

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**NOVEL FUZZY MULTI CRITERIA DECISION MAKING METHODS USING
INTUITIONISTIC FUZZY, PYTHAGOREAN FUZZY, AND NEUTROSOPHIC
SETS**



Ph.D. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**SEZGİSEL BULANIK, PİSAGOR BULANIK VE NÖTROFİK KÜMELER
KULLANILARAK GELİŞTİRİLMİŞ ÖZGÜN ÇOK KRİTERLİ KARAR VERME
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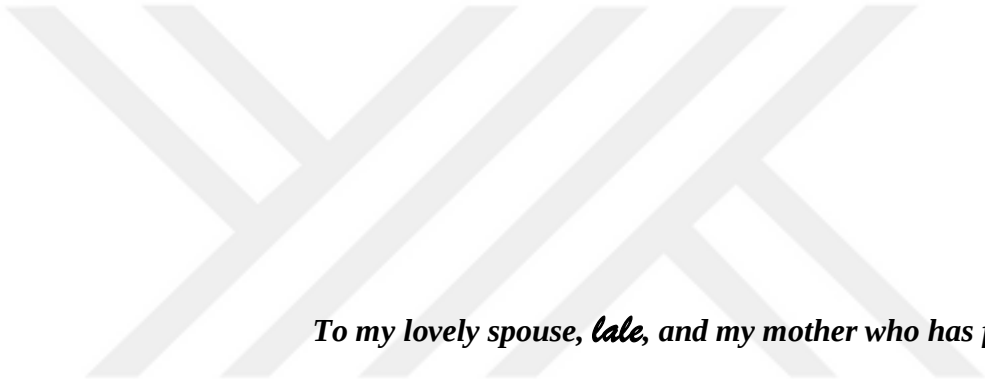
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*To my lovely spouse, ***lale***, and my mother who has full of love,*



FOREWORD

Doctoral thesis studies are critical studies as they contribute to scientific developments and play a milestone role in the development processes. Based on this vision, in this thesis, we aim to use the advantages of fuzzy set extensions to extend multi-criteria decision-making (MCDM) methods and applied to real case studies to validate their applicability. We believe that this study will contribute both literature and field studies to form a basis for future studies through this aim.

During my doctorate education, I am sincerely grateful to my professor, Cengiz KAHRAMAN, who was always with me in my academic career and life processes. He put me on the bus and showed me that there can always be a right way to go.

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As one of the people I trust most said, “every decision made should be verified analytically and conscientiously confirmed”.

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ABBREVIATIONS

AHP	: Analytic Hierarchy Process
ANP	: Analytic Network Process
CWW	: Computing with Words
EDAS	: Evaluation based on Distance from Average Solution
ELECTRE	: ELimination Et Choix Traduisant la REalité
HFSs	: Hesitant fuzzy sets
IFSs	: Intuitionistic fuzzy sets
IVIF	: Interval Valued Intuitionistic Fuzzy
IVIF-AHP	: Interval-valued intuitionistic fuzzy AHP
IVN	: Interval-Valued Neutrosophic
IVN-EDAS	: Interval-Valued Neutrosophic EDAS
MCDM	: Multi Criteria Decision Making
NSs	: Neutrosophic sets
PFSs	: Pythagorean fuzzy sets
SFSs	: Spherical Fuzzy Sets
TOPSIS	: Technique for Order Preference by Similarity to an Ideal Solution



SYMBOLS

$\mathfrak{D}(x)$	: Deneutrosophication function
μ	: Membership Function
ϑ	: Non-Membership Function
F	: Falsity Function
I	: Indeterminacy Function
T	: Truth-membership function
ED_i	: Euclidean distances of alternatives
$\tilde{A}$	: Fuzzy Number
w_j	: Weight of the criterion j
θ	: Threshold Parameter



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NOVEL FUZZY MULTI CRITERIA DECISION MAKING METHODS USING INTUITIONISTIC FUZZY, PYTHAGOREAN FUZZY, AND NEUTROSOPHIC SETS

SUMMARY

People have to constantly make decisions on various issues, make choices, and take actions to solve the problems they have to encounter both in private and business lives. In this context, the simplest definition of decision-making can be expressed as choosing the most appropriate option among the solution alternatives. Thus, the decision-making process consists of defined solution alternatives, experts who evaluate them in line with the intended objectives, and evaluation criteria determined to make the evaluation. Moreover, we may classify the decision-making processes according to the number of criteria, the information topology in the decision process, and the essential characteristics of the decision-makers. In line with our aim, in this thesis, fuzzy extended multi-criteria decision-making methods are applied to real-case problems to consider the uncertain environment.

Multi-criteria decision-making (MCDM) methods are decision-making techniques that are widely used in the literature and can be diversified according to deterministic, stochastic, and probabilistic data types. The concept may involve several main criteria and sub-criteria, which are tangible or intangible. These criteria can be represented by a network or hierarchical structure based on the relationships between them. Alternatives are the other components of the concept, which are solution opportunities for the addressed problem. Through that, experts or decision-makers evaluate the alternatives with respect to criteria to find the most appropriate solution. But, based on the complexity of the constructed decision-making structure and uncertainties in the available data, ordinary MCDM methods may be inefficient to represent the input data in their mathematical operations. Therefore, a new concept is needed to reflect the nature of the problem and input data.

As Zimmerman states, an element can belong to a set or not in the traditional set theory, a solution is either feasible or not in the optimization, and a statement can be true or false but nothing in between in the Boolean logic. But in real life, conditions or events are not precise and are a matter of degree that the traditional logic cannot truly define. Therefore, new concepts are needed for better simulations of the problems. In order to be a solution, Zadeh introduced fuzzy logic and fuzzy sets to represent the membership degree of an element to a set. Unfortunately, although the emergence of fuzzy sets was a significant step forward in modeling uncertainty, it fell short of modeling hesitancy, one of the uncertainty types. Therefore, new extensions are needed to cover the types of uncertainties during the modeling of the problem.

Starting from the introduction of the fuzzy sets (from here on written as ordinary fuzzy sets), many extensions are introduced to the literature to cover types of uncertainties. Type-n fuzzy sets were again introduced by Zadeh to handle uncertainty while assigning the membership function of an element to the belonging set. After that, the most prominent step in ordinary fuzzy sets extension taken with intuitionistic fuzzy

sets, which Atanassov proposes to include hesitancy of the decisions by considering both membership and non-membership functions.

Intuitionistic fuzzy sets were later on regarded as a new space that many researchers focused on. Through that, many extensions were presented by using their conditional properties. One of them is introduced by Smarandache, neutrosophic sets, which defines three functions: Truth (T), Indeterminacy (I), and Falsity (F) for modeling the problems that aim to handle types of uncertainty. The most highlighted characteristics of neutrosophic sets are the concept considers three functions (T,I,F) independently, which their sum can be up to three and offers distinguishment between absolute and relativity. The other one is Pythagorean fuzzy sets, which Yager introduces to provide a larger domain area than intuitionistic fuzzy sets to model the problems. Although they have advantages for different problems against each other, one cannot be superior to the other for sure. Therefore, in many cases, one or more fuzzy extensions may be the most appropriate concept to handle the types of uncertainty based on the available inputs.

In this thesis, we aim to extend multi-criteria decision-making problems to offer applicable methodologies, which generate meaningful solutions, for the decision-making area by involving types of uncertainties based on the available data with extensions of fuzzy sets. Through that, three novel methodologies are introduced to the literature. One is an integrated interval-valued intuitionistic fuzzy DEcision MAKing Trial and Evaluation Laboratory (DEMATEL)- Analytical Network Process (ANP)- Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodology presented in Section 2 and applied to a real-case study considering freight village location selection. First, the extended DEMATEL technique is used to determine the relationship between the evaluation criteria. Then, based on the relationship matrix, the network of the criteria is constructed. A supermatrix is constructed after calculating the local weights of the criteria by using the pairwise comparison matrices. Finally, the convergence of the normalized supermatrix, the limit matrix is obtained, and the final weights of the criteria are determined. Then, freight village location alternatives in Istanbul are evaluated by using the extended TOPSIS method. Finally, the results are analyzed by applying comparative analyses to yield the methodology's verification and validation. Comparative analysis is carried out by considering the ordinary Simple Additive Weighting (SAW) method's results.

The other is a novel interval-valued Pythagorean fuzzy Analytical Hierarchy Process (AHP) method presented in Section 3 and used in a real-case study evaluating landfill site selection. First, the method's inputs are gathered using a scale consisting of linguistic terms and their corresponding interval-valued Pythagorean fuzzy numbers. Next, the developed method is applied to a landfill site selection problem for Istanbul. Finally, the results are analyzed by applying both sensitivity and comparison analyses for verification and validation. The sensitivity analysis is carried out by considering a one-at-a-time concept based on the different simulations. Comparison analyses are conducted by using the results of the ordinary fuzzy AHP and interval-valued intuitionistic fuzzy AHP methods.

The last one is a novel interval-valued neutrosophic EDAS method presented in Section 4 and applied to prioritize the United Nations' national sustainable development goals. First, the method considers a scale, which consists of linguistic terms and corresponded interval-valued neutrosophic numbers. Then the proposed method is applied to prioritize the United Nations national sustainable development

goals for the Turkey case by using three experts evaluations. Finally, the results are analyzed by applying both sensitivity and comparison analyses for verification and validation. The sensitivity analysis is carried out by considering a one-at-a-time concept based on the different simulations. Comparison analysis is conducted by using the results of the interval-valued intuitionistic fuzzy TOPSIS.

To summarize, in this thesis, novel fuzzy multi-criteria decision-making methods are introduced to the literature and then applied to real case studies to offer a meaningful solution for the problem, which aims to show the proposed methodologies' applicability. Then, the results are analyzed by using sensitivity and comparison analyses to validate and verify the proposed methodologies. As a result, we believe that the proposed methodologies can be efficient decision-making tools for the different application areas that involve uncertainty. Through that, managers or researchers can use them to generate meaningful and applicable solutions for their problems. Furthermore, for further problems, the proposed techniques can be applied to situations where to prioritize innovative technologies such as unmanned aerial vehicles' technology selection and their risk analyses, blockchain technologies, autonomous vehicle driving systems, renewable alternative energy selection.



SEZGİSEL BULANIK, PİSAGOR BULANIK VE NÖTROSOFİK KÜMELER KULLANARAK GELİŞTİRİLMİŞ ÖZGÜN ÇOK KRİTERLİ KARAR VERME YÖNTEMLERİ

ÖZET

İnsanlar hem özel hem de iş hayatında karşılaştıkları sorunları çözmek için sürekli olarak çeşitli konularda kararlar almak, seçimler yapmak ve harekete geçmek zorundadırlar. Bu bağlamda karar vermenin en basit tanımı, çözüm alternatifleri arasından en uygun olanın seçilmesi olarak ifade edilebilir. Böylece karar verme süreci, tanımlanmış çözüm alternatifleri, bunları amaçlanan hedefler doğrultusunda değerlendiren uzmanlar ve değerlendirmeyi yapmak için belirlenen değerlendirme kriterlerinden oluşur. Ayrıca karar verme süreçlerini kriter sayısına, karar sürecindeki bilgi topolojisine ve karar vericilerin temel özelliklerine göre sınıflandırabiliriz. Bu tezde amacımız doğrultusunda, belirsiz ortamı göz önünde bulundurarak gerçek durum problemlerine bulanık genişletilmiş çok kriterli karar verme yöntemleri uygulanmıştır.

Çok kriterli karar verme (ÇKKV) yöntemleri, literatürde yaygın olarak kullanılan ve deterministik, stokastik ve olasılıksal veri türlerine göre çeşitlendirilebilen karar verme teknikleridir. Kavram, bazıları somut veya soyut olan birkaç ana kriter ve alt kriter içerebilir. Bu kriterler, aralarındaki ilişkileri gösteren hiyerarşik bir yapı ile temsil edilebilir. Alternatifler, ele alınan problem için çözüm fırsatları olan kavramın diğer bileşenleridir. Bu sayede uzmanlar veya karar vericiler en uygun çözümü bulmak için alternatifleri kriterlere göre değerlendirir. Ancak, yapılandırılmış karar verme yapısının karmaşıklığına ve mevcut verilerdeki belirsizliklere bağlı olarak, sıradan ÇKKV yöntemleri, matematiksel işlemlerinde girdi verilerini temsil etmede yetersiz olabilir. Bu nedenle, sorunun doğasını ve girdi verilerini yansıtacak yeni bir konseptte ihtiyaç vardır.

Zimmerman'ın belirttiği gibi, geleneksel küme teorisinde bir eleman bir kümeye ait olabilir veya olmayabilir, optimizasyonda bir çözüm uygun olabilir veya olmayabilir ve Boolean mantığında bir ifade doğru veya yanlış olabilir, ancak bahsedilen sonuçlar dışında hiçbir değer alamaz. Ancak gerçek hayatta, koşullar veya olaylar kesin değildir ve geleneksel mantığın tam olarak tanımlayamayacağı bir derece meselesidir. Bu nedenle, problemlerin daha iyi simülasyonları için yeni kavramlara ihtiyaç vardır. Çözüm olması için Zadeh, bir elemanın bir kümeye üyelik derecesini temsil etmek için bulanık mantığı ve bulanık kümeleri literatüre sunmuştur. Ancak, bulanık kümelerin ortaya çıkması, belirsizliğin modellenmesinde önemli bir adım olmasına rağmen, uzmanların kararsızlığı gibi durumların matematiksel operasyonlara dahil edilmesinde yetersiz kalmıştır. Bu nedenle, problemin modellenmesi sırasında tüm belirsizlik türlerini kapsayabilecek yeni uzantılara ihtiyaç duyulmuştur.

Bulanık kümelerin literatüre kazandırıldığı tarihten itibaren, belirsizlik türlerini kapsayacak şekilde literatüre birçok uzantı sunulmuştur. Tip-n bulanık kümeler, bir elemanın üyelik fonksiyonunu ait olan kümeye atarken belirsizliği ele almak için yine Zadeh tarafından ortaya konulmuştur. Ardından Atanassov, hem üye olma hem de üye olmama fonksiyonlarını matematiksel operasyonlara dahil ederek karar vericilerin

karar alma süreçlerinde yaşadıkları tereddütleri modellemiş ve böylece bulanık kümelerin ardından en dikkat çekici modelleme kavramı ortaya çıkmıştır.

Sezgisel bulanık kümeler daha sonra birçok araştırmacının odaklandığı yeni bir uzay olarak kabul edildi. Bu sayede birçok bulanık uzantı, sezgisel bulanık kümelerin şartlarının ele alındığı koşullar dikkate alınarak ortaya çıktı. Bunlardan biri, belirsizlik türlerini ele almayı amaçlayan problemleri modellemek için Doğruluk (T), Belirsizlik (I) ve Yanlışlık (F) olmak üzere üç işlevi tanımlayan nütrosifik kümeler, Smarandache tarafından literatüre sunulmuştur. Nütrosifik kümelerin en çok vurgulanan özellikleri, toplamaları üçe kadar çıkabilen ve mutlak ile görecelilik arasında ayırım sunan üç fonksiyonu (T,I,F) bağımsız olarak ele alan kavramdır. Diğeri ise Yager'ın problemlerin modellenmesinde sezgisel bulanık kümelerden daha geniş bir değerlendirme alanı sunan Pisagor bulanık kümeleridir. Bahsedilen uzantıların birbirlerine karşı farklı problemlerde avantajları olsa da, birinin diğerine kesin bir üstünlük sağlaması mümkün değildir. Bu nedenle, çoğu durumda, bir veya daha fazla bulanık uzantı, mevcut girdilere dayalı belirsizlik türlerini ele almak için en uygun kavram olabilir.

Bu tezde, çok kriterli karar verme problemlerini, mevcut verilere dayalı belirsizlik türlerini dahil ederek, karar verme alanına anlamlı çözümler üreten uygulanabilir metodolojiler sunacak şekilde genişletmeyi amaçlıyoruz. Bu amaçla yola çıkarak literatüre üç yeni metodoloji sunulmuştur. Bu çalışmalardan biri, Bölüm 2'de sunulan ve lojistik köyü yer seçimi ile ilgili bir vaka çalışmasına uygulanan entegre bir aralık değerli sezgisel bulanık DEMATEL-ANP-TOPSIS metodolojisidir. İlk olarak, değerlendirme kriterleri arasındaki ilişkiyi belirlemek için genişletilmiş DEMATEL tekniği kullanılmıştır. Daha sonra, elde edilen ilişki matrisine dayalı olarak kriterler arasındaki ağ oluşturulur ve genişletilmiş ANP yöntemi uygulanır. İkili karşılaştırma matrisleri kullanılarak kriterlerin yerel ağırlıkları hesaplandıktan sonra bir süper matris oluşturulur. Son olarak normalize edilmiş süper matrisin yakınsaması ile limit matris elde edilir ve kriterlerin nihai ağırlıkları belirlenir. Daha sonra, genişletilmiş TOPSIS yöntemi kullanılarak İstanbul'daki lojistik köyü lokasyon alternatifleri değerlendirilmiştir. Son olarak, metodolojinin doğrulamasını ve geçerliliğini sağlamak için genenekselsel SAW yöntemi uygulanarak sonuçlar analiz edilmiştir.

