaç kat daha önemlidir?										
1.1 Proje kullanılacak teknoloji	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	1.2 Proje çıktısının yeniliği
1.1 Proje kullanılacak teknoloji	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	1.3 Çalışmanın sistematiği/metodolojisi
1.2 Proje çıktısının yeniliği	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	1.3 Çalışmanın sistematiği/metodolojisi
3) Proje planı ve kuruluşun Ar-Ge yapılanması/kültürü üzerindeki etkileri açısından değerlendirildiğinde aşağıda en sol ve en sağda belirtilen iki kriterden hangisi diğerine göre daha önemlidir ve kaç kat daha önemlidir?										
2.1 Proje planı	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.2 Kuruluşun Ar-Ge yapılanması/ kültürü

Table 16 Continued: The questionnaire for acquiring the relative importance of the R&D project selection criteria

4) Projenin sağlayacağı kazanımlar üzerindeki etkileri açısından değerlendirildiğinde aşağıda en sol ve en sağda belirtilen iki kriterden hangisi diğerine göre daha önemlidir ve kaç kat daha önemlidir?										
3.1 Firmaya sağlayacağı ekonomik kazanımlar	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.2 Sosyo-ekonomik ve sosyo-kültürel kazanımlar
3.1 Firmaya sağlayacağı ekonomik kazanımlar	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.3 Ulusal bilgi birikimine katkı
3.2 Sosyo-ekonomik ve sosyo-kültürel kazanımlar	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.3 Ulusal bilgi birikimine katkı
5) Proje planı üzerindeki etkileri açısından değerlendirildiğinde aşağıda en sol ve en sağda belirtilen iki kriterden hangisi diğerine göre daha önemlidir ve kaç kat daha önemlidir?										
2.1.1 Proje yönetimi planlaması	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.1.2 İş paketleri ve iş planı akış-zaman çizelgesi
2.1.1 Proje yönetimi planlaması	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.1.3 Kaynak planlaması
2.1.1 Proje yönetimi planlaması	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.1.4 Gider kalemlerinin piyasa değerlerine uygunluğu
2.1.2 İş paketleri ve iş planı akış-zaman çizelgesi	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.1.3 Kaynak planlaması
2.1.2 İş paketleri ve iş planı akış-zaman çizelgesi	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.1.4 Gider kalemlerinin piyasa değerlerine uygunluğu
2.1.3 Kaynak planlaması	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.1.4 Gider kalemlerinin piyasa değerlerine uygunluğu

Table 16 Continued: The questionnaire for acquiring the relative importance of the R&D project selection criteria

6) Firmaya sağlayacağı ekonomik kazanımlar üzerindeki etkileri açısından değerlendirildiğinde aşağıda en sol ve en sağda belirtilen iki kriterden hangisi diğerine göre daha önemlidir ve kaç kat daha önemlidir?

3.1.1 Pazarda yer alma potansiyeli	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.1.2 Proje çıktısının karlılık potansiyeli, verimlilik artışına ve/veya maliyete etkisi

7) Sosyo-ekonomik ve sosyo-kültürel kazanımlar üzerindeki etkileri açısından değerlendirildiğinde aşağıda en sol ve en sağda belirtilen iki kriterden hangisi diğerine göre daha önemlidir ve kaç kat daha önemlidir?

3.2.1 Bölgeler arası gelişmişlik farklılığını azaltma	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.2.2 İstihdam
3.2.1 Bölgeler arası gelişmişlik farklılığını azaltma	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.2.3 Canlılara ve çevreye fayda
3.2.1 Bölgeler arası gelişmişlik farklılığını azaltma	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.2.4 Yaşlı, engelli vb. sosyal gruplara fayda
3.2.2 İstihdam	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.2.3 Canlılara ve çevreye fayda
3.2.2 İstihdam	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.2.4 Yaşlı, engelli vb. sosyal gruplara fayda
3.2.3 Canlılara ve çevreye fayda	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.2.4 Yaşlı, engelli vb. sosyal gruplara fayda

8) Ulusal bilgi birikimine katkı üzerindeki etkileri açısından değerlendirildiğinde aşağıda en sol ve en sağda belirtilen iki kriterden hangisi diğerine göre daha önemlidir ve kaç kat daha önemlidir?

3.3.1 Üniversite-sanayi işbirliği	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	3.3.2 Kuruluşlarla işbirliği

Table 16 Continued: The questionnaire for acquiring the relative importance of the R&D project selection criteria

9) Kaynak planlaması üzerindeki etkileri açısından değerlendirildiğinde aşağıda en sol ve en sağda belirtilen iki kriterden hangisi diğerine göre daha önemlidir ve kaç kat daha önemlidir?										
2.1.3.1 İş gücü planlaması, görev paylaşımı ve Ar-Ge çalışmalarına özgün katkı	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.1.3.2 Ar-Ge çalışmaları için gerekli personel haricindeki kalemlere yönelik planlama
2.1.3.1 İş gücü planlaması, görev paylaşımı ve Ar-Ge çalışmalarına özgün katkı	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.1.3.3 Finansal kaynak planlaması
2.1.3.2 Ar-Ge çalışmaları için gerekli personel haricindeki kalemlere yönelik planlama	☐ 9	☐ 7	☐ 5	☐ 3	☐ 1	☐ 3	☐ 5	☐ 7	☐ 9	2.1.3.3 Finansal kaynak planlaması

APPENDIX C

THE INTERVAL PAIRWISE COMPARISON MATRICES

$$Matrix\ 1 = \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array} \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{bmatrix} 1 & [3,7] & [1,7] \\ [1/7,1/3] & 1 & [1,5] \\ [1/7,1] & [1/5,1] & 1 \end{bmatrix} \end{array}$$

$$Matrix\ 2 = \begin{array}{c} \\ 1.1 \\ 1.2 \\ 1.3 \end{array} \begin{array}{c} \begin{array}{ccc} 1.1 & 1.2 & 1.3 \end{array} \\ \begin{bmatrix} 1 & [1/7,5] & [1/7,3] \\ [1/5,7] & 1 & [1/5,7] \\ [1/3,7] & [1/7,5] & 1 \end{bmatrix} \end{array}$$

$$Matrix\ 3 = \begin{array}{c} \\ 2.1 \\ 2.2 \end{array} \begin{array}{c} \begin{array}{cc} 2.1 & 2.2 \end{array} \\ \begin{bmatrix} 1 & [1/3,5] \\ [1/5,3] & 1 \end{bmatrix} \end{array}$$

$$Matrix\ 4 = \begin{array}{c} \\ 3.1 \\ 3.2 \\ 3.3 \end{array} \begin{array}{c} \begin{array}{ccc} 3.1 & 3.2 & 3.3 \end{array} \\ \begin{bmatrix} 1 & [1/7,3] & [1/5,5] \\ [1/3,7] & 1 & [1/5,5] \\ [1/5,5] & [1/5,5] & 1 \end{bmatrix} \end{array}$$

$$Matrix\ 5 = \begin{array}{c} \\ 2.1.1 \\ 2.1.2 \\ 2.1.3 \\ 2.1.4 \end{array} \begin{array}{c} \begin{array}{cccc} 2.1.1 & 2.1.2 & 2.1.3 & 2.1.4 \end{array} \\ \begin{bmatrix} 1 & [1/7,5] & [1/7,5] & [1/3,7] \\ [1/5,7] & 1 & [1/3,5] & [1/3,7] \\ [1/5,7] & [1/5,3] & 1 & [1,7] \\ [1/7,3] & [1/7,3] & [1/7,1] & 1 \end{bmatrix} \end{array}$$

$$Matrix\ 6 = \begin{array}{c} \\ 3.1.1 \\ 3.1.2 \end{array} \begin{array}{c} \begin{array}{cc} 3.1.1 & 3.1.2 \end{array} \\ \begin{bmatrix} 1 & [1/7,5] \\ [1/5,7] & 1 \end{bmatrix} \end{array}$$

$$
Matrix\ 7 = \begin{array}{c} \\ 3.2.1 \\ 3.2.2 \\ 3.2.3 \\ 3.2.4 \end{array}
\begin{array}{c} \begin{array}{cccc} 3.2.1 & 3.2.2 & 3.2.3 & 3.2.4 \end{array} \\
\begin{bmatrix} 1 & [1/5,1] & [1/5,5] & [1/5,5] \\ [1,5] & 1 & [1/5,5] & [1/3,5] \\ [1/5,5] & [1/5,5] & 1 & [1/3,3] \\ [1/5,5] & [1/5,3] & [1/3,3] & 1 \end{bmatrix} \end{array}
$$

$$
Matrix\ 8 = \begin{array}{c} \\ 3.3.1 \\ 3.3.2 \end{array}
\begin{array}{c} \begin{array}{cc} 3.3.1 & 3.3.2 \end{array} \\
\begin{bmatrix} 1 & [3,9] \\ [1/9,1/3] & 1 \end{bmatrix} \end{array}
$$

$$
Matrix\ 9 = \begin{array}{c} \\ 2.1.3.1 \\ 2.1.3.2 \\ 2.1.3.3 \end{array}
\begin{array}{c} \begin{array}{ccc} 2.1.3.1 & 2.1.3.2 & 2.1.3.3 \end{array} \\
\begin{bmatrix} 1 & [3,7] & [1,7] \\ [1/7,1/3] & 1 & [1,5] \\ [1/7,1] & [1/5,1] & 1 \end{bmatrix} \end{array}
$$

APPENDIX D

THE RESULTS OF THE AHP MODELS

The local interval weights of the criteria and sub-criteria obtained from the two methods by solving each matrix separately are given in Table 17 and Table 18. Since the largest matrix size is four, the lower and upper weights are represented by the symbols $w_1^L, \dots, w_4^L$ and $w_1^U, \dots, w_4^U$, respectively. The objective functions of the models at optimality are also given in parenthesis.