Diğer çalışma ise Bölüm 3'te sunulan ve depolama sahası seçimini değerlendiren bir vaka çalışmasında kullanılan yeni bir aralık değerli Pisagor bulanık Analitik Hiyerarşi Prosesi (AHP) yöntemidir. İlk olarak, yöntemin girdileri, dilsel terimlerden ve bunlara karşılık gelen aralık değerli Pisagor bulanık sayılarından oluşan bir ölçek kullanılarak toplanır. Daha sonra geliştirilen yöntem, İstanbul için planlanmış bir düzenli depolama sahası seçim problemine uygulanmıştır. Son olarak, doğrulama ve geçerlilik analizleri için hem duyarlılık hem de karşılaştırma analizleri uygulanarak sonuçlar analiz edilmiştir. Duyarlılık analizi, farklı simülasyonlara dayalı her seferinde bir değişiklik kavramı dikkate alınarak gerçekleştirilmiştir. Ayrıca uygulama sonuçları, bulanık AHP ve aralık değerli sezgisel bulanık AHP yöntemlerinin sonuçları ile karşılaştırılmıştır.

Diğer bir çalışma ise, Bölüm 4'te sunulan ve Birleşmiş Milletler ulusal sürdürülebilir kalkınma hedeflerini önceliklendirebilmek için uygulanan yeni bir aralık değerli nütrosifik EDAS yöntemidir. İlk olarak yöntem, dilsel terimlerden ve karşılık gelen aralık değerli nütrosifik sayılardan oluşan bir ölçeği dikkate almıştır. Daha sonra önerilen yöntem, üç uzman değerlendirmesi kullanılarak Türkiye örneği için Birleşmiş Milletler ulusal sürdürülebilir kalkınma hedeflerinin önceliklendirilebilmesi için

uygulanmıştır. Son olarak, doğrulama ve geçerlilik analizleri için hem duyarlılık hem de karşılaştırma analizleri uygulanarak sonuçlar analiz edilmiştir. Duyarlılık analizi, farklı simülasyonlara dayalı her seferinde bir değişiklik kavramı dikkate alınarak gerçekleştirilir. Uygulamanın sonuçları, aralık değerli sezgisel bulanık TOPSIS yönteminin sonuçları ile karşılaştırılmıştır.

Özetlemek gerekirse, bu tezde, literatüre yeni bulanık çok kriterli karar verme yöntemleri tanıtılmıştır. Ardından, önerilen metodolojilerin uygulanabilirliğini gösterebilmek ve probleme anlamlı bir çözüm sunmak için gerçek vaka çalışmalarına uygulanmışlardır. Sonuçlar, önerilen metodolojileri doğrulamak ve geçerliliklerini test etmek için duyarlılık ve karşılaştırma analizleri kullanılarak analiz edilmişlerdir. Sonuç olarak, uygulama sonuçları ve analizler ışığında önerilen metodolojilerin belirsizlik içeren farklı uygulama alanları için verimli karar verme araçları olarak kullanılabileceklerine inanıyoruz. Bu sayede yöneticiler veya araştırmacılar, sorunlarına anlamlı ve uygulanabilir çözümler üretmek için sunduğumuz modelleri kullanabilirler. Ayrıca ilerleyen yıllarda, önerilen teknikler, insansız hava araçlarının teknoloji seçimi ve ortaya çıkan sistemlerin risk analizleri, otonom araç sürüş sistemleri risk değerlendirmeleri gibi yenilikçi teknolojilerin önceliklendirilmesi ve risk değerlendirmelerinin yapılabilmesi için uygulanabilir.



1. INTRODUCTION

Humans have to constantly make decisions on various issues, make choices, and take actions to solve the problems they have to encounter both in private and business lives. From a wider perspective, they evaluate pre-choice screening decisions, choice decisions, and post-choice implementation and progress decisions (Beach, 1993). This problematic process consists of defined solution alternatives, evaluation criteria, and evaluations of the solution alternatives in line with the intended objectives to reach the most appropriate solution. The process can be classified according to the number of criteria, the information topology in the decision process, and the essential characteristics of the decision-makers. This thesis focused on both types of classes for the decision-making process: multi-criteria, uncertain information, and multi-expert systems.

Multi-criteria decision-making (MCDM) methods are decision-making techniques that are widely used in the literature and can be diversified according to deterministic, stochastic, and probabilistic data types. The concept may involve several main criteria and sub-criteria, some of which can be considered as a quantitative or qualitative type of data. These criteria can be represented by a hierarchical structure in case of no dependency among them or a network structure where there are relationships between them. To find an appropriate solution, alternatives are the other components of the concept that are evaluated with respect to evaluation criteria. Through that, experts or decision-makers evaluate the alternatives with respect to criteria to find the most appropriate solution. But, based on the complexity of the constructed decision-making structure and uncertainties in the available data, ordinary MCDM methods may be inefficient to represent the input data in their mathematical operations. Therefore, a new concept is needed to reflect the nature of the problem and input data.

For the conventional data reflecting concepts, in the traditional set theory, an element can belong to a set or not; in optimization, a solution is either feasible or not; and in Boolean logic, a statement can be true or false but nothing in between (Zimmerman, 2011). But in real-life conditions, most processes are imprecise and cannot be fully

defined by the traditional logic. From the mathematical perspective, involving this uncertainty in mathematical calculations promises meaningful solutions since the model can reflect the data more than the conventional concepts. For this aim, Zadeh (1965) introduced the fuzzy logic and fuzzy sets theory. From now on, ordinary fuzzy sets are used as the synonym of the fuzzy sets theory.

From 1965 to 2000, fuzzy sets theory has been extended in various forms. Type- n fuzzy sets were also developed by Zadeh (1975) for handling the uncertainty of the membership functions in the ordinary fuzzy sets. Atanassov presented intuitionistic fuzzy sets (IFSs) to define better a membership function with its membership and non-membership degrees, which ables one to represent the hesitancy of the decision-makers (Atanassov, 1986). The concept is also fundamental to 2-dimensional uncertainty representation by considering two functions. Later on, Smarandache developed neutrosophic logic and neutrosophic sets (NSs) as an extension of the intuitionistic fuzzy sets (Smarandache, 1999). The extension is consisting of triplet functions: Truth (T), Indeterminacy (I), and Falsity (F). By this representation, impreciseness of the data is represented by truth and falsity values where degrees of belongingness and non-belongingness. The indeterminacy function is incorporated to distinguish relativity and absoluteness of the decision-makers' judgment. The concept is fundamental to 3-dimensional uncertainty representation by considering these three functions. With that, neutrosophic sets handle the uncertainty of the system and reduce indecisiveness of conflicting information. Moreover, it provides the freedom to assign values to these functions independently from each other.

From 2000 to nowadays, there are also extensions for ordinary fuzzy sets to increase their capability to represent types of uncertainty. Hesitant fuzzy sets (HFSs), described by Torra (2010), are the extensions of ordinary fuzzy sets that enable assigning a set of membership functions to a single element in a set. By this description, Torra aims to provide a way of representing the hesitancy of the decision-makers. Yager introduced Pythagorean fuzzy sets to facilitate the representation of a larger body of membership and non-membership degrees, enabling experts to consider uncertainty more effectively than the intuitionistic fuzzy sets (Yager, 2013). In 2013, Cuong and Kreinovich introduced another extension of ordinary fuzzy sets, picture fuzzy sets, representing 3-dimensional uncertainty simultaneously (Cuong and Kreinovich, 2013). The last extension was introduced by Kutlu and Kahraman, spherical fuzzy sets,

which is another extension that has the capability to represent 3-dimensional uncertainty simultaneously (Kutlu and Kahraman 2019).

Based on the literature and the applications that we conducted, these uncertainty representations have advantages for different problems against each other, and for sure, one cannot be superior to the other. Therefore, as we can use these advantages of the proposed extensions in MCDM problems, we better reflect the uncertainty in the data that generates more meaningful outputs. Through that, in many cases, one or more fuzzy extensions may be the most appropriate concept to handle the types of uncertainty based on the available inputs.

1.1 Purpose of Thesis

This thesis aims to use the advantages of intuitionistic fuzzy, Pythagorean fuzzy, and neutrosophic sets by using them to extend multi-criteria decision-making (MCDM) methods. To perform their applicabilities, the extended methods are then applied to real case studies. Moreover, sensitivity and comparative analyses are conducted to show the flexibility of the given decisions and validate the proposed methods, respectively. Through that, we introduced new extensions of MCDM methods, interval-valued neutrosophic EDAS method, interval-valued Pythagorean AHP method, an integrated methodology consists of interval-valued intuitionistic fuzzy DEMATEL-ANP-TOPSIS methodology.

This thesis is prepared based on the Doctoral Theses from Scientific Publications Policy. The scope of this study is limited by the fuzzy extensions of mentioned MCDM methodologies and their applications to the studies from the various areas.

The originality of this thesis can be explained with the following aspects:

- Firstly, we develop various MCDM methods by extending them with fuzzy logic and then applying them to specific areas.
- Secondly, we introduce new and efficient deneutrosophication, division, and subtraction operations for the interval-valued neutrosophic sets.
- Thirdly, we compare the proposed approaches with the various MCDM methods available in the literature for verification and their validity.
- As final, for the flexibility of the proposed methods' decisions, we conduct a one-at-a-time sensitivity analysis with an explanatory pattern and analyze its outputs.

Our proposed approaches are evaluation processes that can be used as decision-making tools by the managers or researchers to make useful inferences, judgments, and decisions for selecting, ranking, or performance measurement techniques for their complex systems. Since the proposed approaches consider both the quantitative and qualitative data, it promises meaningful results for the areas that have uncertainty and indeterminacy in their decision-making processes. We believe that our studies can guide researchers interested in multi-criteria decision-making under an imprecise and indeterminate environment.

1.2 Impact

Based on the thesis context, several articles, proceedings, and book chapters are introduced to the literature. In the following, the lists of the papers, together with their citations with respect to the Google Scholar database, are presented:

1. Articles:

- A novel approach to risk assessment for occupational health and safety using Pythagorean fuzzy AHP & fuzzy inference system, 230 Citations till August 2021.
- A new risk assessment approach: Safety and Critical Effect Analysis (SCEA) and its extension with Pythagorean fuzzy sets, 74 Citations till August 2021.
- A novel intuitionistic fuzzy DEMATEL–ANP–TOPSIS integrated methodology for freight village location selection, 52 Citations till August 2021.
- A novel interval-valued neutrosophic EDAS method: prioritization of the United Nations national sustainable development goals, 51 Citations till August 2021.
- A novel Pythagorean fuzzy AHP and its application to landfill site selection problem, 51 Citations till August 2021.
- A novel neutrosophic CODAS method: Selection among wind energy plant locations, 21 Citations till August 2021.
- An integrated methodology using neutrosophic CODAS & fuzzy inference system: Assessment of livability index of urban districts, 4 Citations till August 2021.

- Selection of the Most Appropriate Renewable Energy Alternatives by Using a Novel Interval-Valued Neutrosophic ELECTRE I Method, 2 Citations till August 2021.
2. Book Chapters:
- Simple Additive Weighting and Weighted Product Methods Using Neutrosophic Sets, 9 Citations till August 2021.
 - Interval-valued neutrosophic EDAS method: an application to prioritization of social responsibility projects, 8 Citations till August 2021.
3. Proceedings:
- Interval-valued neutrosophic extension of EDAS method, 23 Citations till August 2021.
 - Pythagorean fuzzy AHP method for the selection of the most appropriate clean energy technology, 4 Citations till August 2021.
 - An Integrated Interval-Valued Neutrosophic AHP and TOPSIS Methodology for Sustainable Cities' Challenges, 2 Citations till August 2021.
 - An Integrated Pythagorean Fuzzy AHP & TOPSIS Method for the Selection of the Most Appropriate Clean Energy Technology, 0 Citations till August 2021.

1.3 Hypothesis

This thesis aims to extend multi-criteria decision-making problems to offer applicable methodologies, which generate meaningful solutions for the decision-making area by involving types of uncertainties based on the available data. Through that, three novel methodologies are introduced to the literature. One is an integrated interval-valued intuitionistic fuzzy DEcision MAKing Trial and Evaluation Laboratory (DEMATEL)-Analytical Network Process (ANP)- Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodology presented in Section 2 and applied to a real-case study considering freight village location selection. First, the extended DEMATEL technique is used to determine the relationship between the evaluation criteria. Then, based on the relationship matrix, the network of the criteria is constructed. A supermatrix is constructed after calculating the local weights of the criteria by using the pairwise comparison matrices. Finally, the convergence of the normalized supermatrix, the limit matrix is obtained, and the final weights of the

criteria are determined. Then, freight village location alternatives in Istanbul are evaluated by using the extended TOPSIS method. Finally, the results are analyzed by applying comparative analyses to yield the methodology's verification and validation. Comparative analysis is carried out by considering the ordinary Simple Additive Weighting (SAW) method's results.

The other is a novel interval-valued Pythagorean fuzzy Analytical Hierarchy Process (AHP) method presented in Section 3 and used in a real-case study evaluating landfill site selection. First, the method's inputs are gathered using a scale consisting of linguistic terms and their corresponding interval-valued Pythagorean fuzzy numbers. Next, the developed method is applied to a landfill site selection problem for Istanbul. Finally, the results are analyzed by applying both sensitivity and comparison analyses for verification and validation. The sensitivity analysis is carried out by considering a one-at-a-time concept based on the different simulations. Comparison analyses are conducted by using the results of the ordinary fuzzy AHP and interval-valued intuitionistic fuzzy AHP methods.

The last is a novel interval-valued neutrosophic EDAS method presented in Section 4 and applied to prioritize the United Nations' national sustainable development goals. First, the method considers a scale, which consists of linguistic terms and corresponded interval-valued neutrosophic numbers. Then the proposed method is applied to prioritize the United Nations national sustainable development goals for the Turkey case by using three experts evaluations. Finally, the results are analyzed by applying both sensitivity and comparison analyses for verification and validation. The sensitivity analysis is carried out by considering a one-at-a-time concept based on the different simulations. Comparison analysis is conducted by using the results of the interval-valued intuitionistic fuzzy TOPSIS.

To summarize, in this thesis, novel fuzzy multi-criteria decision-making methods are introduced to the literature and then applied to real case studies to offer a meaningful solution for the problem, which aims to show the proposed methodologies' applicability. Then the results are analyzed by using sensitivity and comparison analyses to validate and verify the proposed methodologies. As a result, we believe that the proposed methodologies can be efficient decision-making tools for the different application areas that involve uncertainty. Through that, managers or researchers can use them to generate meaningful and applicable solutions for their

problems. Furthermore, for further problems, the proposed techniques can be applied to situations where to prioritize innovative technologies such as unmanned aerial vehicles' technology selection and risk analyses of the emerged systems such as autonomous vehicle driving systems risk assessments.





2. A NOVEL INTUITIONISTIC FUZZY DEMATEL–ANP–TOPSIS INTEGRATED METHODOLOGY FOR FREIGHT VILLAGE LOCATION SELECTION¹

Today, the increase in human population comes with needs that must be fulfilled satially but generally it concludes with many deficiencies especially in large cities. This insufficient results cause malfunctions in logistical systems such as traffic congestion, decrease of environmental sustainability, and fall of investment attraction of the region. Establishing a robust and flexible supply chain prevent this results and freight village will assume a vital role for it. Freight village is a territory of transport and logistics facilities, activities and services that are established, coordinated and aims for maximum capability and snergy. Even there are many type of freight villages (logistics center, urban logistics, etc.), they have several characteristics in common such as contribute to intermodal transport, promote regional economic activity, and improve land use and local goods distribution (Higgins and Ferguson, 2011). The facility location decision process contains the identification, analysis, evaluation of alternatives and selection of best of them with regard to criteria (Yang and Lee, 1997). Due to its establishment and infrastructure costs, selection of facility location is a very important judgment for decision makers. Not only its costs but also operating and service issues such as excessive transportation costs, a shortage of qualified labor, loss of or some similar conditions that would be detrimental to operations are raised in the selection process (Stevenson, 1993). As it can be seen from the above there are many criteria that influence qualitatively and quantitatively the location decision of a firm. Besides, more than one expert may contribute in the selection process. Taking into consideration all these conditions, it reveals that location selection is a crucial decision for firms and due to so many criteria and alternatives it is a multi-expert and multi-criteria decision-making problem to be solved.