Table 17: The local weights of the criteria and sub-criteria determined from the method proposed by Wang and Elhag (2007)

	Matrix 1 (obj:0.140)	**Matrix 2** (obj:0.010)	**Matrix 3** (obj:0)	**Matrix 4** (obj:0.010)	**Matrix 5** (obj:0.036)	**Matrix 6** (obj:0)	**Matrix 7** (obj:0.121)	**Matrix 8** (obj:0)	**Matrix 9** (obj:0.140)
w_1^L	0.472	0.080	0.250	0.080	0.045	0.125	0.072	0.750	0.472
w_1^U	0.778	0.401	0.833	0.401	0.491	0.833	0.252	0.900	0.778
w_2^L	0.171	0.091	0.167	0.116	0.089	0.167	0.150	0.100	0.171
w_2^U	0.207	0.686	0.750	0.508	0.446	0.875	0.323	0.250	0.207
w_3^L	0.051	0.116	-	0.091	0.121	-	0.077	-	0.051
w_3^U	0.321	0.508	-	0.490	0.335	-	0.416	-	0.321
w_4^L	-	-	-	-	0.061	-	0.044	-	-
w_4^U	-	-	-	-	0.174	-	0.348	-	-

Table 18: The local weights of the criteria and sub-criteria determined from the method proposed by Öztürk (2009)

	Matrix 1 (obj:0.508)	**Matrix 2** (obj:0.181)	**Matrix 3** (obj:0)	**Matrix 4** (obj:0.141)	**Matrix 5** (obj:0.762)	**Matrix 6** (obj:0)	**Matrix 7** (obj:1.099)	**Matrix 8** (obj:0)	**Matrix 9** (obj:0.508)
w_1^L	1.661	0.277	0.577	0.324	0.287	0.378	0.299	1.732	1.661
w_1^U	3.555	1.427	2.236	1.485	2.010	2.236	1.495	3.000	3.555
w_2^L	0.602	0.342	0.447	0.430	0.402	0.447	0.499	0.333	0.602
w_2^U	0.920	2.319	1.732	1.969	2.010	2.646	1.495	0.577	0.920
w_3^L	0.306	0.397	-	0.342	0.402	-	0.299	-	0.306
w_3^U	1.000	2.049	-	1.866	2.010	-	1.495	-	1
w_4^L	-	-	-	-	0.287	-	0.299	-	-
w_4^U	-	-	-	-	0.862	-	1.495	-	-

APPENDIX E

THE CRITERIA VALUES OF THE PROJECTS EVALUATED IN THE CASE STUDY

The performances of the 60 validation sample projects according to the point allocation guide of the evaluation criteria given in Chapter 4 are given in Table 19. The validation sample projects are represented as P.

Table 19: The criteria values of the evaluated projects according to R&D project selection criteria

PROJECT	1			2							3							
	1.1	1.2	1.3	2.1						2.2	3.1		3.2				3.3	
				2.1.1	2.1.2	2.1.3			2.1.4		3.1.1	3.1.2	3.2.1	3.2.2	3.2.3	3.2.4	3.3.1	3.3.2
P1	7.50	5.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.00	2.50	10.00	7.50	5.00
P2	8.33	6.67	10.00	10.00	9.67	10.00	10.00	10.00	8.33	10.00	10.00	10.00	6.67	3.33	2.50	10.00	7.50	5.00
P3	5.83	5.00	10.00	10.00	10.00	10.00	10.00	10.00	8.33	10.00	10.00	10.00	6.67	3.33	7.50	1.67	10.00	5.00
P4	10.00	8.00	10.00	10.00	10.00	9.00	10.00	10.00	10.00	10.00	10.00	10.00	0.00	0.00	10.00	10.00	0.00	5.00
P5	10.00	5.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	8.50	10.00	10.00	0.00	0.00	10.00	2.50	5.00	5.00
P6	10.00	10.00	10.00	10.00	8.33	8.67	5.00	10.00	8.33	9.50	6.67	10.00	0.00	6.67	2.50	2.50	8.33	3.33
P7	9.00	9.00	9.50	8.50	7.50	10.00	10.00	10.00	10.00	9.50	10.00	10.00	5.00	10.00	2.50	6.25	7.50	10.00
P8	10.00	10.00	10.00	9.17	8.33	9.33	9.17	10.00	10.00	9.33	10.00	10.00	0.00	10.00	2.50	5.00	10.00	5.00
P9	7.50	10.00	8.75	10.00	7.50	9.50	10.00	10.00	10.00	7.50	10.00	10.00	0.00	0.00	2.50	2.50	7.50	5.00
P10	8.33	8.33	10.00	10.00	10.00	8.83	7.50	10.00	10.00	9.67	10.00	10.00	0.00	0.00	2.50	2.50	10.00	5.00
P11	10.00	9.50	10.00	9.50	10.00	8.90	10.00	10.00	9.00	9.00	10.00	10.00	0.00	0.00	5.00	2.50	6.67	5.00
P12	6.67	6.67	10.00	10.00	9.17	9.67	10.00	10.00	10.00	10.00	10.00	10.00	0.00	3.33	2.50	7.50	3.33	5.00
P13	10.00	8.33	10.00	8.33	10.00	10.00	9.00	10.00	9.50	8.00	10.00	10.00	3.33	3.33	2.50	2.50	10.00	6.67

Table 19 Continued: The criteria values of the evaluated projects according to R&D project selection criteria

PROJECT	1			2							3							
	1.1	1.2	1.3	2.1						2.2	3.1		3.2				3.3	
				2.1.1	2.1.2	2.1.3			2.1.4		3.1.1	3.1.2	3.2.1	3.2.2	3.2.3	3.2.4	3.3.1	3.3.2
P14	10.00	10.00	6.25	10.00	10.00	9.00	10.00	10.00	10.00	9.50	10.00	8.75	0.00	0.00	2.50	2.50	5.00	7.50
P15	8.33	6.67	10.00	8.33	10.00	9.67	7.50	10.00	10.00	10.00	10.00	10.00	0.00	3.33	10.00	5.00	6.67	10.00
P16	7.50	8.75	10.00	10.00	10.00	9.50	10.00	10.00	10.00	8.75	10.00	10.00	0.00	0.00	6.25	6.25	2.50	5.00
P17	10.00	10.00	9.17	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	8.33	0.00	0.00	2.50	2.50	1.67	5.00
P18	7.50	5.00	10.00	10.00	8.75	8.50	8.75	10.00	10.00	10.00	10.00	10.00	0.00	0.00	6.25	6.25	5.00	5.00
P19	10.00	6.67	5.00	5.00	8.33	8.33	7.50	10.00	8.33	8.00	6.67	10.00	3.33	0.00	2.50	10.00	3.33	5.00
P20	7.50	6.25	3.25	5.00	5.00	10.00	6.50	10.00	10.00	9.00	10.00	10.00	0.00	5.00	10.00	2.50	2.50	5.00
P21	6.67	5.83	3.83	5.00	10.00	6.00	7.50	10.00	10.00	6.33	6.67	8.33	0.00	6.67	2.50	2.50	8.33	5.00
P22	5.00	5.00	5.00	7.50	10.00	10.00	10.00	10.00	10.00	9.50	7.50	10.00	10.00	0.00	2.50	10.00	2.50	5.00
P23	6.67	5.00	5.83	6.67	9.17	5.00	7.50	10.00	10.00	9.33	5.00	6.67	0.00	3.33	10.00	2.50	1.67	5.00
P24	5.00	5.00	7.50	7.50	6.25	10.00	10.00	10.00	10.00	7.50	7.50	10.00	0.00	2.50	2.50	10.00	2.50	5.00
P25	8.33	7.50	5.00	6.67	8.33	3.83	7.50	10.00	8.33	8.33	3.33	10.00	6.67	3.33	5.00	2.50	8.33	5.00
P26	5.00	6.25	5.00	5.00	5.00	9.00	7.50	10.00	10.00	7.00	5.00	7.50	0.00	5.00	2.50	2.50	0.00	6.25

Table 19 Continued: The criteria values of the evaluated projects according to R&D project selection criteria

PROJECT	1			2							3							
				2.1							3.1		3.2				3.3	
	1.1	1.2	1.3	2.1.1	2.1.2	2.1.3			2.1.4	2.2	3.1.1	3.1.2	3.2.1	3.2.2	3.2.3	3.2.4	3.3.1	3.3.2
P27	5.00	4.17	5.00	5.00	8.33	7.33	10.00	10.00	8.33	10.00	3.33	10.00	0.00	1.67	2.50	2.50	0.00	5.00
P28	5.00	3.75	1.25	7.50	5.00	4.00	5.00	10.00	10.00	7.50	7.50	10.00	0.00	0.00	2.50	2.50	0.00	5.00
P29	5.00	2.50	2.50	5.00	10.00	9.00	10.00	10.00	10.00	10.00	5.00	5.00	0.00	0.00	2.50	2.50	0.00	5.00
P30	10.00	5.00	7.00	7.50	7.50	5.50	6.25	10.00	10.00	5.00	6.25	5.00	0.00	0.00	5.00	6.25	10.00	5.00
P31	5.00	5.00	2.50	7.50	7.50	3.00	10.00	10.00	10.00	10.00	5.00	5.00	0.00	0.00	5.00	10.00	0.00	2.50
P32	5.83	5.00	5.00	8.33	9.17	6.33	8.33	10.00	8.33	9.33	6.67	5.00	0.00	0.00	2.50	2.50	6.67	3.33
P33	5.00	6.67	5.00	9.17	10.00	7.33	6.67	10.00	10.00	9.33	3.33	5.00	0.00	0.00	2.50	2.50	6.67	5.00
P34	7.50	6.25	2.50	5.00	3.75	6.25	5.00	10.00	2.50	10.00	7.50	5.00	0.00	0.00	7.50	2.50	0.00	5.00
P35	5.00	3.33	4.17	6.67	8.33	4.67	6.67	10.00	10.00	7.67	6.67	5.00	1.67	8.33	2.50	7.50	10.00	5.00
P36	5.00	5.00	5.00	5.00	7.50	9.00	6.25	10.00	10.00	9.50	2.50	3.00	0.00	2.50	5.00	2.50	2.50	5.00
P37	7.50	5.83	3.33	6.67	5.00	4.33	5.83	10.00	10.00	10.00	6.67	6.67	0.00	0.00	3.33	2.50	8.33	5.00
P38	6.67	5.00	4.33	6.67	9.17	4.67	7.50	10.00	10.00	6.67	6.67	5.00	1.67	1.67	3.33	7.50	8.33	5.00
P39	5.00	4.17	1.67	6.67	6.67	4.17	7.50	10.00	10.00	10.00	5.00	5.00	0.00	3.33	2.50	10.00	3.33	5.00
P40	5.00	6.25	3.75	3.75	7.50	2.50	10.00	10.00	10.00	7.50	2.50	5.00	0.00	0.00	2.50	2.50	5.00	5.00

Table 19 Continued: The criteria values of the evaluated projects according to R&D project selection criteria

PROJECT	1			2								3							
				2.1							2.2	3.1		3.2				3.3	
	1.1	1.2	1.3	2.1.1	2.1.2	2.1.3			2.1.4			3.1.1	3.1.2	3.2.1	3.2.2	3.2.3	3.2.4	3.3.1	3.3.2
P41	5.33	2.17	5.83	3.33	8.33	3.83	6.67	10.00	10.00		6.67	1.67	5.00	10.00	0.00	2.50	2.50	0.00	6.67
P42	7.50	7.50	5.00	7.50	4.75	5.00	7.50	10.00	10.00		10.00	5.00	5.00	0.00	0.00	3.75	10.00	2.50	5.00
P43	5.00	3.75	5.00	4.00	4.75	5.50	6.25	10.00	10.00		10.00	10.00	5.00	0.00	0.00	7.50	6.25	2.50	5.00
P44	5.00	2.50	1.67	5.00	6.67	3.00	5.00	10.00	6.67		8.33	3.33	5.00	0.00	3.33	2.50	2.50	0.00	4.17
P45	5.00	4.17	5.00	6.67	6.67	6.00	6.67	10.00	10.00		10.00	5.00	5.00	0.00	3.33	5.00	5.00	0.00	4.17
P46	5.00	5.83	3.33	8.33	5.83	3.00	5.83	10.00	10.00		8.33	8.33	5.00	0.00	6.67	2.50	5.00	3.33	5.00
P47	4.17	4.17	1.67	5.00	2.50	1.33	10.00	10.00	10.00		5.00	3.33	5.00	0.00	0.00	2.50	2.50	0.00	3.33
P48	5.00	5.00	4.25	3.25	4.50	4.00	7.50	10.00	7.50		2.50	7.50	5.00	2.50	5.00	10.00	10.00	2.50	5.00
P49	3.33	10.00	7.50	8.33	5.83	8.33	7.50	10.00	8.33		10.00	10.00	5.00	0.00	0.00	2.50	2.50	0.00	4.17
P50	3.33	5.00	3.33	3.33	4.17	5.00	5.83	10.00	5.00		7.67	5.83	5.00	0.00	0.00	2.50	2.50	5.00	3.33
P51	5.17	5.75	6.25	5.00	5.00	7.83	6.67	10.00	10.00		6.67	8.33	5.00	0.00	3.33	3.33	2.50	0.00	4.17
P52	5.33	3.33	5.67	5.00	8.33	4.67	6.67	10.00	9.17		9.33	3.67	3.33	0.00	0.00	2.50	2.50	10.00	5.00
P53	2.50	3.33	4.17	4.17	8.33	5.67	8.33	10.00	10.00		6.67	6.67	4.17	0.00	3.33	2.50	2.50	0.00	2.50
P54	1.67	2.50	4.50	5.50	5.00	6.50	8.75	10.00	10.00		10.00	5.00	3.75	2.50	0.00	2.50	2.50	0.00	0.00

Table 19 Continued: The criteria values of the evaluated projects according to R&D project selection criteria

PROJECT	1			2							3							
				2.1						2.2	3.1		3.2				3.3	
	1.1	1.2	1.3	2.1.1	2.1.2	2.1.3			2.1.4		3.1.1	3.1.2	3.2.1	3.2.2	3.2.3	3.2.4	3.3.1	3.3.2
P55	5.00	5.00	3.75	4.50	2.50	2.00	5.00	10.00	10.00	10.00	3.50	5.00	5.00	0.00	6.25	2.50	0.00	5.00
P56	5.00	4.75	5.50	5.00	7.50	5.00	8.75	10.00	10.00	3.75	5.00	5.00	2.50	0.00	2.50	2.50	5.00	5.00
P57	6.25	6.75	7.50	5.00	8.75	7.00	7.50	10.00	7.50	7.50	5.00	5.00	0.00	0.00	10.00	6.25	2.50	3.75
P58	5.83	7.50	6.00	5.00	7.17	5.00	6.67	10.00	10.00	6.00	4.50	4.33	3.33	3.33	2.50	2.50	0.00	3.33
P59	5.00	4.17	5.00	6.67	5.00	4.67	5.00	10.00	10.00	3.33	5.00	6.33	3.33	0.00	2.50	2.50	6.67	4.17
P60	5.75	6.00	5.25	4.00	7.50	5.75	8.75	10.00	10.00	2.50	7.50	5.00	2.50	7.50	2.50	2.50	0.00	5.00

APPENDIX F

THE CRITERIA VALUES OF THE PROJECTS IN THE REFERENCE SETS

The performances of the projects in the Reference Set 1 and Reference Set 2 according to the point allocation guide of the evaluation criteria given in Chapter 4 are given in Table 20. The colors show the priority related four groups considered throughout the case study. The reference set projects are represented as R.

Table 20: The criteria values of the projects in the reference sets according to R&D project selection criteria

PROJECT	1			2							3							
	1.1	1.2	1.3	2.1						2.2	3.1		3.2				3.3	
				2.1.1	2.1.2	2.1.3			2.1.4		3.1.1	3.1.2	3.2.1	3.2.2	3.2.3	3.2.4	3.3.1	3.3.2
R1	8.00	9.00	9.00	9.50	7.50	7.50	7.50	10.00	10.00	10.00	10.00	5.00	2.50	7.50	2.50	2.50	5.00	5.00
R2	6.00	7.50	7.00	10.00	9.75	9.67	10.00	10.00	9.00	9.50	10.00	9.00	5.00	6.67	2.50	2.50	10.00	5.00
R3	7.50	9.50	7.50	8.00	9.50	10.00	9.75	10.00	5.00	7.50	7.50	10.00	0.00	5.00	6.25	2.50	2.50	10.00
R4	8.75	8.00	8.75	6.00	9.00	9.00	8.50	10.00	9.50	7.00	5.00	10.00	0.00	5.00	10.00	2.50	10.00	5.00
R5	6.00	9.17	9.17	8.33	8.33	8.00	8.00	10.00	8.00	7.50	10.00	10.00	0.00	0.00	2.50	10.00	5.00	5.00
R6	10.00	8.75	10.00	10.00	10.00	9.38	7.50	10.00	8.75	9.38	10.00	7.50	0.00	2.50	2.50	3.13	10.00	5.00
R7	10.00	9.17	9.00	10.00	6.67	8.67	5.00	10.00	10.00	10.00	10.00	10.00	0.00	3.33	2.50	2.50	10.00	5.00
R8	8.33	8.33	7.00	10.00	8.33	9.33	6.67	10.00	10.00	9.67	10.00	10.00	0.00	1.67	5.00	2.50	8.33	5.00
R9	7.50	8.13	7.50	7.50	8.00	7.50	8.75	10.00	7.50	8.75	7.50	10.00	3.75	6.25	10.00	3.13	7.50	5.00
R10	8.33	10.00	8.33	8.33	7.00	9.00	8.33	10.00	5.00	9.67	6.67	6.67	0.00	5.00	2.50	2.50	10.00	6.67