¹ This chapter is based on the paper “Karaşan, A., & Kahraman, C. (2019). A novel intuitionistic fuzzy DEMATEL–ANP–TOPSIS integrated methodology for freight village location selection. *Journal of Intelligent & Fuzzy Systems*, 36(2), 1335-1352.”

In these types of problems, one of the major difficulties is handling the uncertainty. There are many risk models incorporating the uncertainty into the location selection of freight villages. Among these models, stochastic location selection models (Marinakis et al., 2016); heuristic optimization models (Xu et al., 2013); fuzzy multi-objective decision models (Abou-Ali, 2002); fuzzy rule-based models (Jiang et al., 2016); and fuzzy multi-attribute decision models (Özdağoğlu, 2012; Çebi and Otay, 2015) are the most applied techniques. Due to the impracticability of using an excessive number of criteria, we need to reduce the number of them to a reasonable level. Besides, there may be inner and outer dependencies between these criteria which must be considered in the evaluation model. Some of these criteria can be tangible which means that they can be assigned to calibration units, e.g. competitive advantage, inadequate supplies of raw materials, cost, or whose value can be calculated numerically, e.g. reliability while the others are intangible, which are usually very hard to measure and evaluate.

A decision matrix may involve both tangible and intangible criteria. Fuzzy sets can capture the vagueness and impreciseness in measuring these criteria numerically. A fuzzy multi-attribute decision-making method must successfully handle these uncertainties for finding the best alternative. A decision matrix may involve both tangible and intangible criteria. Fuzzy sets can capture the vagueness and impreciseness in measuring these criteria numerically.

A fuzzy multi-attribute decision-making method must successfully handle these uncertainties for finding the best alternative. For that, fuzzy sets are extended to many types to use in those methods such as neutrosophic sets, hesitant fuzzy sets, type-2 fuzzy sets, and intuitionistic fuzzy sets.

In this paper, we preferred using intuitionistic fuzzy sets since they can better handle the uncertainty related to the membership of an element to a fuzzy set, employing membership, non-membership, and hesitance. Besides, IFS are the most used fuzzy sets in the literature. A search on the Scopus from the 2000's, in "Article Title, Abstract, and Keywords" gives the following frequencies: 154 for neutrosophic sets, 294 for hesitant fuzzy sets, 1377 for type-2 fuzzy sets, and 2192 for intuitionistic fuzzy sets.

In the proposed methodology, Decision Making Trial and Evaluation Laboratory (DEMATEL) method is used to reduce the number of criteria to a reasonable level

(Fontela and Gabus, 1974; Fontela and Gabus, 1976). For consideration of inner and outer dependencies between criteria, Analytic Network Process (ANP) is used (Saaty, 2006). The decision matrix including tangible and intangible criteria is evaluated by the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) method (Hwang and Yoon, 1981).

The rest of the paper is organized as follows. Section 2.1 presents fuzzy sets and their extensions. Section 2.2 gives the evaluation criteria for freight villages. Section 2.3 includes preliminaries for intuitionistic fuzzy sets. Section 2.4 presents the steps of the proposed integrated methodology. Section 2.5 illustrates the application of the methodology. Section 2.6 concludes the paper and gives suggestions for further research.

2.1 Fuzzy Sets Extensions and Intuitionistic Fuzzy Sets

History starting from ordinary fuzzy sets, fuzzy sets have many types of it and named extensions. The historical developments and fundings of fuzzy sets are given in Figure 2.1.

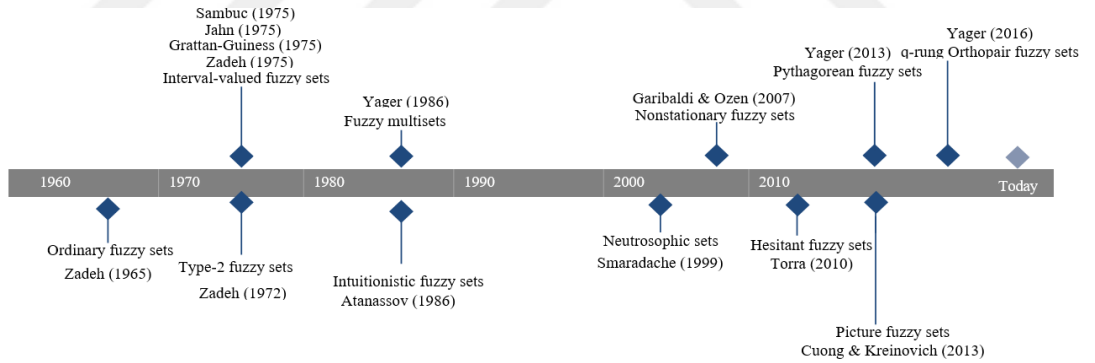


Figure 2.1 : Extensions of fuzzy sets.

In the following, fuzzy sets and their extensions are briefly given (Kahraman et al., 2016b).

2.1.1 Ordinary Fuzzy Sets

A fuzzy set is a class of objects with the continuum of grades of membership (Zadeh, 1965; Zadeh, 1972). An ordinary fuzzy set is given as in Eq. (2.1):

$$\tilde{A} = \{(a, \mu_{\tilde{A}}(a) | a \in X)\}, \quad (2.1)$$

where $\mu_{\tilde{A}}(a)$ is the membership function of element a , which maps to X .

2.1.2 Type-n Fuzzy Sets

Type-2 fuzzy sets introduced by Zadeh in 1975 (Zadeh, 1975). A type-2 fuzzy set $\tilde{\tilde{A}}$ in the universe of discourse X can be represented by a type-2 membership function $\mu_{\tilde{\tilde{A}}}$ shown as follows (Mendel, 2003):

$$\tilde{\tilde{A}} = \{(a, b), \mu_{\tilde{\tilde{A}}}(a, b) | \forall a \in X, \forall b \in J_x \subseteq [0, 1], 0 \leq \mu_{\tilde{\tilde{A}}}(a, b) \leq 1\}, \quad (2.2)$$

where J_x denotes an interval $[0, 1]$.

2.1.3 Interval-valued Fuzzy Sets

Interval-valued fuzzy sets (IVFSs) were introduced independently by (Zadeh, 1975; Grattan-Guinness, 1975; Jahn, 1975; Sambuc, 1975). An IVFS is defined by a mapping F from the universe U to the set of closed intervals in $[0, 1]$ which can be represented as:

$$\{(a, b): a, b \in [0, 1], a \leq b\} \quad (2.3)$$

2.1.4 Fuzzy Multisets

Let X be a non-empty set. A fuzzy multiset $\tilde{A}$ drawn from X is characterized by a function, “count membership” of $\tilde{A}$ denoted by CM_A such that (Yager, 1986):

$$CM_A: X \rightarrow Q \quad (2.4)$$

where Q is the set of all crisp multisets drawn from the unit interval $[0, 1]$. Then for any $x \in X$, the value $CM_A(x)$ is a crisp multiset drawn from $[0, 1]$.

2.1.5 Nonstationary Fuzzy Sets

Let T be a set of time points t_i (possibly infinite) and $f: T \rightarrow \mathfrak{R}$ denote a perturbation function (Garibaldi et al., 2008). A non-stationary fuzzy set $\tilde{A}$ of the universe of discourse X is characterized by a nonstationary membership function $\mu_{\tilde{A}}: T \times X \rightarrow [0, 1]$, which associates with each element (t, x) of $T \times X$ with a time-specific variation of $\mu_{\tilde{A}}(x)$. The non-stationary fuzzy set $\tilde{A}$ is denoted by:

$$\tilde{A} = \int_{t \in T} \int_{x \in X} \mu_{\tilde{A}}(t, x) / t / x \quad (2.5)$$

2.1.6 Neutrosophic Sets

Smarandache introduced neutrosophic sets in 2003. A neutrosophic set helps to handle uncertainty and convert it into the fuzzy set theory. Smarandache explains

neutrosophic sets as (T, I, F) where, percentage of truth in a subset T , the percentage of indeterminacy in a subset I , and the percentage of falsity in a subset F (Smarandache, 2003). Ye introduces a single valued neutrosophic set to handle uncertainty while imprecise, incomplete, and inconsistent information is very common in the data set (Ye, 2014).

2.1.7 Hesitant Fuzzy Sets

Hesitant fuzzy sets (HFSs) are the extensions of regular fuzzy sets which handle the situations where a set of values are possible for the membership of a single element (Torra, 2010). Let X be a fixed set, an HFS on X is in terms of a function that when applied to X returns a subset of $[0, 1]$.

$$E = \{\langle x, h_E(x) \rangle | x \in X\}, \quad (2.6)$$

where $h_E(x)$ is a set of some values in $[0, 1]$, denoting the possible membership degrees of the element $x \in X$ to the set E .

2.1.8 Intuitionistic Fuzzy Sets

Intuitionistic fuzzy sets (IFSs) presented by Atanassov in 1986. An IFS includes two membership values named as membership and non-membership for describing any x in X such that their sum is at most equal to 1 (Atanassov, 1986).

Intuitionistic fuzzy sets are the most used extension of fuzzy sets in the literature. Scopus database gives 924 document results when the keyword is intuitionistic fuzzy sets in article title whereas it is 3048 when the keyword is intuitionistic fuzzy in article title. Types of IFSs are single-valued, interval-valued, triangular, and trapezoidal IFSs. We use interval-valued IFSs in this paper since they can easily incorporate uncertainty into decision making process.

Let $X \neq \emptyset$ be a given set. An intuitionistic fuzzy set in X is an object A given by

$$\tilde{A} = \{\langle x, \mu_{\tilde{A}}(x), \nu_{\tilde{A}}(x) \rangle; x \in X\}, \quad (2.7)$$

where $\mu_{\tilde{A}}: X \rightarrow [0, 1]$ and $\nu_{\tilde{A}}: X \rightarrow [0, 1]$ satisfy the following condition:

$$0 \leq \mu_{\tilde{A}} + \nu_{\tilde{A}} \leq 1 \quad (2.8)$$

for every $x \in X$.

2.2 Evaluation Criteria for Freight Villages

Today, a freight village is perceived as an integrator that gathers modes of transportation and logistics firms in a certain area, making the supply chain more rapid and systematic (Tsamboulas, 2002; Wan et al., 2014). Among the general characteristics of a freight village, the followings are the most important benefits: Global roaming lanes, region countries, proximity to production and consumption centres, suitability for through transportation; focability to trade on export, import, transit and customs procedure, simplicity in legislation; international and national railways, seaway, highway, inland waterway, piping connections; combined transportation infrastructure; standardization of business processes; advanced information and communication technology infrastructure; high variety in logistics career field and human resources; proper fields for logistics enterprises; distribution centers; and training in logistics fields. Taking into account all of these factors, locating a freight village is a quite complicated and there will be so many criteria to be determined. A search on the Scopus from the 2000s, in “Article Title” for first and “Article Title, Abstract, and Keywords” for second keyword gives the following frequencies: 6 for freight village and decision making, 63 for logistics centre and decision making, 23 for urban logistics and decision making. We analysis 28 of them in detail (Avittathur et al., 2005; Yang et al., 2007; Chen et al., 2007; Chan et al., 2007; Farahani and Asgari, 2007; Sharma et al., 2008; Kengpol, 2008; Bowen, 2008; Sun et al., 2008; Ho and Emrouznejad, 2009; Ou and Chou, 2009; Guneri et al., 2009; Kayikci, 2010; Turskis and Zavadskas, 2010; Tamagawa et al., 2010; Kuo, 2011; Hong and Xiaohua, 2011; Awasthi et al., 2011a; Awasthi et al., 2011b; Li et al., 2011; Ka, 2011; Liu et al., 2011; Awasthi and Chauhan, 2012; Long and Grasman, 2012; Chakraborty et al., 2013; Tadic et al., 2014; Elevli, 2014; Rao et al., 2015). After analyzing the above criteria, the equivalent terms have been removed and the most functional ones have been sorted for the inputs of DEMATEL method. The input criteria are given as below:

A1–Transportation cost

A2–Building cost

A3–Capacity

A4–Operational costs

A5–Workforce

A6–Transportation and distribution systems

A7–Infrastrustructure
A8–Intermodal operations and management
A9–International market location
A10–Suitability to extension of land
A11–Taxing
A12–Workforce cost
A13–Pollution
A14–Noise
A15–Logistical service level
A16–Value-added services
A17–Deliver costs
A18–Accidents
A19–Traffic congestion
A20–Conservation of energy
A21–Earthquake risk
A22–Delivery time
A23–Integration
A24–Transportation and logistical competition level
A25–Investment attraction
A26–Origin/Destination proximities
A27–Average traffic speed
A28–Governmental incentive

The flowchart of the proposed method is shown in Figure 2.2.

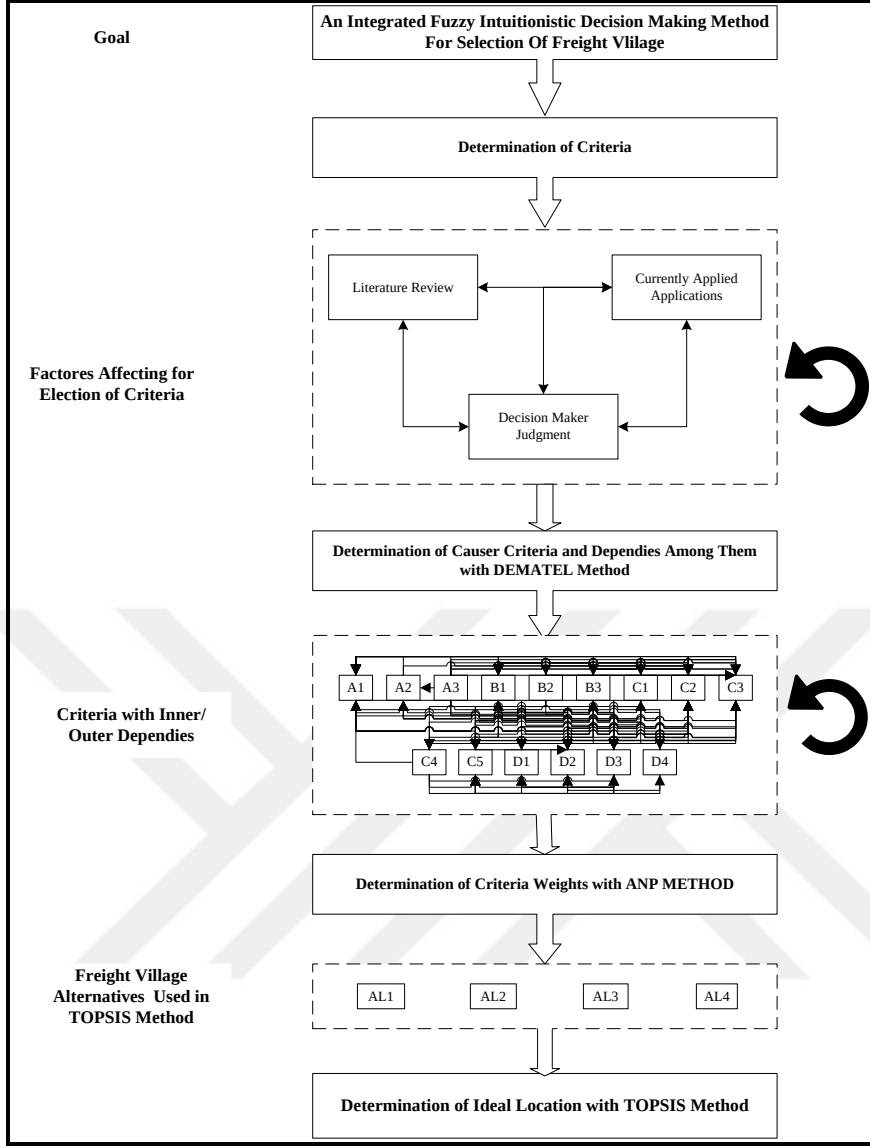


Figure 2.2 : Flowchart of the proposed method.

2.3 Preliminaries for Intuitionistic Fuzzy Sets

Atanassov's intuitionistic fuzzy sets (IFS) take into account the membership value as well as the non-membership value for describing any x in X such that the sum of membership and non-membership is less than or equal to 1 (Atanassov, 1986). In the following, we define the basic definitions of intuitionistic fuzzy sets.