Table 20 Continued: The criteria values of the projects in the reference sets according to R&D project selection criteria

PROJECT	1			2							3							
	1.1	1.2	1.3	2.1						2.2	3.1		3.2				3.3	
				2.1.1	2.1.2	2.1.3			2.1.4		3.1.1	3.1.2	3.2.1	3.2.2	3.2.3	3.2.4	3.3.1	3.3.2
R11	6.25	7.00	6.25	7.50	10.00	8.50	7.50	10.00	9.75	5.00	2.50	5.00	0.00	0.00	2.50	2.50	5.00	5.00
R12	8.75	6.00	7.50	5.00	9.50	5.00	9.50	10.00	10.00	7.50	10.00	10.00	0.00	0.00	2.50	2.50	5.00	5.00
R13	8.33	7.50	6.00	6.67	10.00	9.33	8.33	10.00	9.50	10.00	5.00	5.00	0.00	0.00	2.50	2.50	0.00	3.00
R14	5.00	6.67	7.00	10.00	8.33	5.50	6.67	10.00	6.67	9.00	6.67	10.00	6.67	3.33	5.00	7.50	3.33	3.33
R15	7.50	6.67	6.50	5.00	6.67	6.67	6.67	10.00	9.95	9.67	5.00	6.67	0.00	0.00	2.50	5.00	5.00	5.00
R16	6.25	6.50	7.50	5.00	7.50	9.00	8.75	10.00	10.00	10.00	10.00	10.00	5.00	5.00	2.50	2.50	5.00	5.00
R17	8.50	6.67	6.67	10.00	5.50	9.33	6.67	10.00	8.00	10.00	6.67	7.50	5.00	3.33	2.50	2.50	6.67	4.00
R18	7.50	6.25	10.00	7.50	10.00	9.00	10.00	10.00	10.00	10.00	5.00	10.00	0.00	0.00	2.50	2.50	7.50	5.00
R19	7.50	8.33	6.67	5.00	7.50	6.00	7.50	10.00	10.00	8.33	10.00	7.00	0.00	3.33	2.50	5.00	0.00	5.00
R20	6.25	10.00	6.25	10.00	7.50	5.00	7.50	10.00	10.00	10.00	7.50	10.00	10.00	2.50	7.50	2.50	0.00	5.00
R21	8.13	6.88	6.25	10.00	7.00	5.50	6.88	10.00	10.00	8.50	10.00	8.00	2.50	0.00	2.50	4.38	6.25	5.00
R22	5.83	5.83	8.33	8.33	10.00	8.33	9.17	10.00	10.00	9.67	10.00	10.00	3.33	5.00	5.00	5.00	1.67	5.00
R23	5.00	6.50	6.67	5.00	8.00	5.00	7.50	10.00	10.00	5.17	5.50	6.67	0.00	0.00	2.50	2.50	10.00	5.00

Table 20 Continued: The criteria values of the projects in the reference sets according to R&D project selection criteria

PROJECT	1			2							3							
	1.1	1.2	1.3	2.1						2.2	3.1		3.2				3.3	
				2.1.1	2.1.2	2.1.3			2.1.4		3.1.1	3.1.2	3.2.1	3.2.2	3.2.3	3.2.4	3.3.1	3.3.2
R24	3.75	5.00	4.75	5.00	7.50	6.00	5.00	10.00	10.00	5.00	10.00	10.00	0.00	0.00	2.50	2.50	5.00	2.50
R25	5.00	4.00	5.00	9.67	6.00	5.00	9.50	10.00	10.00	9.00	7.50	7.50	0.00	0.00	7.50	2.50	0.00	5.00
R26	3.00	5.00	6.00	7.50	7.50	7.50	7.50	10.00	10.00	7.50	8.75	5.00	0.00	0.00	2.50	2.50	2.50	5.00
R27	7.50	6.25	3.75	5.00	5.50	6.25	10.00	10.00	9.00	10.00	5.00	5.00	0.00	5.00	2.50	6.25	10.00	5.00
R28	6.67	7.33	4.33	8.33	6.67	4.17	7.50	10.00	8.33	8.00	8.33	6.67	6.67	3.33	10.00	10.00	1.67	6.67
R29	5.00	4.75	4.25	7.50	7.50	4.50	5.00	10.00	10.00	10.00	7.50	8.75	0.00	5.00	2.50	2.50	0.00	5.00
R30	6.67	4.17	5.50	6.67	7.00	7.17	9.17	10.00	10.00	5.00	5.83	5.00	1.67	0.00	2.50	7.50	0.00	5.00
R31	4.50	5.00	5.83	8.33	7.50	5.00	10.00	10.00	10.00	8.33	5.00	6.67	1.67	3.33	10.00	5.00	6.67	8.33
R32	3.33	5.50	5.00	5.00	3.33	6.00	6.67	10.00	8.33	6.67	5.00	5.00	0.00	3.33	2.50	5.00	0.00	4.17
R33	5.00	3.75	4.50	4.75	7.00	6.75	8.75	10.00	10.00	2.50	7.50	5.00	0.00	10.00	2.50	2.50	5.00	5.00
R34	4.00	5.00	5.00	5.00	6.75	5.75	7.50	10.00	10.00	7.50	7.50	10.00	0.00	0.00	2.50	10.00	0.00	5.00
R35	5.00	5.00	4.00	7.50	6.00	7.50	7.50	10.00	10.00	9.50	5.00	7.50	0.00	0.00	2.50	10.00	7.50	5.00
R36	6.67	4.00	5.83	8.33	7.50	4.17	7.50	10.00	7.00	10.00	10.00	8.33	6.67	10.00	5.83	7.50	1.67	6.67

Table 20 Continued: The criteria values of the projects in the reference sets according to R&D project selection criteria

PROJECT	1			2							3							
				2.1							3.1		3.2				3.3	
	1.1	1.2	1.3	2.1.1	2.1.2	2.1.3			2.1.4	2.2	3.1.1	3.1.2	3.2.1	3.2.2	3.2.3	3.2.4	3.3.1	3.3.2
R37	7.50	5.00	3.50	5.00	2.00	2.00	2.00	10.00	10.00	3.75	5.00	7.50	0.00	5.00	2.50	6.25	0.00	5.00
R38	1.50	3.00	3.75	7.50	6.25	6.50	7.50	10.00	10.00	10.00	3.00	5.00	0.00	0.00	2.50	2.50	0.00	2.50
R39	2.50	2.50	3.00	5.00	6.67	5.33	6.67	10.00	9.17	9.33	3.33	5.00	0.00	0.00	2.50	2.50	1.67	3.33
R40	5.00	2.00	3.33	5.83	7.50	3.33	5.83	10.00	9.00	5.00	3.33	3.33	3.33	0.00	3.33	2.50	0.00	3.33
R41	2.50	2.50	6.25	8.75	6.25	8.00	7.50	10.00	8.00	9.50	2.00	2.00	0.00	0.00	2.50	6.25	0.00	5.00
R42	1.67	4.17	5.67	6.67	6.67	5.67	6.67	10.00	6.67	9.33	1.67	5.00	0.00	3.33	3.33	2.50	0.00	3.33
R43	3.75	5.00	2.50	5.00	8.75	8.75	7.50	10.00	7.50	5.00	2.50	5.00	10.00	0.00	2.50	2.50	0.00	5.00
R44	4.00	2.00	3.50	4.17	6.67	3.50	4.17	10.00	7.50	1.67	3.00	3.00	0.00	3.33	2.50	10.00	0.00	3.33
R45	3.67	5.00	3.00	6.67	4.17	2.00	5.83	10.00	10.00	6.33	3.33	3.33	3.33	0.00	2.50	5.00	6.67	6.67
R46	3.67	2.50	3.83	5.00	6.67	4.67	4.67	10.00	5.00	2.67	1.67	2.00	0.00	6.67	3.33	7.50	0.00	3.33

APPENDIX G

THE ASSURANCE REGION CONSTRAINTS OF THE PROPOSED MODELS

$$\frac{0.01}{12.809} \le \frac{v_{1f}}{v_{2f}} \le \frac{3.54}{0.037}$$

$$\frac{0.01}{19.890} \le \frac{v_{1f}}{u_{1f}} \le \frac{3.54}{0.022}$$

$$\frac{0.037}{19.890} \le \frac{v_{2f}}{u_{1f}} \le \frac{12.809}{0.022}$$

$$\frac{0.073}{4.323} \le \frac{v_{3f}}{v_{4f}} \le \frac{4.323}{0.148}$$

$$\frac{0.073}{0.914} \le \frac{v_{3f}}{v_{8f}} \le \frac{4.323}{0.073}$$

$$\frac{0.148}{0.914} \le \frac{v_{4f}}{v_{8f}} \le \frac{4.323}{0.073}$$

$$\frac{1.078}{0.988} \le \frac{v_{5f}}{v_{6f}} \le \frac{240.591}{0.111}$$

$$\frac{1.078}{1} \le \frac{v_{5f}}{v_{7f}} \le \frac{240.591}{0.006}$$

$$\frac{0.111}{1} \le \frac{v_{6f}}{v_{7f}} \le \frac{0.988}{0.006}$$

$$\frac{0.073}{4.323} \le \frac{v_{3f}}{v_{5f} + v_{6f} + v_{7f}} \le \frac{4.323}{0.148}$$

$$\frac{0.148}{4.323} \le \frac{v_{4f}}{v_{5f} + v_{6f} + v_{7f}} \le \frac{4.323}{0.148}$$

$$\frac{0.073}{4.323} \le \frac{v_{8f}}{v_{5f} + v_{6f} + v_{7f}} \le \frac{0.914}{0.148}$$

$$\frac{0.603}{1.657} \leq \frac{v_{3f} + v_{4f} + v_{5f} + v_{6f} + v_{7f} + v_{8f}}{v_{9f}} \leq \frac{2.097}{0.477}$$

$$\frac{1.661}{0.920} \leq \frac{v_{1f} + v_{2f} + u_{1f}}{v_{3f} + v_{4f} + v_{5f} + v_{6f} + v_{7f} + v_{8f} + v_{9f}} \leq \frac{3.555}{0.602}$$

$$\frac{0.236}{4.242} \leq \frac{u_{2f}}{u_{3f}} \leq \frac{3.303}{0.302}$$

$$\frac{0.093}{2.207} \leq \frac{u_{4f}}{u_{5f}} \leq \frac{2.207}{0.254}$$

$$\frac{0.093}{2.207} \leq \frac{u_{4f}}{u_{6f}} \leq \frac{2.207}{0.093}$$

$$\frac{0.093}{2.207} \leq \frac{u_{4f}}{u_{7f}} \leq \frac{2.207}{0.093}$$

$$\frac{0.254}{2.207} \leq \frac{u_{5f}}{u_{6f}} \leq \frac{2.207}{0.093}$$

$$\frac{0.254}{2.207} \leq \frac{u_{5f}}{u_{7f}} \leq \frac{2.207}{0.093}$$

$$\frac{0.093}{2.207} \leq \frac{u_{6f}}{u_{7f}} \leq \frac{2.207}{0.093}$$

$$\frac{1.207}{0.829} \leq \frac{u_{8f}}{u_{9f}} \leq \frac{7.768}{0.128}$$

$$\frac{0.324}{1.969} \leq \frac{u_{2f} + u_{3f}}{u_{4f} + u_{5f} + u_{6f} + u_{7f}} \leq \frac{1.485}{0.430}$$

$$\frac{0.324}{1.866} \leq \frac{u_{2f} + u_{3f}}{u_{8f} + u_{9f}} \leq \frac{1.485}{0.342}$$

$$\frac{0.430}{1.866} \leq \frac{u_{4f} + u_{5f} + u_{6f} + u_{7f}}{u_{8f} + u_{9f}} \leq \frac{1.969}{0.342}$$

$$\frac{1.661}{1} \leq \frac{v_{1f} + v_{2f} + u_{1f}}{u_{2f} + u_{3f} + u_{4f} + u_{5f} + u_{6f} + u_{7f} + u_{8f} + u_{9f}} \leq \frac{3.555}{0.306}$$

$$\frac{0.602}{1} \leq \frac{v_{3f} + v_{4f} + v_{5f} + v_{6f} + v_{7f} + v_{8f} + v_{9f}}{u_{2f} + u_{3f} + u_{4f} + u_{5f} + u_{6f} + u_{7f} + u_{8f} + u_{9f}} \leq \frac{0.920}{0.306}$$

APPENDIX H

THE CRITERIA SUBINTERVALS DETERMINED BY HEUR 2 FOR UTADIS APPLICATION

For Reference Set 1

The criteria that have one subinterval

2.1.3.3: [0, 10]

3.1.1: [0, 10]

3.2.1: [0, 10]

3.2.2: [0, 10]

3.2.3: [0, 10]

3.2.4: [0, 10]

3.3.2: [0, 10]

The criteria that have two subintervals

1.1: [0, 7.5] [7.5, 10]

1.2: [0, 7] [7, 10]

1.3: [0, 6.25] [6.25, 10]

2.1.1: [0, 8.33] [8.33, 10]

2.1.2: [0, 8.33] [8.33, 10]

2.1.3.1: [0, 6.5] [6.5, 10]

2.1.3.2: [0, 8.33] [8.33, 10]

2.1.4: [0, 9.95] [9.95, 10]

2.2: [0, 9] [9, 10]

3.1.2: [0, 9] [9, 10]

3.3.1: [0, 5] [5, 10]

For Reference Set 2

The criteria that have one subinterval

2.1.3.3: [0, 10]

The criteria that have two subintervals

3.2.1: [0, 3.33] [3.33, 10]

3.2.3: [0, 7.5] [7.5, 10]

The criteria that have three subintervals

3.2.2: [0, 3.33] [3.33, 5] [5, 10]

3.2.4: [0, 5] [5, 7.5] [7.5, 10]

3.3.2: [0, 5] [5, 6.67] [6.67, 10]

The criteria that have four subintervals

2.1.1: [0, 7.5] [7.5, 8.33] [8.33, 9.67] [9.67, 10]

2.1.2: [0, 6.67] [6.67, 7.5] [7.5, 9.75] [9.75, 10]

2.1.3.2: [0, 6.67] [6.67, 7.5] [7.5, 8.33] [8.33, 10]

2.1.4: [0, 8] [8, 9] [9, 9.95] [9.95, 10]

2.2: [0, 7.5] [7.5, 9.33] [9.33, 9.67] [9.67, 10]

3.1.1: [0, 5] [5, 7.5] [7.5, 8.75] [8.75, 10]

3.1.2: [0, 6.67] [6.67, 7.5] [7.5, 9] [9, 10]

The criteria that have five subintervals

1.2: [0, 5] [5, 6.25] [6.25, 7] [7, 8.75] [8.75, 10]

1.3: [0, 3.75] [3.75, 5] [5, 6.67] [6.67, 8.33] [8.33, 10]

3.3.1: [0, 1.67] [1.67, 5] [5, 6.67] [6.67, 8.33] [8.33, 10]

The criteria that have six subintervals

1.1: [0, 3.67] [3.67, 5] [5, 6.25] [6.25, 7.5] [7.5, 8.33] [8.33, 10]

2.1.3.1: [0, 5] [5, 6] [6, 7.5] [7.5, 8.33] [8.33, 9.33] [9.33, 10]

APPENDIX I

THE INFLUENCE OF THE MODEL PARAMETERS ON THE ESTIMATED THRESHOLDS

Table 21: The effect of the second objective function coefficient on the decision variables of PM1 for Reference Set 1 when $\alpha_1 = 1,\ \delta = 0.001$ *and* $s = 0.01$

Decision Variables	α_2				
	1	**10**	***15***	**20**	**30**
Objective Function	19.976	19.830	*19.820*	19.820	19.820
Objective 1	20.000	19.850	*19.820*	19.820	19.820
Objective 2	0.024	0.020	*0*	0	0
z_1	1.011	1.001	*0.999*	0.999	0.999
z_2	1.001	0.991	*0.989*	0.989	0.989
z_3	0.991	0.981	*0.979*	0.979	0.979

Table 22: The effect of the parameter δ on the decision variables of PM1 for Reference Set 1 when $\alpha_2 = 15$ and $s = 0.01$

Decision Variables	δ		
	0.0001	**0.005**	**0.0075**
Objective Function	19.847	19.700	19.550
Objective 1	19.847	19.700	19.550
Objective 2	0	0	0
z_1	1.000	0.995	0.993
z_2	0.990	0.985	0.978
z_3	0.980	0.975	0.963

Table 23: The effect of the parameter s *on the decision variables of PM1 for Reference Set 1 when* $\alpha_2 = 15$ *and* $\delta = 0.0075$

Decision Variables	s			
	0.05	**0.1**	**0.15**	**0.2**
Objective Function	19.025	18.275	17.525	16.775
Objective 1	19.025	18.275	17.525	16.775
Objective 2	0	0	0	0
z_1	0.992	0.992	0.993	0.993
z_2	0.942	0.892	0.843	0.793
z_3	0.892	0.792	0.693	0.593

Table 24: The effect of the second objective function coefficient on the decision variables of PM1 for Reference Set 2 when $\alpha_1 = 1,\ \delta = 0.001\ and\ s = 0.01$

Decision Variables	α_2					
	1	**10**	**20**	**30**	***36***	**50**
Objective Function	45.976	45.760	45.654	45.610	*45.598*	45.598
Objective 1	46.000	45.904	45.854	45.670	*45.598*	45.598
Objective 2	0.024	0.144	0.200	0.060	*0*	0
z_1	1.011	1.009	1.009	1.001	*0.999*	0.999
z_2	1.001	0.999	0.999	0.991	*0.989*	0.989
z_3	0.991	0.989	0.989	0.981	*0.979*	0.979

Table 25: The effect of the parameter δ *on the decision variables of PM1 for Reference Set 2 when* $\alpha_2 = 36$ *and* $s = 0.01$

Decision Variables	δ		
	0.0001	**0.005**	**0.0075**
Objective Function	45.663	45.310	44.965
Objective 1	45.663	45.310	44.965
Objective 2	0	0	0
z_1	1.000	0.995	0.992
z_2	0.990	0.985	0.978
z_3	0.980	0.975	0.963

Table 26: The effect of the parameter s *on the decision variables of PM1 for Reference Set 2 when* $\alpha_2 = 36$ *and* $\delta = 0.0075$