Definition 1 (Atanassov, 1989). Let $X \neq \emptyset$ be a given set. An intuitionistic fuzzy set in X is an object A given by:

$$\tilde{A} = \{\langle x, \mu_{\tilde{A}}(x), \nu_{\tilde{A}}(x) \rangle; x \in X\}, \quad (2.9)$$

where $\mu_{\tilde{A}}: X \rightarrow [0, 1]$ and $\nu_{\tilde{A}}: X \rightarrow [0, 1]$ satisfy the condition $0 \leq \mu_{\tilde{A}}(x) + \nu_{\tilde{A}}(x) \leq 1$, for every $x \in X$.

Definition 2 (Atanassov, 2012). α -cut of an intuitionistic fuzzy number is given by the following equations. For an IF-set, the α -cut is defined in as:

$$\tilde{A}_\alpha = \{x \in X | \mu_{\tilde{A}}(x) \geq \alpha, v_{\tilde{A}}(x) \leq 1 - \alpha\} \quad (2.10)$$

Definition 3 (Atanassov, 2012; Wu et al., 2013; Mahapatra and Roy, 2013; Kumar and Hussain, 2014; Onar et al., 2015). A Triangular Intuitionistic Fuzzy Number (TIFN) $\tilde{A}$ is a subset of IFS in $\mathbb{R}$ with the following membership and non-membership functions as follows:

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{x-a_1}{a_2-a_1}, & \text{for } a_1 \leq x \leq a_2 \\ \frac{a_3-x}{a_3-a_2}, & \text{for } a_2 \leq x \leq a_3 \\ 0, & \text{otherwise} \end{cases} \quad (2.11)$$

$$v_{\tilde{A}}(x) = \begin{cases} \frac{a_2-x}{a_2-a'_1}, & \text{for } a'_1 \leq x \leq a_2 \\ \frac{x-a_2}{a'_3-a_2}, & \text{for } a_2 \leq x \leq a'_3 \\ 1, & \text{otherwise} \end{cases} \quad (2.12)$$

where $a'_1 \leq a_1 \leq a_2 \leq a_3 \leq a'_3$, $0 \leq \mu_{\tilde{A}}(x) + v_{\tilde{A}}(x) \leq 1$.

Definition 4. Let $D \subseteq [0, 1]$ be the set of all closed subintervals of the interval and X be a universe of discourse. An interval-valued intuitionistic fuzzy set in $\tilde{A}$ over X is an object having the form:

$$\tilde{A} = \{ \langle x, [\mu_{\tilde{A}}^-(x), \mu_{\tilde{A}}^+(x)], [v_{\tilde{A}}^-(x), v_{\tilde{A}}^+(x)] \rangle | x \in X \} \quad (2.13)$$

where $0 \leq \mu_{\tilde{A}}^+(x) + v_{\tilde{A}}^+(x) \leq 1$, $\mu_{\tilde{A}}^-(x) \geq 0$.

$v_{\tilde{A}}^-(x) \geq 0$, $\mu_{\tilde{A}} \rightarrow D \subseteq [0, 1]$, $v_{\tilde{A}}(x) \rightarrow D \subseteq [0, 1]$, with the following condition:

$$0 \leq \sup \mu_{\tilde{A}}(x) + \sup v_{\tilde{A}}(x) \leq 1, \forall x \in X \quad (2.14)$$

The intervals $\mu_{\tilde{A}}(x)$ and $v_{\tilde{A}}(x)$ denote the membership function and the non-membership function of the element x to the set $\tilde{A}$, respectively. Thus for each $x \in X$, $\mu_{\tilde{A}}(x)$ and $v_{\tilde{A}}(x)$ are closed intervals and their starting and ending points are denoted by $\mu_{\tilde{A}}^-(x)$, $\mu_{\tilde{A}}^+(x)$, $v_{\tilde{A}}^-(x)$ and $v_{\tilde{A}}^+(x)$, respectively (Kahraman et al., 2015; Kahraman et al., 2016a).

For each element x , we can compute the unknown degree (hesitancy degree) of an interval-valued intuitionistic fuzzy set of $x \in X$ in $\tilde{A}$ defined as follows: $\pi_{\tilde{A}}(x) = 1 -$

$$\mu_{\tilde{A}}(x) - v_{\tilde{A}}(x) = \left([1 - \mu_{\tilde{A}}^+(x) - v_{\tilde{A}}^+(x)], 1 - \mu_{\tilde{A}}^-(x) - v_{\tilde{A}}^-(x) \right) \quad (2.15)$$

For convenience, let $\mu_{\tilde{A}}(x) = [\mu_{\tilde{A}}^-(x), \mu_{\tilde{A}}^+(x)] = [\mu_{\tilde{A}}^-, \mu_{\tilde{A}}^+]$, $v_{\tilde{A}}(x) = [v_{\tilde{A}}^-(x), v_{\tilde{A}}^+(x)] = [v_{\tilde{A}}^-, v_{\tilde{A}}^+]$, so $\tilde{A} = ([\mu_{\tilde{A}}^-, \mu_{\tilde{A}}^+], [v_{\tilde{A}}^-, v_{\tilde{A}}^+])$.

Some arithmetic operations with interval-valued intuitionistic fuzzy numbers and $\lambda \geq 0$ are given in the following. Let $\tilde{A} = ([\mu_{\tilde{A}}^-, \mu_{\tilde{A}}^+], [v_{\tilde{A}}^-, v_{\tilde{A}}^+])$ and $\tilde{B} = ([\mu_{\tilde{B}}^-, \mu_{\tilde{B}}^+], [v_{\tilde{B}}^-, v_{\tilde{B}}^+])$ be two interval-valued intuitionistic fuzzy numbers. Then,

$$\tilde{A} \oplus \tilde{B} = ([\mu_{\tilde{A}}^- + \mu_{\tilde{B}}^- - \mu_{\tilde{A}}^- \mu_{\tilde{B}}^-, \mu_{\tilde{A}}^+ + \mu_{\tilde{B}}^+ - \mu_{\tilde{A}}^+ \mu_{\tilde{B}}^+], [v_{\tilde{A}}^- v_{\tilde{B}}^-, v_{\tilde{A}}^+ v_{\tilde{B}}^+]) \quad (2.16)$$

$$\tilde{A} \otimes \tilde{B} = ([\mu_{\tilde{A}}^- \mu_{\tilde{B}}^-, \mu_{\tilde{A}}^+ \mu_{\tilde{B}}^+], [v_{\tilde{A}}^- + v_{\tilde{B}}^- - v_{\tilde{A}}^- v_{\tilde{B}}^-, v_{\tilde{A}}^+ + v_{\tilde{B}}^+ - v_{\tilde{A}}^+ v_{\tilde{B}}^+]) \quad (2.17)$$

2.3.1 Defuzzification of Intuitionistic Fuzzy Numbers

In the following, we propose two defuzzification methods: one for triangular IFNs and one for interval-valued IFNs.

Let $I_i = (a_i^L, a_i^M, a_i^U; a_i'^L, a_i'^M, a_i'^U)$ is a triangular intuitionistic fuzzy number. Then, the defuzzification is realized by using function defined in Eq. (2.18).

$$d_f = \frac{a_i^L + a_i^M + a_i^U}{3} + \frac{a_i'^L + a_i'^M + a_i'^U}{\tau} \quad (2.18)$$

where τ is a very large number.

Let $\tilde{\alpha} = ([a, b], [c, d])$ be an interval-valued intuitionistic fuzzy number. The following score function is proposed for defuzzifying $\tilde{\alpha}$:

$$I(\tilde{\alpha}) = \frac{a+b+(1-c)+(1-d)+a \times b - \sqrt{(1-c) \times (1-d)}}{4} \quad (2.19)$$

In Eq.(2.19), the terms $(1 - c)$ and $(1 - d)$ convert non-membership degrees to membership degrees while the term $\sqrt{(1 - c) \times (1 - d)}$ decreases the defuzzified value.

2.3.2 Aggregation Operators for Triangular Intuitionistic Fuzzy Sets

Let $\tilde{A}_j = ((l_j, m_j, u_j), (\hat{l}_j, \hat{m}_j, \hat{u}_j)), j = 1, 2, \dots, n$ be a set of Triangular Fuzzy Number Intuitionistic Fuzzy Numbers (TFNIFN) and $w = (w_1, w_2, \dots, w_n)$ is the weighting vector where $w_j > 0$ and $\sum_{j=1}^n w_j = 1$.

Triangular fuzzy number intuitionistic fuzzy weighted geometric (TFNIFWG_w) operator given in Eq. (2.20) can be used for aggregating triangular intuitionistic fuzzy sets (Chen and Tan, 2010).

$$\text{TFNIFWG}_w(\tilde{A}_1, \tilde{A}_2, \dots, \tilde{A}_n) = \left(\left(\prod_{j=1}^n l_j^{w_j}, \prod_{j=1}^n m_j^{w_j}, \prod_{j=1}^n u_j^{w_j} \right), \left(1 - \prod_{j=1}^n (1 - \hat{l}_j)^{w_j}, 1 - \prod_{j=1}^n (1 - \hat{m}_j)^{w_j}, 1 - \prod_{j=1}^n (1 - \hat{u}_j)^{w_j} \right) \right) \quad (2.20)$$

2.3.3 Aggregation Operators for Interval-Valued Intuitionistic Fuzzy Sets

Let $\tilde{A}_j = ([l_j, r_j], [\hat{l}_j, \hat{r}_j])$, $j = 1, 2, \dots, n$ be a set of Interval-Valued Intuitionistic Fuzzy Hybrid Geometric (IIFGH) operator and $w = w_1, w_2, \dots, w_n$ is the weighting vector where $w_j > 0$ and $\sum_{j=1}^n w_j = 1$.

Interval-valued fuzzy intuitionistic fuzzy hybrid geometric (IIFGH_w) operator given in Eq. (2.21) can be used for aggregating triangular intuitionistic fuzzy sets (Xu, 2007).

$$\begin{aligned} \tilde{r}_{ij} &= \text{IIFGH}_{\alpha, \lambda} \left(r_{ij}^{(1)}, r_{ij}^{(2)}, \dots, r_{ij}^{(n)} \right), \text{ where} \\ &\left(\hat{r}_{ij}^{\sigma(1)} \right)^{\alpha_1} \otimes \left(\hat{r}_{ij}^{\sigma(2)} \right)^{\alpha_2} \otimes \dots \otimes \left(\hat{r}_{ij}^{\sigma(n)} \right)^{\alpha_n}, \text{ and} \\ &= \left\langle \left[\prod_{k=1}^n \hat{a}_{ij}^{\sigma(k) \alpha_k} \right], \left[\prod_{k=1}^n \hat{b}_{ij}^{\sigma(k) \alpha_k} \right], \left\langle \left[1 - \prod_{k=1}^n (1 - \hat{c}_{ij}^{\sigma(k)})^{\alpha_k}, 1 - \prod_{k=1}^n (1 - \hat{d}_{ij}^{\sigma(k)})^{\alpha_k} \right] \right\rangle \right\rangle \quad (2.21) \end{aligned}$$

2.4 A Novel Integrated Intuitionistic Fuzzy Method Based on DEMATEL-ANP-TOPSIS

In the following, the integrated techniques mentioned in Figure 2.2 are given in detail.

2.4.1 Triangular Intuitionistic Fuzzy DEMATEL

We extend Sumrit & Anuntavoranich's ordinary fuzzy DEMATEL method to intuitionistic triangular fuzzy DEMATEL and imply it for our application (Sumrit and Anuntavoranich, 2014). In this extension, defuzzification process is postponed to the final step of intuitionistic triangular fuzzy DEMATEL method. The procedure of the extended method consists of the following steps:

Step 1: Construct the average matrix $\tilde{Z}$

Step 2: Calculate the normalized initial direct-relation matrix $\tilde{M}$

The normalized initial direct-relation matrix $\tilde{M} = [\tilde{d}_{ij}]$, where the value of each element in matrix $\tilde{M}$ is ranged between $[0, 1]$. The calculation is given in Eq. (2.22).

$$\tilde{M} = k \times \tilde{Z} \quad (2.22)$$

where

$$k = \text{Min} \left(\frac{1}{\max_{l \leq i \leq n} \sum_{i=1}^n |a_{ij}|}, \frac{1}{\max_{l \leq j \leq n} \sum_{j=1}^n |a_{ij}|} \right) \quad (2.23)$$

where, $i, j = \{1, 2, 3, \dots, n\}$.

Step 3: Derive the total relation matrix $\tilde{S}$

The total-influence matrix $\tilde{S}$ is obtained by utilizing Eq. (2.23), in which, I is an $n \times n$ identity matrix. The matrix $\tilde{S}$ reflects the total relationship between elements of membership and non-membership functions.

$$\tilde{S} = \tilde{M} + \tilde{M}^2 + \tilde{M}^3 + \dots = \sum_{i=1}^{\infty} \tilde{M}^i \quad (2.23)$$

where $\tilde{S} = \tilde{M}(I - \tilde{M})^{-1}$.

Step 4: Calculate the sums of rows and columns of matrix $\tilde{S}$

In the total-influence matrix $\tilde{S}$, the sum of rows and the sum of columns are represented by vectors $\tilde{D}$ and $\tilde{R}$, respectively.

$$\tilde{S} = [\tilde{s}_{ij}]_{n \times n}, i, j \in \{1, 2, 3, \dots, n\}$$

$$\tilde{D} = \sum_{i=1}^n s_{i,j} \quad (2.24)$$

$$\tilde{R} = \sum_{j=1}^n s_{i,j} \quad (2.25)$$

Step 5: Set a threshold value (α)

The threshold value (α), was computed by the average of the elements in matrix $\tilde{S}$, as computed by Eq. (2.26). This calculation aimed to show inner and outer dependencies of factors in matrix $\tilde{S}$ (Yang et al. 2008).

$$\alpha = \frac{\sum_{i=1}^n \sum_{j=1}^n [t_{ij}]}{N} \quad (2.26)$$

Step 6: Build a cause and effect relationship diagram

We defuzzify $\tilde{D}$ and $\tilde{R}$ in this step using Eq. (2.18). The cause and effect diagram is constructed by mapping all coordinate sets of $(D_i + R_i), (D_i - R_i)$ to visualize the complex interrelationship and provide information to judge which are the most important factors and how influence affected factors (Shieh et al., 2010). The scale given in Table 2.1 is used to assign the interval-valued intuitionistic fuzzy preferences.

Table 2.1 : Scale for DEMATEL method.

Fuzzy Numbers	Linguistic Terms
$((0.65, 0.7, 0.8), (0, 0.1, 0.2))$	Very Important (VI)
$((0.6, 0.65, 0.7), (0.2, 0.25, 0.3))$	Quite Important (QI)
$((0.45, 0.5, 0.55), (0.35, 0.4, 0.45))$	Bit Important (BI)
$((0.45, 0.5, 0.5), (0.45, 0.5, 0.5))$	Proximately Important (PI)
$((0.35, 0.4, 0.45), (0.45, 0.5, 0.55))$	Reverse of Bit Important
$((0.2, 0.25, 0.3), (0.6, 0.65, 0.7))$	Reverse of Quite Important
$((0, 0.1, 0.2), (0.65, 0.7, 0.8))$	Reverse of Very Important
$((0.5, 0.5, 0.5), (0.5, 0.5, 0.5))$	Equal (CE)

2.4.2 Interval-valued Intuitionistic Fuzzy ANP

The proposed interval-valued intuitionistic Fuzzy ANP procedure is an extension of (Yanik and Kahraman, 2016). This procedure includes a new defuzzification method and a new linguistic scale.

Let $\tilde{R} = (\tilde{r}_{ij})_{n \times n} = ([\mu_{ij}^-, \mu_{ij}^+], [v_{ij}^-, v_{ij}^+])_{n \times n}$ be an interval-valued intuitionistic judgment matrix as follows:

The reciprocal value of $([\mu_{ij}^-, \mu_{ij}^+], [v_{ij}^-, v_{ij}^+])$ in $\tilde{R}$ is $([v_{ji}^-, v_{ji}^+], [\mu_{ji}^-, \mu_{ji}^+])$. For instance, the reciprocal value of $([\mu_{n1}^-, \mu_{n1}^+], [v_{n1}^-, v_{n1}^+])$ is $([v_{1n}^-, v_{1n}^+], [\mu_{1n}^-, \mu_{1n}^+])$.

Step 1: Assign the interval-valued intuitionistic preferences for each pair of alternatives and obtain the interval-valued intuitionistic preference relation $\tilde{R} = (\tilde{r}_{ij})_{n \times n}$ where,

$$\begin{bmatrix} ([\mu_{11}^-, \mu_{11}^+], [v_{11}^-, v_{11}^+]) & \cdots & ([\mu_{1n}^-, \mu_{1n}^+], [v_{1n}^-, v_{1n}^+]) \\ \vdots & \ddots & \vdots \\ ([\mu_{n1}^-, \mu_{n1}^+], [v_{n1}^-, v_{n1}^+]) & \cdots & ([\mu_{nn}^-, \mu_{nn}^+], [v_{nn}^-, v_{nn}^+]) \end{bmatrix} \quad (2.27)$$

Step 2: Calculate the score judgment matrix $\tilde{S} = (\tilde{s}_{ij})_{n \times n}$ and the interval multiplicative matrix $\tilde{A} = (\tilde{a}_{ij})_{n \times n}$.

$\tilde{S} = (\tilde{s}_{ij})_{n \times n} = [\mu_{ij}^- - v_{ij}^+, \mu_{ij}^+ - v_{ij}^-]$ as follows:

$$\begin{bmatrix} [\mu_{11}^- - v_{11}^+, \mu_{11}^+ - v_{11}^-] & \cdots & [\mu_{1n}^- - v_{1n}^+, \mu_{1n}^+ - v_{1n}^-] \\ \vdots & \ddots & \vdots \\ [\mu_{n1}^- - v_{n1}^+, \mu_{n1}^+ - v_{n1}^-] & \cdots & [\mu_{nn}^- - v_{nn}^+, \mu_{nn}^+ - v_{nn}^-] \end{bmatrix} \quad (2.28)$$

Step 3: Determine the priority vector of the interval multiplicative matrix $\tilde{A} = (\tilde{a}_{ij})_{n \times n}$ by calculating the $\tilde{w}_i$ interval for each criterion using Eq. (2.30):

The interval multiplicative matrix $\tilde{A} = (\tilde{a}_{ij})_{n \times n} = [10^{(\mu_{ij}^- - v_{ij}^+)}, 10^{(\mu_{ij}^+ - v_{ij}^-)}]$ is given as follows:

$$\begin{bmatrix} [10^{(\mu_{11}^- - v_{11}^+)}, 10^{(\mu_{1n}^+ - v_{1n}^-)}] & \dots & [10^{(\mu_{1j}^- - v_{1j}^+)}, 10^{(\mu_{1j}^+ - v_{1j}^-)}] \\ \vdots & \ddots & \vdots \\ [10^{(\mu_{n1}^- - v_{n1}^+)}, 10^{(\mu_{n1}^+ - v_{n1}^-)}] & \dots & [10^{(\mu_{nn}^- - v_{nn}^+)}, 10^{(\mu_{nn}^+ - v_{nn}^-)}] \end{bmatrix} \quad (2.29)$$

$$\tilde{w}_i = \left[\frac{\sum_{j=1}^n \tilde{a}_{ij}^-}{\sum_{i=1}^n \sum_{j=1}^n \tilde{a}_{ij}^+}, \frac{\sum_{j=1}^n \tilde{a}_{ij}^+}{\sum_{i=1}^n \sum_{j=1}^n \tilde{a}_{ij}^-} \right] \quad (2.30)$$

Step 4: Construct the possibility degree matrix $P = (p_{ij})_{m \times n}$ by comparing the obtained weights in Step 3. To do this, use Eq. (2.31):

$$P(w_i \geq w_j) = \frac{\min\{L_{w_i} + L_{w_j}, \max(w_i^+ - w_j^-, 0)\}}{L_{w_i} + L_{w_j}} \quad (2.31)$$

where $L_{w_i} = w_i^+ - w_i^-$ and $L_{w_j} = w_j^+ - w_j^-$ and $p_{ij} \geq 0$. $p_{ij} + p_{ji} = 1$, $p_{ii} = 1/2$.

Step 5: Prioritize the $P = (p_{ij})_{m \times n}$ by Eq. (2.32):

$$w_i = \frac{1}{n} \left[\sum_{j=1}^n p_{ij} + \frac{n}{2} - 1 \right] \quad (2.32)$$

Step 6: Normalize the weights vector obtained in Step 5 by Eq. (2.33).

$$I(\tilde{\alpha}) = \frac{a+b+(1-c)+(1-d)+a \times b - \sqrt{(1-c) \times (1-d)}}{4} \quad (2.33)$$

The scale given in Table 2.2 is used to assign the interval-valued intuitionistic fuzzy preferences.

Table 2.2 : Scale for ANP method.

Linguistic terms	Fuzzy Equality
Certainly Low	([0.1, 0.25], [0.65, 0.75])
Very Low	([0.15, 0.3], [0.6, 0.7])
Low	([0.2, 0.35], [0.55, 0.65])
Below Average	([0.25, 0.4], [0.5, 0.6])
Average	([0.45, 0.55], [0.3, 0.45])
Above Average	([0.5, 0.6], [0.25, 0.4])
High	([0.55, 0.65], [0.2, 0.35])
Very High	([0.6, 0.7], [0.15, 0.3])
Certainly High	([0.65, 0.75], [0.1, 0.25])
Equal	([0.5, 0.5], [0.5, 0.5])

2.4.3 Interval-valued Intuitionistic Fuzzy TOPSIS

Intuitionistic fuzzy TOPSIS procedure consists of the following steps (Xu, 2005):

Step 1: Determine the members of decision makers group.

Step 2: Gather the alternatives' scores with respect to criteria from decision makers.

$$R^k = (\tilde{r}_{ij}^k)_{m \times n}, k = \{1, 2, \dots, l\} \quad (2.34)$$

where $(\tilde{r}_{ij})^k = \langle [a_{ij}^{(k)}, b_{ij}^{(k)}], [c_{ij}^{(k)}, d_{ij}^{(k)}] \rangle$ is an IVIFN which represents rates of alternatives with respect to criteria. Also weights of criteria are represented as $w = (w_1, w_2, \dots, w_m)^T$.

Step 3: Aggregate fuzzy ratings. Interval-valued intuitionistic fuzzy hybrid geometric (IIFGH) operator is preferred for the aggregation of the decision-makers opinions.

Let $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_l)$ be weight vector of IIFHG operator. $\alpha_k > 0$ $k = 1, 2, \dots, l$ and $\sum_{k=1}^l \alpha_k = 1$. μ_l is the mean operator of the collection $1, 2, \dots, l$ and σ_l is the standard deviation of the collection $1, 2, \dots, l$ (Xu, 2005).

$$\mu_l = \frac{1+l}{2} \quad (2.35)$$

$$\sigma_l = \sqrt{\frac{1}{l} * \sum_{i=1}^l (i - \mu_l)^2} \quad (2.36)$$

Then the weight vector $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_l)$ of IIFHG is defined as in Eq. (2.37):

$$\begin{aligned} \alpha_i &= \frac{\frac{1}{\sqrt{2\pi\sigma_l}} e^{-[(i-\mu_l)^2/2\sigma_l^2]}}{\sum_{j=1}^l \frac{1}{\sqrt{2\pi\sigma_l}} e^{-[(i-\mu_l)^2/2\sigma_l^2]}} \text{ where} \\ &= \frac{e^{-[(i-\mu_l)^2/2\sigma_l^2]}}{\sum_{j=1}^l e^{-[(i-\mu_l)^2/2\sigma_l^2]}}, i = \{1, 2, \dots, l\} \end{aligned} \quad (2.37)$$

Let the second parameter of IIFGH operator be $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_l)^T$, $\lambda_k \geq 0$, $k = 1, 2, \dots, l$ and $\sum_{k=1}^l \lambda_k = 1$. Weight vector of decision-makers will be applied to $\tilde{r}_{ij}^{(k)}$ to get the weighted IVIFNs:

$$\dot{\tilde{r}}_{ij}^{(k)} = \left(\tilde{r}_{ij}^{(k)} \right)^{l\lambda_k}, i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (2.38)$$

If $(\dot{\tilde{r}}_{ij})^{\sigma k} = \langle [\dot{a}_{ij}^{(\sigma k)}, \dot{b}_{ij}^{(\sigma k)}], [\dot{c}_{ij}^{(\sigma k)}, \dot{d}_{ij}^{(\sigma k)}] \rangle$ indicates the k^{th} largest of the weighted IVIFNs then components of the collective interval-valued intuitionistic fuzzy decision matrix are obtained by Eq. (2.21).

Step 4: Apply attribute weights $w = (w_1, w_2, \dots, w_n)^T$ on the aggregated fuzzy decision matrix obtained in Step 3:

$$R^* = (\tilde{r}_{ij}^*)_{m \times n} \quad (2.39)$$

where $\sum_{i=1}^m w = 1, w_i > 0$ and $\tilde{r}_{ij}^* = \langle [1 - (1 - a_{ij})^{w_i}, 1 - (1 - b_{ij})^{w_i}], [c_{ij}^{w_i}, d_{ij}^{w_i}] \rangle$.

Step 5: Determine interval-valued intuitionistic fuzzy positive (IVIFP) and negative (IVIFN) ideal solutions.

$$O^* = \left\{ \langle e_i, (\max_j \tilde{r}_{ij}^* | i \in B), (\min_j \tilde{r}_{ij}^* | i \in C) \rangle | i = 1, 2, \dots, m \right\}^T, \quad (2.40)$$

where $= \{\tilde{r}_1^+, \tilde{r}_2^+, \dots, \tilde{r}_m^+\}$.

$$O^- = \left\{ \langle e_i, (\min_j \tilde{r}_{ij}^* | i \in B), (\max_j \tilde{r}_{ij}^* | i \in C) \rangle | i = 1, 2, \dots, m \right\}^T, \quad (2.41)$$

where $= \{\tilde{r}_1^-, \tilde{r}_2^-, \dots, \tilde{r}_m^-\}$. $\tilde{r}_i^+ = \langle [a_i^+, b_i^+], [c_i^+, d_i^+] \rangle$, $\tilde{r}_i^- = \langle [a_i^-, b_i^-], [c_i^-, d_i^-] \rangle$, $i = 1, 2, \dots, m$.

Step 6: Calculate the distance between positive and negative ideal solutions for each alternative. Grzegorzewski's method is used for distance calculation (Grzegorzewski, 2004).

$$S_j^* = \frac{1}{2n} \sum_{i=1}^m [\max(|a_{ij}^* - a_i^+|, |b_{ij}^* - b_i^+|) + \max(c_{ij}^* - c_i^+, |d_{ij}^* - d_i^+|)] \quad (2.42)$$

$$S_j^- = \frac{1}{2n} \sum_{i=1}^m [\max(|a_{ij}^* - a_i^-|, |b_{ij}^* - b_i^-|) + \max(c_{ij}^* - c_i^-, |d_{ij}^* - d_i^-|)] \quad (2.43)$$

Step 7: Calculate the closeness coefficient.

$$C_j = \frac{S_j^-}{S_j^+ + S_j^-} \quad (2.44)$$

Step 8: Rank the alternatives based on the closeness coefficients.

2.5 An Application for Istanbul

The integrated model proposed in this paper is used for the selection of freight village location alternatives in Istanbul. Due to the urban traffic problems, legal regulations, need of trained and qualified human resource, lack of infrastructure, lack of urban logistics management center, unfair competition, informal economy, high land costs, customs issues, and lack of central logistics planning lead us to work on the selection of the best freight village location. Due to these problems, we determine 28 criteria that are given in Section 2.3.

It is planned to establish a logistic village in order to reduce the above problems caused by customs, oil transmission stations, solid waste stations, explosive material storage, ports, airports, and fruit and vegetable stations in Istanbul region. Freight villages

location alternatives planned to be built have been taken from the Istanbul 2010 Environment Planning Report. The reasons why we apply our proposed model for Istanbul are its organized industrial zones and its population that is the largest in Turkey. On the other hand, when the density in customs located in Istanbul is evaluated, it is seen that the busiest points are located at the European side and meet 69.4% of the total density. Therefore, most of the alternative locations have been determined at European side of Istanbul. They are given as follows:

Gümüşyaka (European side)–AL1

Kavaklı (European side)–AL2

Hadımköy, Ambarlı (European side)–AL3

Pendik, Orhanlı (Anatolian side)–AL4

In the first phase. DEMATEL method is used for finding the most appropriate and influential factors to use in ANP method and determining those factors' inner and outer dependencies.

The first step is constructing the initial matrix. Initial matrix is shown in Table 2.3. Three experts whose members are 1 academician and 2 supply chain experts make their compromised decision in a meeting as follows:

Table 2.3 : Initial matrix for DEMATEL.

Initial Matrix	F1	F2	...	F27	F28
F1	((0.5, 0.5, 0.5), (0.5, 0.5, 0.5))	((0.3, 0.4, 0.5), (0.3, 0.4, 0.5))	...	((0.4, 0.5, 0.6), (0.3, 0.4, 0.4))	((0, 0.1, 0.2), (0, 0.1, 0.2))
F2	((0.3, 0.4, 0.5), (0.3, 0.4, 0.5))	((0.5, 0.5, 0.5), (0.5, 0.5, 0.5))	...	((0.4, 0.5, 0.6), (0.3, 0.4, 0.4))	((0, 0.1, 0.2), (0, 0.1, 0.2))
⋮	⋮	⋮	⋮	⋮	⋮
F27	((0.4, 0.5, 0.6), (0.3, 0.4, 0.4))	((0.4, 0.5, 0.6), (0.3, 0.4, 0.4))	...	((0.5, 0.5, 0.5), (0.5, 0.5, 0.5))	((0.1, 0.2, 0.3), (0.1, 0.2, 0.3))
F28	((0.7, 0.8, 0.9), (0.1, 0.1, 0.1))	((0.7, 0.8, 0.9), (0.1, 0.1, 0.1))	...	((0.4, 0.5, 0.6), (0.3, 0.4, 0.4))	((0.5, 0.5, 0.5), (0.5, 0.5, 0.5))

In the second step, every criteria weight are normalized column by column. During processing of this step Eq. (2.23) is applied:

- Every column is summed respectively.
- The largest sum of the columns are determined for membership and non-membership functions' members (L, M, R).
- Every member in the initial matrix is divisible those which are determined as largest ones respectively.

Normalized initial matrix is shown in Table 2.4.

Table 2.4 : Normalized initial matrix.

Normalization	F1	F2	...	F27	F28
F1	((0.033, 0.028, 0.025), (0.033, 0.028, 0.025))	((0.02, 0.023, 0.025), (0.02, 0.023, 0.025))	...	((0.026, 0.028, 0.03), (0.02, 0.023, 0.02))	((0, 0.006, 0.01), (0, 0.006, 0.01))
F2	((0.02, 0.023, 0.025), (0.02, 0.023, 0.025))	((0.033, 0.028, 0.025), (0.033, 0.028, 0.025))	...	((0.026, 0.028, 0.03), (0.02, 0.023, 0.02))	((0, 0.006, 0.01), (0, 0.006, 0.01))
⋮	⋮	⋮	⋮	⋮	⋮
F27	((0.026, 0.028, 0.03), (0.02, 0.023, 0.02))	((0.026, 0.028, 0.03), (0.02, 0.023, 0.02))	...	((0.033, 0.028, 0.025), (0.033, 0.028, 0.025))	((0.007, 0.011, 0.015), (0.007, 0.011, 0.015))
F28	((0.046, 0.045, 0.045), (0.007, 0.006, 0.005))	((0.046, 0.045, 0.045), (0.007, 0.006, 0.005))	...	((0.026, 0.028, 0.03), (0.02, 0.023, 0.02))	((0.033, 0.028, 0.025), (0.033, 0.028, 0.025))

In the third step, Eq. (2.24) is applied to the normalized initial matrix for obtaining the total relation matrix. Total relation matrix is shown in Table 2.5.

Table 2.5 : Total relation matrix.

Total Relation Matrix	F1	F2	...	F27	F28
F1	((0.05, 0.06, 0.069), (0.04, 0.043, 0.042))	((0.036, 0.052, 0.068), (0.028, 0.038, 0.042))	...	((0.041, 0.056, 0.072), (0.028, 0.037, 0.037))	((0.01, 0.019, 0.32), (0.003, 0.013, 0.02))
F2	((0.042, 0.059, 0.077), (0.029, 0.038, 0.042))	((0.055, 0.065, 0.077), (0.042, 0.044, 0.042))	...	((0.025, 0.064, 0.082), (0.029, 0.038, 0.037))	((0.007, 0.021, 0.035), (0.004, 0.014, 0.021))
⋮	⋮	⋮	⋮	⋮	⋮
F27	((0.05, 0.066, 0.084), (0.32, 0.042, 0.04))	((0.05, 0.066, 0.084), (0.032, 0.042, 0.04))	...	((0.057, 0.067, 0.08), (0.045, 0.047, 0.045))	((0.014, 0.027, 0.041), (0.011, 0.021, 0.028))
F28	((0.088, 0.105, 0.122), (0.015, 0.018, 0.015))	((0.087, 0.103, 0.121), (0.015, 0.018, 0.015))	...	((0.068, 0.087, 0.106), (0.029, 0.035, 0.031))	((0.047, 0.053, 0.062), (0.034, 0.035, 0.033))

In the fourth step, we use Eq. (2.25) for the sum of rows and the sum of columns. It is represented by vectors D and R , respectively. D means represented as a fuzzy number of effect on the other factors directly or indirectly. R means represented as a fuzzy number of affected by other factors directly or indirectly. Vectors D and R are shown for every factor in Table 2.6.