Decision Variables	s			
	0.05	**0.1**	**0.15**	**0.2**
Objective Function	43.810	42.160	40.510	38.860
Objective 1	43.810	42.160	40.510	38.860
Objective 2	0	0	0	0
z_1	0.992	0.992	0.992	0.992
z_2	0.942	0.892	0.842	0.792
z_3	0.892	0.792	0.692	0.592

Table 27: The effect of the objective function coefficients on the decision variables of PM2 for Reference Set 1 when $s = 0.01$ *and* $\delta = 0.001$

Decision Variables									
	α_1	**1**	**1**	**1**	**1**	**1**	**1**	***1***	**1**
	α_2	**1**	**100**	**10,000**	**1,000,000**	**100,000,000**	**5,000,000**	***10,000,000***	**100,000,000**
	α_3	**1**	**1**	**10**	**1000**	**1000**	**10,000**	***10,000***	**100,000**
Objective Function		-30.613	-32.104	-446.844	-46,028	-46,028	-460,400	*-460,400*	-4,604,122
Objective 1		13.977	14.329	13.573	13.559	13.559	13.559	*13.559*	13.559
Objective 2		0.087	0	0	0	0	0	*0*	0
Objective 3		44.503	46.433	460.417	46,041	46,041	460,414	*460,414*	4,604,136
z_1		0.939	0.892	0.976	0.974	0.974	0.879	*0.879*	0.879
z_2		0.705	0.735	0.697	0.697	0.697	0.697	*0.697*	0.697
z_3		0.489	0.607	0.532	0.530	0.530	0.530	*0.530*	0.530

Table 28: The effect of the parameter δ on the decision variables of PM2 for Reference Set 1 when $\alpha_1 = 1$, $\alpha_2 = 10{,}000{,}000$, $\alpha_3 = 10{,}000$ and $s = 0.01$

Decision Variables	δ		
	0.0001	**0.005**	**0.0075**
Objective Function	-460,202	-461,284	-461,840
Objective 1	13.563	13.446	13.315
Objective 2	0	0	0
Objective 3	460,216	461,297	461,853
z_1	0.975	0.875	0.936
z_2	0.698	0.691	0.684
z_3	0.530	0.529	0.530

Table 29: The effect of the parameter s *on the decision variables of PM2 for Reference Set 1 when* $\alpha_1 = 1$, $\alpha_2 = 10{,}000{,}000$, $\alpha_3 = 10{,}000$ *and* $\delta = 0.0075$

Decision Variables	*s*			
	0.05	**0.1**	**0.15**	**0.2**
Objective Function	-461,840	-461,840	-461,840	-462,812
Objective 1	13.315	13.315	13.315	13.629
Objective 2	0	0	0	0
Objective 3	461,853	461,853	461,853	462,826
z_1	0.936	0.874	0.874	0.915
z_2	0.684	0.684	0.684	0.715
z_3	0.530	0.530	0.530	0.515

Table 30: The effect of the objective function coefficients on the decision variables of PM2 for Reference Set 2 when $s = 0.01$ *and* $\delta = 0.001$

Decision Variables									
	α_1	**1**	**1**	**1**	**1**	**1**	**1**	***1***	**1**
	α_2	**1**	**100**	**10,000**	**1,000,000**	**100,000,000**	**5,000,000**	***10,000,000***	**100,000,000**
	α_3	**1**	**1**	**10**	**1000**	**1000**	**10,000**	***10,000***	**100,000**
Objective Function		-430.892	-438.137	-4,698	-472,883	-472,883	-4,729,104	-4,729.104	-47,291,313
Objective 1		33.412	32.791	31.074	30.710	30.710	30.710	30.710	30.710
Objective 2		0.099	6.3	0	0	0	0	0	0
Objective 3		464.205	464.628	4,729	472,914	472,914	4,729,135	4,729,135	47,291,344
z_1		0.912	0.852	0.832	0.830	0.830	0.830	0.830	0.830
z_2		0.722	0.768	0.714	0.696	0.696	0.696	0.696	0.696
z_3		0.566	0.547	0.512	0.505	0.505	0.505	0.505	0.505

Table 31: The effect of the parameter δ on the decision variables of PM2 for Reference Set 2 when $\alpha_1 = 1$, $\alpha_2 = 10{,}000{,}000$, $\alpha_3 = 10{,}000$ and $s = 0.01$

Decision Variables	δ		
	0.0001	**0.005**	**0.0075**
Objective Function	-4,727,852	-4,734,666	-4,738,142
Objective 1	30.722	30.653	30.618
Objective 2	0	0	0
Objective 3	4,727,883	4,734,697	4,738,173
z_1	0.830	0.828	0.827
z_2	0.696	0.699	0.701
z_3	0.506	0.499	0.495

Table 32: The effect of the parameter s on the decision variables of PM2 for Reference Set 2 when $\alpha_1 = 1$, $\alpha_2 = 10{,}000{,}000$, $\alpha_3 = 10{,}000$ *and* $\delta = 0.0075$

Decision Variables	*s*			
	0.05	**0.1**	**0.15**	**0.2**
Objective Function	-4,738,142	-4,738,142	-4,738,635	-4,740,287
Objective 1	30.618	30.618	30.987	31.324
Objective 2	0	0	0	0
Objective 3	4,738,173	4,738,173	4,738,666	4,740,318
z_1	0.827	0.827	0.857	0.907
z_2	0.701	0.701	0.707	0.707
z_3	0.495	0.495	0.504	0.507

APPENDIX J

THE AVERAGE WEIGHTS OF INPUT AND OUTPUT CRITERIA DETERMINED FROM THE PROSPOSED THRESHOLD ESTIMATION MODELS

PM1 and POST OPT 1 for Reference Set 1

$v_{1,ave} = 0.197$	$u_{1,ave} = 0.141$
$v_{2,ave} = 0.045$	$u_{2,ave} = 0.013$
$v_{3,ave} = 0.010$	$u_{3,ave} = 0.013$
$v_{4,ave} = 0.005$	$u_{4,ave} = 0.006$
$v_{5,ave} = 0.002$	$u_{5,ave} = 0.006$
$v_{6,ave} = 0.00026$	$u_{6,ave} = 0.003$
$v_{7,ave} = 0.00009$	$u_{7,ave} = 0.003$
$v_{8,ave} = 0.005$	$u_{8,ave} = 0.011$
$v_{9,ave} = 0.050$	$u_{9,ave} = 0.001$

PM1 and POST OPT 1 for Reference Set 2

$\mathrm{v}_{1,\mathrm{ave}} = 0.192$	$u_{1,ave} = 0.070$
$\mathrm{v}_{2,\mathrm{ave}} = 0.069$	$u_{2,ave} = 0.024$
$\mathrm{v}_{3,\mathrm{ave}} = 0.013$	$u_{3,ave} = 0.015$
$\mathrm{v}_{4,\mathrm{ave}} = 0.008$	$u_{4,ave} = 0.007$
$\mathrm{v}_{5,\mathrm{ave}} = 0.011$	$u_{5,ave} = 0.008$
$\mathrm{v}_{6,\mathrm{ave}} = 0.007$	$u_{6,ave} = 0.006$
$\mathrm{v}_{7,\mathrm{ave}} = 0.00043$	$u_{7,ave} = 0.020$
$\mathrm{v}_{8,\mathrm{ave}} = 0.008$	$u_{8,ave} = 0.017$
$\mathrm{v}_{9,\mathrm{ave}} = 0.071$	$u_{9,ave} = 0.004$

PM2 and POST OPT 1 for Reference Set 1

$v_{1,ave} = 0.148$ $u_{1,ave} = 0.078$
$v_{2,ave} = 0.044$ $u_{2,ave} = 0.010$
$v_{3,ave} = 0.073$ $u_{3,ave} = 0.005$
$v_{4,ave} = 0.004$ $u_{4,ave} = 0.018$
$v_{5,ave} = 0.005$ $u_{5,ave} = 0.002$
$v_{6,ave} = 0.002$ $u_{6,ave} = 0.013$
$v_{7,ave} = 0.001$ $u_{7,ave} = 0.00074$
$v_{8,ave} = 0.004$ $u_{8,ave} = 0.013$
$v_{9,ave} = 0.030$ $u_{9,ave} = 0.00057$

PM2 and POST OPT 1 for Reference Set 2

$v_{1,ave} = 0.104$ $u_{1,ave} = 0.044$
$v_{2,ave} = 0.138$ $u_{2,ave} = 0.013$
$v_{3,ave} = 0.010$ $u_{3,ave} = 0.019$
$v_{4,ave} = 0.021$ $u_{4,ave} = 0.004$
$v_{5,ave} = 0.016$ $u_{5,ave} = 0.006$
$v_{6,ave} = 0.013$ $u_{6,ave} = 0.002$
$v_{7,ave} = 0.00008$ $u_{7,ave} = 0.007$
$v_{8,ave} = 0.024$ $u_{8,ave} = 0.018$
$v_{9,ave} = 0.031$ $u_{9,ave} = 0.012$

APPENDIX K

THE OPTIMAL VALUES OF THE SUBINTERVAL UTILITY VALUES USED IN UTADIS APPLICATION

<u>For Reference Set 1</u>

The criteria that have one subinterval

$w_1(2.1.3.3) = 0$

$w_1(3.1.1) = 0$

$w_1(3.2.1) = 0$

$w_1(3.2.2) = 0$

$w_1(3.2.3) = 0$

$w_1(3.2.4) = 0$

$w_1(3.3.2) = 0$

The criteria that have two subintervals

$w_2(1.1, 1) = 0.096$

$w_2(1.1, 2) = 0$

$w_2(1.2, 1) = 0.162$

$w_2(1.2, 2) = 0.082$

$w_2(1.3, 1) = 0.196$

$w_2(1.3, 2) = 0.048$

$w_2(2.1.1, 1) = 0$

$w_2(2.1.1, 2) = 0.055$

$w_2(2.1.2, 1) = 0$

$w_2(2.1.2, 2) = 0$

$w_2(2.1.3.1, 1) = 0.078$

$w_2(2.1.3.1, 2) = 0.056$

$w_2(2.1.3.2, 1) = 0.050$

$w_2(2.1.3.2, 2) = 0$

$w_2(2.1.4, 1) = 0$

$w_2(2.1.4, 2) = 0.014$

$w_2(2.2, 1) = 0$

$w_2(2.2, 2) = 0$

$w_2(3.1.2, 1) = 0.122$

$w_2(3.1.2, 2) = 0$

$w_2(3.3.1, 1) = 0.040$

$w_2(3.3.1, 2) = 0$

<u>For Reference Set 2</u>

The criteria that have one subinterval

$w_1(2.1.3.3) = 0$

The criteria that have two subintervals

$w_2(3.2.1, 1) = 0$
$w_2(3.2.1, 2) = 0$
$w_2(3.2.3, 1) = 0$
$w_2(3.2.3, 2) = 0$

The criteria that have three subintervals

$w_3(3.2.2, 1) = 0.006$
$w_3(3.2.2, 2) = 0.015$
$w_3(3.2.2, 3) = 0$
$w_3(3.2.4, 1) = 0$
$w_3(3.2.4, 2) = 0$
$w_3(3.2.4, 3) = 0$
$w_3(3.3.2, 1) = 0$
$w_3(3.3.2, 2) = 0$
$w_3(3.3.2, 3) = 0$

The criteria that have four subintervals

$w_4(2.1.1, 1) = 0$
$w_4(2.1.1, 2) = 0$
$w_4(2.1.1, 3) = 0$
$w_4(2.1.1, 4) = 0$
$w_4(2.1.2, 1) = 0$
$w_4(2.1.2, 2) = 0.041$
$w_4(2.1.2, 3) = 0.040$
$w_4(2.1.2, 4) = 0$
$w_4(2.1.3.2, 1) = 0$
$w_4(2.1.3.2, 2) = 0$
$w_4(2.1.3.2, 3) = 0$
$w_4(2.1.3.2, 4) = 0$

$w_4(2.1.4, 1) = 0$
$w_4(2.1.4, 2) = 0$
$w_4(2.1.4, 3) = 0$
$w_4(2.1.4, 4) = 0$
$w_4(2.2, 1) = 0$
$w_4(2.2, 2) = 0$
$w_4(2.2, 3) = 0.009$
$w_4(2.2, 4) = 0$
$w_4(3.1.1, 1) = 0.179$
$w_4(3.1.1, 2) = 0.021$
$w_4(3.1.1, 3) = 0$
$w_4(3.1.1, 4) = 0$

$w_4(3.1.2, 1) = 0.002$
$w_4(3.1.2, 2) = 0$
$w_4(3.1.2, 3) = 0.025$
$w_4(3.1.2, 4) = 0$

The criteria that have five subintervals

$w_5(1.2, 1) = 0$

$w_5(1.2, 2) = 0.080$

$w_5(1.2, 3) = 0.067$

$w_5(1.2, 4) = 0.113$

$w_5(1.2, 5) = 0$

$w_5(1.3, 1) = 0$

$w_5(1.3, 2) = 0.154$

$w_5(1.3, 3) = 0$

$w_5(1.3, 4) = 0$

$w_5(1.3, 5) = 0$

$w_5(3.3.1, 1) = 0.021$

$w_5(3.3.1, 2) = 0.073$

$w_5(3.3.1, 3) = 0$

$w_5(3.3.1, 4) = 0.025$

$w_5(3.3.1, 5) = 0.004$

The criteria that have six subintervals

$w_6(1.1, 1) = 0$

$w_6(1.1, 2) = 0.064$

$w_6(1.1, 3) = 0$

$w_6(1.1, 4) = 0.012$

$w_6(1.1, 5) = 0$

$w_6(1.1, 6) = 0$

$w_6(2.1.3.1, 1) = 0$

$w_6(2.1.3.1, 2) = 0.047$

$w_6(2.1.3.1, 3) = 0$

$w_6(2.1.3.1, 4) = 0$

$w_6(2.1.3.1, 5) = 0$

$w_6(2.1.3.1, 6) = 0$

APPENDIX L

THE GLOBAL EFFICIENCIES OF THE UNEVALUATED PROJECTS DETERMINED FROM THE PROPOSED ASSIGNMENT MODELS AND UTADIS

In this part, the global efficiencies of 60 validation sample projects obtained from the proposed models, post optimality analysis applied UTADIS methods and integrating the proposed threshold estimation models and average weight approach. are given in Table 33.

Table 33: The global efficiency values of the unevaluated projects determined from the proposed assignment models and UTADIS

Threshold Estimation Model	Assignment Method	The Reference Set	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
PM1	Ave. Weights	Reference Set 1	2.34	4.09	1.41	726.00	14.20	38.90	6.39	36.20	2.58	4.50	27.30	1.95	13.45	8.84	3.89
	APM1		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
PM1	Ave. Weights	Reference Set 2	2.44	3.85	1.33	112.00	8.97	11.50	4.78	17.40	1.69	3.28	13.00	1.73	7.36	4.10	3.30
	APM1		1.000	1.000	1.000	1.000	1.000	0.968	1.000	infeas.	0.426	1.000	1.000	1.000	1.000	1.000	1.000
PM2	Ave. Weights	Reference Set 1	2.33	3.68	1.44	183.00	16.40	23.40	3.62	12.10	2.08	3.62	13.80	1.53	5.57	5.55	2.41
	APM2		0.919	0.985	0.823	1.000	1.000	1.000	1.000	1.000	0.985	0.857	1.000	0.737	1.000	0.949	0.768
	APM3		1.000	0.998	0.932	1.000	0.924	1.000	1.000	1.000	0.760	0.699	1.000	0.628	1.000	0.743	0.727
	APM4		0.809	0.900	0.898	1.000	1.000	1.000	1.000	1.000	1.000	0.969	1.000	0.764	1.000	1.000	0.894
	APM5		1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.928	0.882	1.000	0.737	1.000	0.900	0.949
PM2	Ave. Weights	Reference Set 2	2.85	3.79	1.59	51.70	15.70	5.50	4.20	12.90	1.66	3.65	12.30	1.93	9.73	1.94	3.69
	APM2		0.873	0.942	0.884	1.000	1.000	1.000	1.000	1.000	0.853	0.810	1.000	0.687	1.000	0.825	0.854
	APM3		0.973	0.987	0.916	1.000	0.929	1.000	1.000	1.000	0.806	0.755	1.000	0.662	1.000	0.784	0.787
	APM4		0.812	0.901	0.829	1.000	1.000	1.000	1.000	1.000	0.971	0.945	1.000	0.804	1.000	0.933	0.926
	APM5		0.880	0.944	0.896	1.000	0.941	1.000	1.000	1.000	0.902	0.875	1.000	0.763	1.000	0.868	0.940
UTADIS - POST OPT 1		Reference Set 1	0.871	0.895	0.835	0.888	0.871	0.944	0.916	0.961	0.975	0.930	0.937	0.880	0.884	0.932	0.844
UTADIS - POST OPT 2			0.700	0.823	0.711	0.806	0.679	0.957	0.937	0.964	0.911	0.950	0.939	0.757	0.947	0.939	0.812
UTADIS - POST OPT 1		Reference Set 2	0.911	0.985	0.911	0.654	0.911	0.868	0.966	0.927	0.956	0.904	0.899	0.870	0.963	0.888	0.921
UTADIS - POST OPT 2			0.346	0.985	0.346	0.991	0.346	0.986	1.001	1.001	1.001	1.001	1.001	0.980	1.001	0.896	0.985

Table 33 Continued: The global efficiency values of the unevaluated projects determined from the proposed assignment models and UTADIS