Table 2.6 : D and R vectors.

Criteria	D	R
F1	((0.971, 1.395, 1.848), (0.512, 0.757, 0.866))	((1.088, 1.535, 2.015), (0.723, 1.003, 1.069))
F2	((1.303, 1.759, 2.249), (0.587, 0.81, 0.873))	((1.077, 1.523, 2.003), (0.723, 1.003, 1.079))
⋮	⋮	⋮
F27	((1.392, 1.851, 2.345), (0.734, 0.965, 1.01))	((1.077, 1.509, 1.986), (0.701, 0.994, 1.046))
F28	((2.439, 2.853, 3.292), (0.485, 0.585, 0.525))	((0.371, 0.663, 0.985), (0.287, 0.508, 0.646))

In the fifth step, in the first defuzzifying process is applied via Eq. (2.18). then threshold value (α) is calculated via Eq. (2.26) and found as 0.075398461. Through this informations, Table 2.7 is constructed for ANP method.

In the sixth step, we build cause and effect relationship diagram. The aim of this process is to find factors effects and their levels and the importance of each criterion. With this process. we aimed to eliminate minor effect factors like F1, F3, F4, F11, F12, F13, F14, F15, F17, F18, F19, F20, F21. The remaining factors (F2, F5, F6, F7, F8, F9, F10, F16, F22, F23, F24, F25, F26, F27, F28) are the most effective factors that are used in interval-valued intuitionistic ANP method. The diagram is shown in Figure 3. For intance, the point F28 (2.28, 1.12) is the most affecting criterion whereas F21 (2.12, -092) is the least affecting criterion among all in the considered problem. The network of the problem for ANP method which is given in Figure 2.4 uses the threshold value of causes and effects that are notated in Figure 2.3 as $D + R$ and $D - R$, respectively to determine the sub-criteria sets.

In the second phase. we use ANP method for weighting the criteria. As an input of ANP method, we use DEMATEL method outputs. We redominate the criteria's shortcut as follows:

- o A1 Building cost
- o A2 Workforce
- o A3 Governmental incentive
- o B1 Transportation and distribution system
- o B2 Intermodal operations and management
- o B3 Integration
- o C1 International market location
- o C2 Delivery time
- o C3 Investment attraction
- o C4 Origin/Destination proximities
- o C5 Average traffic speed
- o D1 Suitability to extension of land
- o D2 Value-added services
- o D3 Transportation and logistical competition level
- o D4 Infrastructure

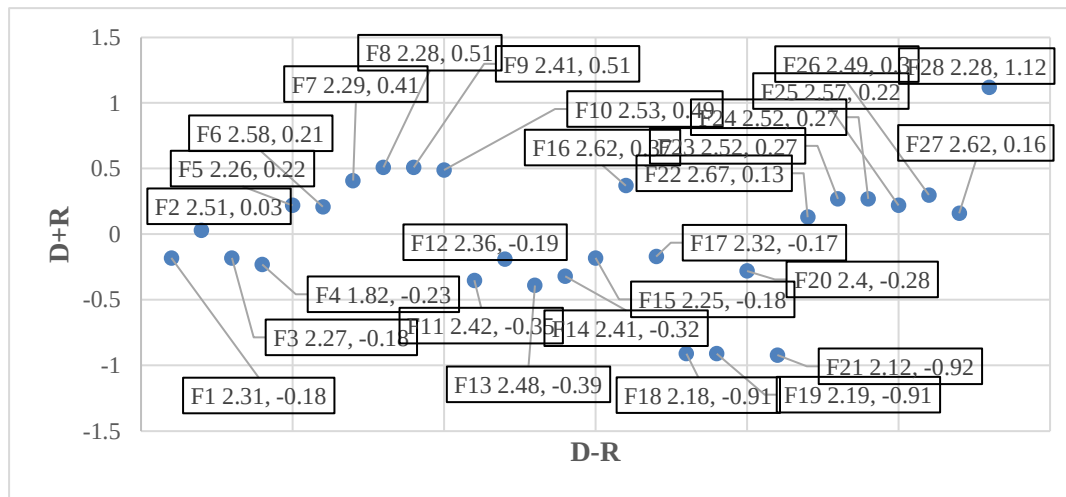


Figure 2.3 : Cause and effect relationship diagram.

After merging data that comes from DEMATEL method for inner and outer dependencies, we construct super-matrix network as shown in Table 2.7. Four clusters to use in ANP method is designed and named as Financial aspect, System design, Regional and geographic impact, and Service level respectively. The matrix shows the inner and outer dependencies of criteria.

Table 2.7 : Design of super-matrix.

		AA			BB			CC					DD			
		A1	A2	A3	B1	B2	B3	C1	C2	C3	C4	C5	D1	D2	D3	D4
AA	A1	1	0	0	1	0	0	0	1	0	0	1	0	1	0	0
	A2	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0
	A3	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1
BB	B1	1	1	0	1	0	0	0	1	1	0	1	0	1	1	0
	B2	1	0	0	1	0	1	0	1	1	0	1	1	1	1	0
	B3	1	0	0	1	0	1	0	1	1	0	1	1	1	1	0
CC	C1	1	1	0	1	0	1	1	1	1	1	1	0	1	1	0
	C2	1	0	0	1	0	1	0	1	1	0	1	1	1	1	0
	C3	1	0	0	1	0	1	1	1	1	0	1	1	1	1	0
	C4	1	0	0	1	0	1	1	1	1	1	1	1	1	1	0
	C5	1	0	0	1	0	0	0	1	1	0	1	1	1	1	0
DD	D1	1	1	0	1	0	1	0	1	1	1	1	1	1	1	0
	D2	1	1	0	1	0	1	0	1	1	1	1	1	1	1	1
	D3	1	0	0	1	0	1	1	1	1	0	1	1	1	1	0
	D4	1	1	0	1	0	0	0	1	0	0	1	0	0	0	0

As a result of hierarchy that we demonstrated in Table 2.9, the constructed network is given in Figure 2.4.

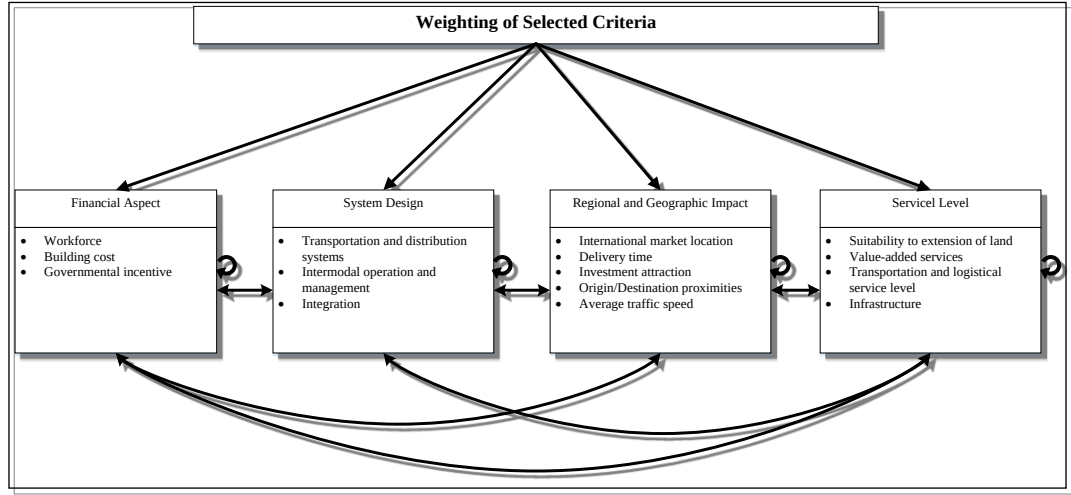


Figure 2.4 : Network of the problem.

For the ANP method, we will give just one pair-wise comparison for Financial Aspect cluster's comparison due to Financial Aspect. The first step, constructing the interval-valued intuitionistic judgment matrix represented by matrix $\tilde{R}$. The second step, constructing the score judgment matrix of $\tilde{R}$ is represented by the matrix $\tilde{S}$. The third step, constructing the interval multiplicative matrix $\tilde{A}$.

$$\tilde{R} = \begin{bmatrix} ([0.5, 0.5], [0.5, 0.5]) & ([0.5, 0.6], [0.25, 0.4]) & ([0.2, 0.35], [0.55, 0.65]) \\ ([0.25, 0.4], [0.5, 0.6]) & ([0.5, 0.5], [0.5, 0.5]) & ([0.15, 0.3], [0.6, 0.7]) \\ ([0.25, 0.4], [0.5, 0.6]) & ([0.6, 0.7], [0.15, 0.3]) & ([0.5, 0.5], [0.5, 0.5]) \end{bmatrix}$$

$$\tilde{S} = \begin{bmatrix} [0, 0] & [0.1, 0.35] & [-0.5, -0.2] \\ [-0.4, -0.1] & [0, 0] & [-0.6, -0.3] \\ [-0.4, -0.1] & [0.3, 0.55] & [0, 0] \end{bmatrix}$$

$$\tilde{A} = \begin{bmatrix} [1, 1] & [1.26, 2.24] & [0.35, 0.63] \\ [0.45, 0.79] & [1, 1] & [0.28, 0.5] \\ [0.45, 0.79] & [2, 3.55] & [1, 1] \end{bmatrix}$$

The fourth step, determining the priority vector $\tilde{w}_i$ by calculating the interval for each criterion via Eq. (2.30). The priority vectors are shown in Table 2.8.

Table 2.8 : Priority vectors.

	w_i^+	w_i^-		L_w
A1	0.43	0.19	A1	0.24
A2	0.26	0.13	A2	0.13
A3	0.83	0.34	A3	0.49

The fifth step, constructing the possibility degree matrix P for each criterion using Eq. (2.31) as follows. The possibility degree matrix is shown in Table 2.9.

Table 2.9 : Possibility degree matrix.

A1	A2	0.83	A2	A1	0.17	A3	A1	0.87
A1	A3	0.13	A2	A3	0	A3	A2	1

The sixth step, prioritize the matrix P then normalize. Final weights are found as $A1=0.32$, $A2=0.15$, $A3=0.53$. We construct the super matrix after finding weights of all criteria. The final weights of criteria are shown in Table 2.10 after the calculations.

Table 2.10 : Final weights of criteria.

Criterion	Weight	Criterion	Weight	Criterion	Weight
Building cost	0.01	Integration	0.01	Average traffic speed	0.06
Workforce	0.001	International market location	0.12	Suitability to extension of land	0.07
Governmental incentive	0.23	Delivery time	0.06	Value-added services	0.08
Transportation and distribution systems	0.03	Investment attraction	0.13	Transportation & logistical competition level	0.06
Intermodal operations and management	0.03	Origin/Destination proximities	0.08	Infrastructure	0.01

The third phase of the integration of method is TOPSIS method to find the best alternative. The first step is forming of decision makers and their weights. To do so, we select 3 decision makers and its fuzzy weightnessess. The scale that we used for calculations is given in Table 2.11. We use interval-valued fuzzy numbers for this scale.

Table 2.11 : Scale for decision makers.

Linguistic Term	Fuzzy Numbers
Very Important	$([0.75, 0.9], [0.1, 0.1])$
Important	$([0.55, 0.7], [0.25, 0.3])$
Medium	$([0.45, 0.5], [0.45, 0.5])$
Unimportant	$([0.25, 0.3], [0.55, 0.7])$
Niggling	$([0.1, 0.1], [0.75, 0.9])$

Two of decision makers' opinion is set as Very Important and the other one is Important. To find crisp values of decision makers with Eq. (2.34). Final decision makers' weights are found as follows after normalization: $DM1= 0.36$; $DM2= 0.36$; $DM3= 0.28$. In the second step we form matrix R , given in Table 2.12 as follows:

Table 2.12 : Initial decision matrix.

Alternative	Criterion	Type	Weight	DM1	...	DM3
AL1	A1	Benefit	0.01	$([0.4, 0.45], [0.5, 0.55])$	...	$([0.4, 0.45], [0.5, 0.55])$
	A2	Cost	0.001	$([0.6, 0.65], [0.3, 0.35])$	...	$([0.45, 0.5], [0.45, 0.5])$
	⋮	⋮	⋮	⋮	⋮	⋮
	D4	Benefit	0.01	$([0.5, 0.55], [0.4, 0.45])$	...	$([0.6, 0.65], [0.3, 0.35])$
⋮	⋮	⋮	⋮	⋮	⋮	⋮
AL4	A1	Benefit	0.01	$([0.7, 0.75], [0.2, 0.25])$	...	$([0.7, 0.75], [0.2, 0.25])$
	A2	Cost	0.001	$([0.4, 0.45], [0.5, 0.55])$	...	$([0.2, 0.25], [0.7, 0.75])$
	⋮	⋮	⋮	⋮	⋮	⋮
	D4	Benefit	0.01	$([0.5, 0.55], [0.4, 0.45])$	...	$([0.5, 0.55], [0.4, 0.45])$

In the third step, we aggregate the initial matrix with respect to decision makers. Weight vector of decision makers was found as $\lambda = (0.45, 0.35, 0.2)^T$ according to their expertise level. Also IIFGH operator weights were found as $\alpha = (0.243, 0.514, 0.243)^T$. Table 2.13 gives the aggregated initial matrix.

Table 2.13 : Aggregated decision matrix.

Alternative	Criterion	Type	Weight	Aggregate Weights
AL1	A1	Benefit	0.01	$([0.08, 0.09], [0.56, 0.61])$
	A2	Cost	0.001	$([0.11, 0.12], [0.46, 0.51])$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	D4	Benefit	0.01	$([0.1, 0.11], [0.46, 0.51])$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$([0.1, 0.12], [0.49, 0.54])$
AL4	A1	Benefit	0.01	$([0.17, 0.18], [0.29, 0.34])$
	A2	Cost	0.001	$([0.08, 0.09], [0.64, 0.69])$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	D4	Benefit	0.01	$([0.1, 0.12], [0.49, 0.54])$

In the fourth step, we apply the attribute weights to find weighted decision matrix. Table 2.14 gives the weighted decision matrix. Since the value of membership functions drop off very small numbers, we give all the decimal places.

Table 2.14 : Weighted decision matrix.

Alternative	Criterion	Type	Weight	Aggregate Weights
AL1	A1	Benefit	0.01	$([0.0007789, 0.0009292], [0.9945473, 0.9952863])$
	A2	Cost	0.001	$([0.0003441, 0.0003969], [0.9977719, 0.9980498])$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	D4	Benefit	0.01	$([0.0006479, 0.0007531], [0.9951645, 0.9957812])$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
AL4	A1	Benefit	0.01	$([0.0018299, 0.0020409], [0.9875964, 0.9892635])$
	A2	Cost	0.001	$([0.0002481, 0.0002974], [0.9986399, 0.9988494])$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	D4	Benefit	0.01	$([0.0006847, 0.0007917], [0.9954871, 0.9960572])$

In the fifth step, we determine interval-valued intuitionistic fuzzy positive and negative ideal solutions. Table 2.15 gives the positive and negative ideal solutions.

Table 2.15 : IVIFPIS and IVIFNIS.

	A1	A2	...	D4
o^+	$([0.001829957, 0.002040941], [0.986835884, 0.988779799])$	$([0.000248165, 0.000297486], [0.998639905, 0.998849487])$	...	$([0.000684795, 0.000791715], [0.995164508, 0.995781132])$
o^-	$([0.001798889, 0.002009034], [0.987596457, 0.989263586])$	$([0.000440212, 0.000498383], [0.997128970, 0.997488983])$	...	$([0.000684795, 0.000791715], [0.995487117, 0.996057295])$

In the sixth step, we calculate the distances of each alternative from positive and negative ideal solutions. Table 2.16 gives the distances and the solutions for alternatives.

Table 2.16 : Distances of each alternative.

AL1			AL2			AL3			AL4		
S_1^*	0.0329	C_1 0.6305	S_2^*	0.0543	C_2 0.2717	S_3^*	0.0473	C_3 0.3572	S_4^*	0.0483	C_4 0.3445
S_1^-	0.0562		S_2^-	0.0202		S_3^-	0.0263		S_4^-	0.0254	

Gümüsyaka (European side) – AL1 is the first alternative and the ranking is followed as *Gümüsyaka (European side) – AL1 > Hadımköy, Ambarlı (European side) – AL3 > Pendik, Orhanlı (Anatolian side) – AL4 > Kavaklı (European side) – AL2*.

To demonstrate and validate the efficiency of the proposed method, the defuzzified decision matrix and crisp criteria weights have been used in the Simple Additive Weighting (SAW) method. The decision matrix is given in Table 2.17. In Table 2.18, the total weighted normalized scores of the alternatives and their ranks are given.

Table 2.17 : Decision matrix of Crisp SAW Method.

Criterion	A1	A2	A3	B1	B2	B3	C1	C2	C3	C4	C5	D1	D2	D3	D4
Weights	0.01	0	0.29	0.08	0.08	0.03	0.11	0.05	0.12	0.07	0.05	0.03	0.04	0.03	0.01
AL1	0.38	0.5	0.68	0.35	0.38	0.32	0.44	0.48	0.67	0.58	0.48	0.68	0.36	0.33	0.49
AL2	0.67	0.58	0.48	0.68	0.36	0.33	0.49	0.38	0.5	0.68	0.35	0.38	0.32	0.44	0.48
AL3	0.68	0.36	0.33	0.49	0.38	0.5	0.68	0.35	0.67	0.58	0.48	0.38	0.32	0.44	0.48
AL4	0.68	0.36	0.33	0.49	0.38	0.5	0.68	0.35	0.38	0.5	0.68	0.35	0.67	0.58	0.48

Table 2.18 : Total weighted normalized scores and rank of the alternatives.

Criterion	A1	A2	A3	B1	B2	B3	C1	C2	C3	C4	C5	D1	D2	D3	D4	Total	Rank
Weights	0.01	0.003	0.29	0.08	0.08	0.03	0.11	0.05	0.12	0.07	0.05	0.03	0.04	0.03	0.01		
AL1	0.001	0.001	0.147	0.010	0.021	0.005	0.015	0.009	0.041	0.017	0.012	0.017	0.006	0.003	0.002	0.306	1
AL2	0.003	0.000	0.071	0.037	0.019	0.005	0.018	0.013	0.023	0.012	0.006	0.005	0.005	0.006	0.002	0.227	4
AL3	0.003	0.001	0.034	0.019	0.021	0.012	0.036	0.016	0.041	0.017	0.012	0.005	0.005	0.006	0.002	0.229	3
AL4	0.003	0.001	0.034	0.019	0.021	0.012	0.036	0.016	0.013	0.023	0.024	0.004	0.020	0.011	0.002	0.238	2

AL1 is again the best alternative as in our proposed method. The rankings of AL3 and AL4 have changed. The final ranking is *Gümüsyaka (European side) – AL1 > Pendik, Orhanlı (Anatolian side) – AL4 > Hadımköy, Ambarlı (European side) – AL3 > Kavaklı (European side) – AL2*. AL1 is again the best alternative as in our proposed method. The rankings of AL3 and AL4 have changed

The final ranking is *Gümüsyaka (European side) – AL1 > Pendik, Orhanlı (Anatolian side) – AL4 > Hadımköy, Ambarlı (European side) – AL3 > Kavaklı (European side) – AL2*. This result indicates the validity of our proposed method together with the slight changes with respect to the crisp method, which the fuzziness causes.

In the literature, there are some papers applying the similar methodologies. Zhou et al. propose a new method called D-DEMATEL combining D number theory and DEMATEL to identify the critical success factors in emergency management (Zhou et al., 2017). Their method can capture the fuzziness and subjectivity in linguistic assessments. Their paper is different from ours since they convert the IFNs into D numbers and use the combination rule of D numbers to fuse group opinions. Zhang et al. propose a methodology based on the fuzzy set theory and ANP to address both the uncertain information involved and the interrelationships among the attributes (Zhang et al., 2015). However, they do not use DEMATEL method to determine the most efficient attributes. Zhang et al. propose flexible and effective methods combining ANP with Dempster–Shafer evidence theory for supplier selection problems (Zhang et al., 2016). Wei et al. propose a grey relational analysis method for intuitionistic fuzzy multiple attribute decision making with preference information on alternatives (Wei et al., 2011a). Wei et al. propose an interval-valued intuitionistic fuzzy multiple attribute decision making method with incomplete weight information to handle uncertainty while the missing part of the system is occurred (Wei et al., 2011b). Tang et al. propose approaches for multiple attribute group decision making based on the generalized Dice similarity measures with intuitionistic fuzzy information (Tang et al., 2017). These approaches can be used in intuitionistic fuzzy TOPSIS method to measure the distances. The above integrated methods are possible alternative methods for the freight village location selection problems for comparison purposes.

2.6 Conclusion

A freight village contains and depends global roaming lanes, region countries, proximity to production and consumption centres, suitability for trough transportation; focusability to trade on export, import, transit and customs procedure, simplicity in legislation; international and national railways, seaway, highway, inland waterway, piping connections; combined transportation infrastructure; standardization of business processes; advanced information and communication technology infrastructure; high variety in logistics career field and human resources; proper fields for logistics enterprises; distribution centers. Due to its numerous dependent factor, location selection of freight villages should be evaluated by using a multi-criteria decision making method under uncertainty. Our purpose in this system is figuring out how many criteria exist in it, building a set of possible strategies, collecting the

appropriate information about strategies with respect to criteria, and evaluating them to reach the goal with multicriteria decision making (Tzeng and Huang, 2011). The source of this uncertainty is fuzziness rather than randomness. Hence, the proposed methodology has been based on an intuitionistic fuzzy MCDM method.

In this paper, an intuitionistic fuzzy multi-criteria group-decision making with the integration of DEMATEL, ANP and TOPSIS methodologies has been proposed for the selection of the most appropriate location for freight village. The proposed methodology is composed of the integration of TIF DEMATEL, IVIF ANP, and TIF TOPSIS techniques. Defuzzification process has been postponed up to the last step of the TIF DEMATEL. Besides, elimination of criteria and their inner and outer dependencies have been determined through TIF DEMATEL instead of a direct assignment by experts. This integrated methodology has successfully evaluated freight village location alternatives based on a comprehensive set of criteria. It lets the experts fill in the decision matrix by using linguistics terms rather than exact numerical values.

We suggest the same methodology to be developed by the other extensions of fuzzy sets such as hesitant, type-2, and neutrosophic sets. The proposed methodology can also be employed for a different multi-criteria decision making problems such as supplier selection, energy, health care problems.

3 A NOVEL PYTHAGOREAN FUZZY AHP AND ITS APPLICATION TO LANDFILL SITE SELECTION PROBLEM²

Multi-criteria decision-making (MCDM) problems involve several main criteria and sub-criteria which some of them are tangible or intangible. These criteria can be represented by a hierarchical structure indicating the relationships between them. One of the MCDM methods utilizing this structure is analytical hierarchy process (AHP). AHP is performed through pairwise comparisons. In the pairwise comparison, judgments of experts are used to obtain weights of the criteria in the decision-making process. This process continues with the determination of domination of an element over another one with respect to an attribute or an alternative. In this way, AHP is able to detect the inconsistencies in the judgments, and consequently, it allows experts to revise their judgments (Saaty 2008). Traditional AHP utilizes a linguistic scale whose values are integers between 1 and 9. However, according to Buckley (1985), the representation of a linguistic term through a crisp number may not reflect the judgments of decision makers in their minds. For instance, a linguistic evaluation such as *Very High Importance* is represented by 7 in the scale of classical AHP. However, the decision makers judgment *Very High Importance* may not be clear enough to assign 7. By *Very High Importance*, the decision maker might mean *around seven* which corresponds to a triangular fuzzy number such as (6.5, 7, 7.5). This can provide a better representation of the decision makers judgment.

The new versions of AHP with fuzzy sets and their extensions such as type-2 fuzzy AHP, intuitionistic fuzzy AHP, hesitant fuzzy AHP have been proposed due to incompetency of ordinary AHP to handle lack of knowledge and imprecise information of complex systems. Fuzzy sets were proposed by Zadeh (1965) which are used to represent the degree of membership corresponding to the complexity. Since its development, fuzzy sets have been extended in many forms. Type-*n* fuzzy sets were

² This chapter is based on the paper “Karasan, A., Ilbahar, E., & Kahraman, C. (2019). A novel Pythagorean fuzzy AHP and its application to landfill site selection problem. *Soft Computing*, 23(21), 10953-10968.”

developed by Zadeh (1975) to deal with the uncertainty of the membership function in the fuzzy set theory. After that, interval-valued fuzzy sets (IVFSs) were proposed independently by Zadeh (1975), Grattan Guinness (1976), Jahn (1975) and Sambuc (1975). In 1986, intuitionistic fuzzy sets (IFSs) were proposed by Atanassov (1986) to deal with the problem of assigning non-membership degrees. Hesitant fuzzy sets (HFSs), initially described by Torra (2010), are the extensions of regular fuzzy sets where a single element can have a set of values for its membership degree. Atanassov proposed intuitionistic type-2 fuzzy sets (IFS2) in 1999 Atanassov (1999). Later, Yager extended IFS2 and called them as Pythagorean fuzzy sets in 2013 Yager (2013).

There is a need for better and flexible definition of membership functions in fuzzy MCDM methods. Pythagorean fuzzy sets facilitate the representation on a larger body of membership and non-standard membership grades which enables experts to take uncertainty into consideration more effectively than the other types of fuzzy extensions Yager (2016). Therefore, this study aims at proposing an MCDM method better handling imprecise information in a more flexible manner.

In this study, an interval-valued Pythagorean fuzzy AHP (IVPF-AHP) is developed and an application of IVPF-AHP is given for landfill site selection problem. Along with the increasing population and consumption, waste disposal has become an important problem. Landfilling which is a relatively quite cheap way of disposal has been commonly preferred. However, determining an appropriate location for a landfill is a complicated problem because various criteria, even some of them are conflicting, should be considered in the evaluation process. Therefore, with the increasing environmental concerns, landfill site selection for the disposal of municipal solid waste has been widely studied throughout the literature Al-Jarrah and Abu-Qdais (2006), Sumathi et al. (2008), Chang et al. (2008), Moeinaddini et al. (2010), Marin et al. (2012), Effat and Hegazy (2012), Gbanie et al. (2013), Beskese et al. (2015), Siddiqui et al. (1996), Wang et al. (2009), Sener et al. (2010), Sener et al. (2011), Alavi et al. (2013), Uyan (2014), Vatalis and Manoliadis (2002), Sener et al. (2006) and Gorsevski et al. (2012). The criteria used in the application are determined by examining papers in the literature, taking experts' opinions and systems in practice into account. Then, the most suitable alternative for a landfill is selected by using the proposed method.

The rest of this paper is organized as follows: literature review on different versions of fuzzy AHP, Pythagorean fuzzy sets and landfill site selection is given in Section

3.1. Arithmetic operations, aggregation operators and defuzzification are examined in Section. 3.2 Steps in Pythagorean fuzzy AHP and consistency are discussed in Section 3.3. Application of the proposed method and conclusions are presented in Sections 3.4 and 3.5, respectively.

3.1 Literature Review

Our literature review is divided into two subsections. In the first subsection, ordinary fuzzy AHP and its fuzzy extensions such as type-2 fuzzy AHP, intuitionistic fuzzy AHP and hesitant fuzzy AHP are elaborated. In the first subsection, various studies conducted to determine the most suitable landfill site are reviewed. In the second subsection, past studies on Pythagorean fuzzy sets are examined.

3.1.1 Fuzzy AHP

There are many studies utilizing fuzzy AHP in the literature to address all kinds of MCDM problems. The method is updated with the new extensions of fuzzy sets, and different forms of fuzzy AHP emerged. Van Laarhoven and Pedrycz (1983) proposed a fuzzy version of Saaty's pairwise comparison method and Buckley (1985) developed a version of fuzzy AHP. Ruoning and Xiaoyan (1992) investigated AHP in fuzzy environment and discussed the properties of a positive bounded closed fuzzy number and then applied the fuzzy extension principle to the altered gradient eigenvector method. Zhang et al. (2005) calculated the criteria weights for weapon system evaluation by using ordinary trapezoidal fuzzy AHP. Moreover, the hierarchical fuzzy integral model is developed using λ -fuzzy measure and Sugeno integral Zhang et al. (2005). Ohnishi et al. (2006) utilized fuzzy reciprocal matrix in AHP. Wang et al. (2012) employed fuzzy logic and AHP to build a decision-making model for different green initiatives in the fashion industry. Figure 3.1 presents the number of journal papers on ordinary fuzzy AHP with respect to their publication years. There is a continuously increasing trend on this research area as in Figure 3.1:

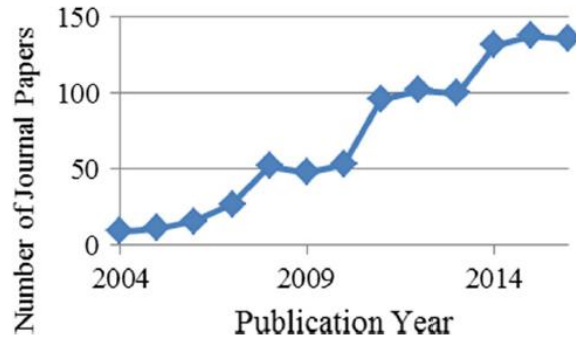


Figure 3.1 : Ordinary fuzzy AHP Publication trend.

Kahraman et al. (2014) proposed an interval type-2 fuzzy AHP method along with a new ranking method for type-2 fuzzy sets while providing a solution for supplier selection problem. Cevik Onar et al. (2014) determined criteria weights in the evaluation of strategic decisions by using interval type-2 fuzzy AHP. Abdullah and Najib (2014) also preferred interval type-2 fuzzy sets instead of type-1 fuzzy sets to incorporate with the AHP method to improve judgment in the fuzzy decision-making process. Oztaysi (2015) utilized the combination of AHP and Interval type-2 fuzzy sets to solve ERP selection problem. Kilic and Kaya (2015) used both type-2 fuzzy AHP and type-2 fuzzy TOPSIS methods to evaluate investment projects. Erdogan and Kaya (2016) integrated type-2 fuzzy AHP to their method in order to handle both qualitative and quantitative criteria under uncertainty in the process of choosing the best alternative fuel bus for public transportation in Istanbul. Figure 3.2 illustrates the number of journal papers on type-2 fuzzy AHP with respect to their publication years. There is a linear increasing trend on type-2 fuzzy AHP after 2015 as in Figure 3.2:

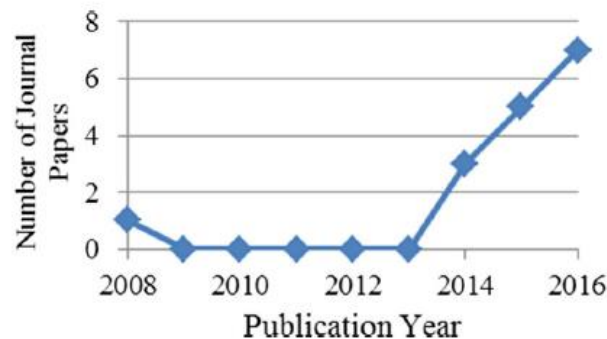


Figure 3.2 : Type-2 fuzzy AHP publication trend.

Abdullah et al. (2009) used the combination of IFSs and AHP to propose a framework for ranking multi-attribute decision-making problem. Sadiq and Tesfamariam (2009) used intuitionistic fuzzy AHP to evaluate drilling fluids. Wu et al. (2013) used an

interval-valued intuitionistic fuzzy AHP for the selection of an e-commerce enterprise. Xu and Liao (2014) used this method for global supplier development. Ren et al. (2016) extended the intuitionistic multiplicative information into AHP to improve its ability to deal with the all sorts of decision-making problems. A framework on intuitionistic multiplicative AHP is presented, and then it is applied on the evaluation of hydropower stations to show effectiveness of the proposed method. Based on the data obtained from Scopus database, Figure 3.3 presents the number of journal papers with respect to their publication years. It can be seen from this figure that there is a significant increase in the number of publications on IF AHP studies after 2010 as in Figure 3.3:

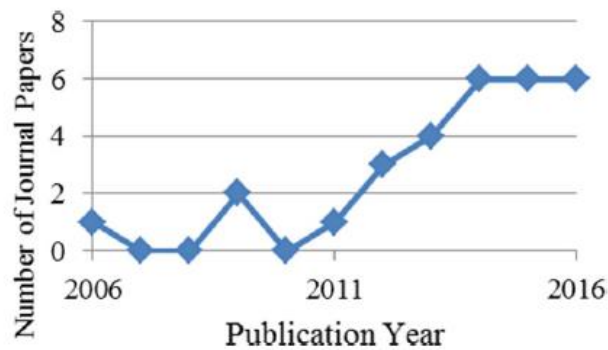


Figure 3.3 : Intuitionistic fuzzy AHP publication trend.