Threshold Estimation Model	Assignment Method	The Reference Set	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30
PM1	Ave. Weights	Reference Set 1	2.81	45	2.12	3.17	1.35	0.994	0.843	1.01	0.804	2.01	0.762	0.617	0.495	0.366	2.31
	APM1		1.00	1.00	1.00	1.00	1.00	0.637	1.00	0.673	0.824	1.00	0.328	0.461	0.455	0.315	1.00
PM1	Ave. Weights	Reference Set 2	2.14	20.5	1.95	1.78	0.907	0.670	0.748	0.688	0.712	1.14	0.484	0.435	0.354	0.293	1.33
	APM1		1.00	1.00	1.00	1.00	0.417	0.224	0.497	0.265	0.406	0.533	0.143	0.129	0.091	0.084	0.486
PM2	Ave. Weights	Reference Set 1	2.33	26.7	1.80	1.17	0.748	0.571	0.665	0.654	0.530	1.20	0.431	0.332	0.315	0.213	1.35
	APM2		0.877	0.848	0.574	0.825	0.725	0.686	0.893	0.573	0.598	1.00	0.663	0.471	0.422	0.280	0.561
	APM3		0.689	0.818	0.521	0.727	0.652	0.639	0.958	0.504	0.520	1.00	0.548	0.390	0.360	0.247	0.504
	APM4		0.955	1.00	0.693	0.782	0.820	0.723	0.767	0.640	0.597	0.969	0.624	0.449	0.457	0.309	0.682
	APM5		0.869	0.878	0.721	0.799	0.811	0.710	0.902	0.642	0.627	1.00	0.587	0.473	0.484	0.336	0.677
PM2	Ave. Weights	Reference Set 2	2.51	8.32	2.05	0.915	0.570	0.552	0.586	0.516	0.651	0.774	0.409	0.373	0.265	0.226	0.966
	APM2		0.733	0.836	0.591	0.718	0.698	0.759	0.764	0.554	0.589	0.953	0.596	0.424	0.377	0.273	0.641
	APM3		0.719	0.803	0.561	0.743	0.672	0.690	0.900	0.530	0.562	1.00	0.571	0.418	0.377	0.262	0.569
	APM4		0.859	0.864	0.743	0.760	0.761	0.769	0.688	0.555	0.696	0.818	0.603	0.505	0.532	0.352	0.690
	APM5		0.832	0.822	0.716	0.769	0.782	0.755	0.772	0.608	0.672	0.905	0.597	0.486	0.481	0.331	0.687
UTADIS - POST OPT 1		Reference Set 1	0.937	0.953	0.847	0.708	0.672	0.624	0.677	0.607	0.732	0.681	0.644	0.581	0.404	0.450	0.643
UTADIS - POST OPT 2			0.884	0.864	0.670	0.728	0.490	0.608	0.617	0.495	0.536	0.736	0.547	0.479	0.291	0.381	0.608
UTADIS - POST OPT 1		Reference Set 2	0.827	0.801	0.788	0.691	0.788	0.571	0.715	0.346	0.718	0.621	0.519	0.298	0.240	0.351	0.532
UTADIS - POST OPT 2			0.993	0.991	0.346	0.764	0.755	0.540	0.136	0.110	0.302	0.755	0.709	0.090	0.134	0.046	0.222

Table 33 Continued: The global efficiency values of the unevaluated projects determined from the proposed assignment models and UTADIS

Threshold Estimation Model	Assignment Method	The Reference Set	P31	P32	P33	P34	P35	P36	P37	P38	P39	P40	P41	P42	P43	P44	P45
PM1	Ave. Weights	Reference Set 1	0.642	0.850	0.908	1.130	0.583	0.651	1.290	0.892	0.574	0.711	0.348	1.620	0.610	0.324	0.608
	APM1		0.749	0.480	0.442	0.774	0.721	0.310	0.876	0.897	0.779	0.295	0.875	1.000	0.595	0.264	0.477
PM1	Ave. Weights	Reference Set 2	0.488	0.604	0.579	0.647	0.541	0.422	0.807	0.676	0.477	0.424	0.266	1.030	0.540	0.233	0.458
	APM1		0.156	0.099	0.090	0.214	0.187	0.128	0.159	0.198	0.164	0.077	0.343	0.268	0.163	0.070	0.123
PM2	Ave. Weights	Reference Set 1	0.415	0.599	0.662	0.600	0.422	0.394	0.738	0.602	0.353	0.401	0.285	0.913	0.383	0.186	0.384
	APM2		0.518	0.517	0.661	0.603	0.551	0.512	0.613	0.623	0.499	0.614	0.559	0.748	0.425	0.306	0.461
	APM3		0.405	0.434	0.513	0.480	0.631	0.427	0.520	0.594	0.450	0.473	0.704	0.564	0.404	0.289	0.408
	APM4		0.542	0.607	0.702	0.694	0.569	0.539	0.713	0.676	0.494	0.640	0.438	0.753	0.561	0.298	0.481
	APM5		0.509	0.557	0.626	0.626	0.647	0.500	0.674	0.690	0.516	0.573	0.592	0.675	0.580	0.326	0.476
PM2	Ave. Weights	Reference Set 2	0.289	0.457	0.482	0.332	0.435	0.332	0.508	0.508	0.305	0.346	0.255	0.585	0.372	0.169	0.326
	APM2		0.435	0.514	0.617	0.496	0.741	0.495	0.629	0.676	0.537	0.561	0.494	0.640	0.450	0.320	0.443
	APM3		0.428	0.470	0.566	0.491	0.674	0.458	0.572	0.634	0.493	0.520	0.634	0.607	0.424	0.305	0.425
	APM4		0.483	0.583	0.632	0.556	0.674	0.454	0.703	0.680	0.554	0.572	0.320	0.666	0.553	0.338	0.453
	APM5		0.502	0.550	0.617	0.564	0.708	0.486	0.670	0.691	0.563	0.563	0.438	0.671	0.553	0.343	0.476
UTADIS - POST OPT 1		Reference Set 1	0.426	0.581	0.656	0.492	0.490	0.567	0.567	0.560	0.416	0.528	0.469	0.635	0.513	0.308	0.511
UTADIS - POST OPT 2			0.294	0.624	0.678	0.413	0.510	0.445	0.452	0.527	0.317	0.370	0.335	0.638	0.491	0.191	0.460
UTADIS - POST OPT 1		Reference Set 2	0.258	0.534	0.672	0.331	0.459	0.578	0.571	0.534	0.397	0.561	0.109	0.480	0.369	0.135	0.221
UTADIS - POST OPT 2			0.046	0.085	0.695	0.709	0.085	0.048	0.496	0.085	0.051	0.675	0.110	0.703	0.092	0.046	0.046

Table 33 Continued: The global efficiency values of the unevaluated projects determined from the proposed assignment models and UTADIS

Threshold Estimation Model	Assignment Method	The Reference Set	P46	P47	P48	P49	P50	P51	P52	P53	P54	P55	P56	P57	P58	P59	P60
PM1	Ave. Weights	Reference Set 1	0.774	0.380	0.578	1.100	0.494	0.750	0.566	0.327	0.252	0.637	0.566	1.100	0.965	0.525	0.722
	APM1		0.492	0.200	0.635	0.625	0.217	0.382	0.516	0.222	0.197	0.504	0.319	0.702	0.420	0.387	0.434
PM1	Ave. Weights	Reference Set 2	0.546	0.231	0.464	0.704	0.337	0.502	0.444	0.250	0.204	0.396	0.384	0.749	0.541	0.371	0.458
	APM1		0.134	0.052	0.181	0.147	0.058	0.113	0.097	0.073	0.093	0.163	0.138	0.328	0.159	0.147	0.175
PM2	Ave. Weights	Reference Set 1	0.521	0.231	0.404	0.750	0.300	0.442	0.367	0.203	0.186	0.418	0.388	0.676	0.571	0.404	0.433
	APM2		0.648	0.413	0.673	0.906	0.509	0.583	0.385	0.371	0.332	0.655	0.570	0.671	0.820	0.565	0.728
	APM3		0.585	0.313	0.690	0.647	0.413	0.483	0.364	0.313	0.325	0.630	0.528	0.540	0.698	0.559	0.682
	APM4		0.662	0.421	0.707	0.944	0.576	0.613	0.480	0.392	0.344	0.625	0.593	0.774	0.754	0.589	0.667
	APM5		0.621	0.386	0.769	0.745	0.509	0.547	0.492	0.352	0.341	0.650	0.593	0.710	0.663	0.621	0.636
PM2	Ave. Weights	Reference Set 2	0.383	0.175	0.342	0.567	0.257	0.404	0.391	0.204	0.147	0.269	0.361	0.586	0.424	0.339	0.394
	APM2		0.657	0.334	0.701	0.662	0.477	0.503	0.498	0.341	0.252	0.533	0.543	0.597	0.641	0.562	0.653
	APM3		0.608	0.329	0.698	0.648	0.445	0.486	0.425	0.328	0.298	0.601	0.541	0.573	0.676	0.570	0.662
	APM4		0.653	0.380	0.633	0.729	0.541	0.545	0.523	0.381	0.266	0.449	0.542	0.605	0.546	0.562	0.577
	APM5		0.648	0.370	0.731	0.680	0.514	0.528	0.510	0.369	0.283	0.530	0.549	0.657	0.587	0.575	0.607
UTADIS - POST OPT 1		Reference Set 1	0.483	0.350	0.494	0.719	0.466	0.616	0.504	0.428	0.413	0.433	0.578	0.667	0.611	0.543	0.578
UTADIS - POST OPT 2			0.397	0.145	0.387	0.671	0.281	0.520	0.529	0.339	0.329	0.200	0.533	0.533	0.590	0.493	0.581
UTADIS - POST OPT 1		Reference Set 2	0.494	0.209	0.407	0.535	0.528	0.424	0.438	0.195	0.146	0.248	0.511	0.512	0.344	0.485	0.320
UTADIS - POST OPT 2			0.506	0.017	0.092	0.865	0.025	0.558	0.108	0.029	0.000	0.046	0.095	0.857	0.778	0.056	0.605