There are relatively few studies on hesitant fuzzy AHP, only five journal papers in Scopus database. Mousavi et al. (2014) developed a hesitant fuzzy AHP in which experts' opinions are aggregated by the hesitant fuzzy geometric operator. Oztaysi et al. (2015) proposed the hesitant fuzzy AHP in which opinions of experts are aggregated by OWA operator. Onar et al. (2016) developed a hesitant fuzzy QFD method to identify the design requirements of a computer workstation. Then, the hesitant AHP and TOPSIS are used to compare the results. Zhu et al. (2016) used hesitant AHP to reflect the hesitancy of the experts into the evaluation process. Zhou and Xu (2016) proposed the terms of the hesitant fuzzy preference format and the hesitant fuzzy continuous preference term. Moreover, the asymmetric hesitant fuzzy sigmoid preference relation is introduced and utilized in AHP in the study of Zhou and Xu (2016).

3.1.2 Pythagorean Fuzzy Sets

Yager (2013) proposed Pythagorean fuzzy sets and its basic set operations. Furthermore, Yager and Abbasov (2013) investigated the link between Pythagorean membership degrees and complex numbers. A MCDM method involving Pythagorean fuzzy geometric mean and the order weighted geometric operator is developed. In the study of Yager (2014), aggregation operations for Pythagorean fuzzy sets were introduced. Zhang and Xu (2014) introduced Pythagorean fuzzy TOPSIS. Peng and Yang (2015) developed division and subtraction operations in PFSs and investigated their properties. Moreover, a Pythagorean fuzzy superiority and inferiority ranking method was introduced to tackle multiple attribute group decision-making problems with uncertainty. Zhang et al. (2016) developed a closeness index-based ranking method for Pythagorean fuzzy numbers. In the study of Zhang et al. (2016), interval-valued Pythagorean fuzzy set and the basic operations of interval valued Pythagorean fuzzy numbers were discussed. Then, Pythagorean fuzzy QUALIFLEX method is introduced to deal with MCDM problems. Dick et al. (2016) investigated interpretations of complex-valued membership grades by using Pythagorean fuzzy sets. Zhang et al. (2016) proposed Pythagorean fuzzy multi-granulation rough set over two universes. Garg (2016) indicated the weakness of correlation coefficients between IFSs and developed a new correlation coefficient and weighted correlation coefficient formulation between Pythagorean fuzzy sets. Garg (2017) provided an improved accuracy function for the ranking order of interval valued Pythagorean fuzzy sets to eradicate the weakness of the current score and accuracy functions in interval-valued Pythagorean environment. Thus, the extensions of PFSs enable experts to deal with the MCDM problems under uncertainty more effectively.

3.2 Preliminaries

The basic concepts of Pythagorean fuzzy sets and IFSs are briefly reviewed in this section.

3.2.1 Intuitionistic Fuzzy Sets (IFSs)

IFS was introduced by Atanassov (1986). An IFS includes two membership values named as membership and non-membership for describing any x in X such that their sum is at most equal to 1 which is demonstrated in Definition 5 Atanassov (1986).

Definition 5. Let $X \neq \emptyset$ be a given set. An intuitionistic fuzzy set in X is an object A , called intuitionistic fuzzy number (IFN), if it holds the following conditions:

$$\tilde{A} \cong \{\langle x, \mu_{\tilde{A}}(x), \nu_{\tilde{A}}(x) \rangle; x \in X\}, \quad (3.1)$$

where $\mu_{\tilde{A}}(x): X \rightarrow [0,1]$ and $\nu_{\tilde{A}}(x): X \rightarrow [0,1]$ satisfy the condition of

$$0 \leq \mu_{\tilde{A}}(x) + \nu_{\tilde{A}}(x) \leq 1 \quad (3.2)$$

for every $x \in X$.

Besides, $\pi_{\tilde{A}}(x) = 1 - \mu_{\tilde{A}}(x) - \nu_{\tilde{A}}(x)$ is the hesitation degree of element $\tilde{A}$ in set X . It is obvious that we obtain $0 \leq \pi_{\tilde{A}}(x) \leq 1$.

Definition 6. The operations of addition $\oplus$ and multiplication $\otimes$ on IFNs were defined by Atanassov in 1986. as follows:

Let $\tilde{A} \cong \langle \mu_{\tilde{A}}, \nu_{\tilde{A}} \rangle$ and $\tilde{B} \cong \langle \mu_{\tilde{B}}, \nu_{\tilde{B}} \rangle$ be IFNs.

$$\tilde{A} \oplus \tilde{B} \cong \langle \mu_{\tilde{A}} + \mu_{\tilde{B}} - \mu_{\tilde{A}}\mu_{\tilde{B}}, \nu_{\tilde{A}}\nu_{\tilde{B}} \rangle \quad (3.3)$$

$$\tilde{A} \otimes \tilde{B} \cong \langle \mu_{\tilde{A}}\mu_{\tilde{B}}, \nu_{\tilde{A}} + \nu_{\tilde{B}} - \nu_{\tilde{A}}\nu_{\tilde{B}} \rangle \quad (3.4)$$

3.2.2 Pythagorean Fuzzy Sets (PFSs)

Atanassov (1999) proposed intuitionistic type-2 fuzzy sets, which they are later called Pythagorean fuzzy sets by Yager (2013). In PFSs, the sum of membership degree and nonmembership degree assigned by experts may be greater than 1, but sum of their squares is less than or equal to 1 in some practical problems (Peng and Yang 2015).

Definition 7. Let X be a fixed set. A Pythagorean fuzzy set $\tilde{P}$ is an object having the form Yager (2016):

$$\tilde{P} \cong \{\langle x, \mu_{\tilde{P}}(x), \nu_{\tilde{P}}(x) \rangle; x \in X\}, \quad (3.5)$$

where the function $\mu_{\tilde{P}}(x): X \rightarrow [0,1]$ defines the degree of membership and $\nu_{\tilde{P}}(x): X \rightarrow [0,1]$ defines the degree of non-membership of the element $x \in X$ to P , respectively, and, for every $x \in X$, it holds that:

$$0 \leq \mu_{\tilde{P}}(x)^2 + \nu_{\tilde{P}}(x)^2 \leq 1 \quad (3.6)$$

The degree of hesitancy condition is

$$\pi_{\tilde{P}}(x) = \sqrt{1 - \mu_{\tilde{P}}(x)^2 - \nu_{\tilde{P}}(x)^2} \quad (3.7)$$

$$\pi_{\tilde{P}}(x)^2 = 1 - \mu_{\tilde{P}}(x)^2 - v_{\tilde{P}}(x)^2 \quad (3.8)$$

Definition 8 (Zhang and Xu, 2014). Let $\tilde{A} = \langle \mu_1, v_1 \rangle, \tilde{B} = \langle \mu_2, v_2 \rangle$ be two PFNs, and $\lambda > 0$, then the operations of these two PFNs are defined as follows:

$$\tilde{A} \oplus \tilde{B} = \left(\sqrt{\mu_1^2 + \mu_2^2 - \mu_1^2 \mu_2^2}, v_1 v_2 \right) \quad (3.9)$$

$$\tilde{A} \otimes \tilde{B} = \left(\mu_1 \mu_2, \sqrt{v_1^2 + v_2^2 - v_1^2 v_2^2} \right) \quad (3.10)$$

$$\lambda \tilde{A} = \left(\sqrt{1 - (1 - \mu^2)^\lambda}, v^\lambda \right) \quad (3.11)$$

$$\tilde{A}^\lambda = \left(\mu^\lambda, \sqrt{1 - (1 - v^2)^\lambda} \right) \quad (3.12)$$

Definition 9 (Peng and Yang 2015). $\tilde{A}_i = \langle \mu_i, v_i \rangle, i = (1, 2, \dots, n)$ be a collection of PFNs and $w = (w_1, w_2, \dots, w_n)^T$ be the weight vector of $\tilde{A}_i, i = (1, 2, \dots, n)$ with $\sum_{i=1}^n w_i = 1$. Then the Pythagorean fuzzy weighted power average (PFWPA) operator is given as follows:

$$PFWPA(\tilde{A}_1, \tilde{A}_2, \dots, \tilde{A}_n) = \left(\left(\sum_{i=1}^n w_i \mu_i^2 \right)^{1/2}, \left(\sum_{i=1}^n w_i v_i^2 \right)^{1/2} \right) \quad (3.13)$$

Definition 10 (Peng and Yang 2015). $\tilde{A}_i = \langle \mu_i, v_i \rangle, i = (1, 2, \dots, n)$ be a collection of PFNs and $w = (w_1, w_2, \dots, w_n)^T$ be the weight vector of $\tilde{A}_i, i = (1, 2, \dots, n)$ with $\sum_{i=1}^n w_i = 1$. Then the Pythagorean fuzzy weighted power geometric (PFWPG) operator is given as follows:

$$PFWPG(\tilde{A}_1, \tilde{A}_2, \dots, \tilde{A}_n) = \left(\left(1 - \prod_{i=1}^n (1 - \mu_i^2)^{w_i} \right)^{1/2}, \left(1 - \prod_{i=1}^n (1 - v_i^2)^{w_i} \right)^{1/2} \right) \quad (3.14)$$

3.3 Proposed Method: IVPF-AHP

Before presenting the proposed Pythagorean fuzzy AHP in detail, we will briefly give the outline of the main points and the steps of the method.

3.3.1 Essentials of the Approach

Since we are working on interval-valued space, we extend the hesitancy degree for both lower and upper points as follows:

Definition 11. Let $\tilde{A} = \langle [\mu_L, \mu_U], [v_L, v_U] \rangle$ be an interval valued PFN, and π_L and π_U are the hesitancy degree of the lower and upper points of A , respectively, which can be calculated as in Eqs. (3.15) and (3.16):

$$\pi_L^2 = 1 - (\mu_U^2 + v_U^2) \quad (3.15)$$

$$\pi_U^2 = 1 - (\mu_L^2 + v_L^2) \quad (3.16)$$

The logic behind the definition of hesitancy degrees for both lower and upper points is to consider the impact of the gap between the beginning and end of the interval. For example, hesitancy degrees of both $\langle [0.1, 0.7], [0.1, 0.7] \rangle$ and $\langle [0.5, 0.7], [0.5, 0.7] \rangle$ become equal if they are calculated using the ordinary method, since the ordinary method only takes upper values of membership and nonmembership functions into account to calculate the hesitancy. However, in our logic, hesitancies should be different for lower and upper points. This will help us to determine more accurate defuzzifying method and distance of two PFNs.

We know that the score functions or defuzzifying procedures are efficient when we compare the majority or minority of PFNs in MADM problems. However, the score functions in the literature Ren et al. (2016); Zeng et al. (2016) are insufficient to indicate which one is better since they do not properly associate the hesitancy. Motivated by the definition of the hesitancy degree function for PFNs and defuzzifying function for IFNs (Karasan and Kahraman 2017), we developed a new defuzzifying function given in Definition 12.

Definition 12. Let $\tilde{A} = \langle [\mu_L, \mu_U], [v_L, v_U] \rangle$ be an interval valued PFN and π_L and π_U are the hesitancy degree of the lower and upper points of $\tilde{A}$, then the defuzzifying procedure of this number is calculated by Eq. (3.17):

$$\mathfrak{S}(\tilde{A}) = \frac{\mu_L^2 + \mu_U^2 + (1 - \pi_L^4 - v_L^2) + (1 - \pi_U^4 - v_U^2) + \mu_L \mu_U + \sqrt[1/4]{(1 - \pi_L^4 - v_L^2)(1 - \pi_U^4 - v_U^2)}}{6} \quad (3.17)$$

The bigger value of $\mathfrak{S}(\tilde{A})$ indicates the superiority among the compared ones. Also, since $0 \leq \mu_U^2 + v_U^2 \leq 1$, $\mathfrak{S}(\tilde{A}) \in [0, 1]$.

When we review the literature about intuitionistic and Pythagorean fuzzy sets and its applications in MCDM with all its extensions and developments, we discover the insufficiency of distance measurements for interval-valued numbers. With this

motivation, we propose a novel distance based measurement of interval-valued PFNs which is given in Definition 13.

Definition 13. Let $\tilde{A} = \langle [\mu_L^A, \mu_U^A], [v_L^A, v_U^A] \rangle$ and $\tilde{B} = \langle [\mu_L^B, \mu_U^B], [v_L^B, v_U^B] \rangle$ be interval-valued PFNs and $\pi_L^A, \pi_U^A, \pi_L^B$ and π_U^B are the hesitancy degrees of lower and upper points of the $\tilde{A}$ and $\tilde{B}$, respectively. The distance between $\tilde{A}$ and $\tilde{B}$ can be calculated as in Eq. (3.18):

$$d(\tilde{A}, \tilde{B}) = \frac{\sqrt{\left((\mu_L^A)^2 - (\mu_L^B)^2\right)\left(1 - \left(\frac{\pi_L^A - \pi_L^B}{2}\right)\right)} + \sqrt{\left((\mu_U^A)^2 - (\mu_U^B)^2\right)\left(1 - \left(\frac{\pi_U^A - \pi_U^B}{2}\right)\right)}}{2} \quad (3.18)$$

We adapt Eq. (3.18) to our novel interval-valued Pythagorean fuzzy AHP method to find the criteria weights in the hierarchy levels to select most appropriate landfill location.

3.3.2 Scale of the Pythagorean Fuzzy AHP Method

Since the effectiveness of description level for uncertainty of Pythagorean fuzzy sets discovered by Yager, there is no weighting scale for PFNs which can be applied to weighting methods including AHP. Here, we develop a weighting scale for PFNs which is given in Table 3.1.

Table 3.1 : Weighting scale for the interval-valued Pythagorean fuzzy AHP method.

Linguistic terms	PFN equivalents IVP numbers			
	μ_L	μ_U	v_L	v_U
Certainly low importance (CLI)	0	0	0.9	1
Very low importance (VLI)	0.1	0.2	0.8	0.9
Low importance (LI)	0.2	0.35	0.65	0.8
Below average importance (BAI)	0.35	0.45	0.55	0.65
Average importance (AI)	0.45	0.55	0.45	0.55
Above average importance (AAI)	0.55	0.65	0.35	0.45
High importance (HI)	0.65	0.8	0.2	0.35
Very high importance (VHI)	0.8	0.9	0.1	0.2
Certainly high importance (CHI)	0.9	1	0	0
Equal importance (EI)	0.5	0.5	0.5	0.5

In the literature, setting of AHP linguistic scale is essentially realized in two ways: the studies using a constant linguistic scales as in Kwong and Bai (2003), Lee et al. (2008), Kulak and Kahraman (2005), Wang et al. (2007) and Kwong and Bai (2002) and the studies using tools such as mathematical programming or statistical modeling to determine the intervals corresponding to the linguistic terms as in Dong and Herrera-Viedma (2015), Dong et al. (2013), Dong et al. (2009), HerreraViedma and

LpezHerrera (2007), Herrera et al. (2008), Li et al. (2017) and Pedrycz and Song (2014). Our paper falls in the studies using a constant linguistic scale, and it does not fit the model given in Dong and Herrera-Viedma (2015) since both membership and non-membership intervals for the scales have to be determined in Pythagorean fuzzy environment.

As a brief explanation for implementation of Pythagorean fuzzy sets to AHP method, the experts aim to select the most desirable location for a landfill from a set of alternatives that are evaluated by criteria based on Table 3.1 which is constituted by Pythagorean fuzzy information. This can be also represented mathematically as follows: Let $E_k, k = 1, \dots, p$ be the k^{th} expert; $A_i, i = 1, \dots, n$ be the set of alternatives and $C_j, j = 1, \dots, m$ be the set of criteria. The evaluation of the alternatives based on the criteria with respect to experts is expressed as $r_{ij}^k = \langle [\mu_{L_{ij}}^k, \mu_{U_{ij}}^k], [v_{L_{ij}}^k, v_{U_{ij}}^k] \rangle$ and $w_E, E = 1, \dots, j$ is the weight vector of the experts based on Pythagorean fuzzy numbers. $[\mu_{L_{ij}}^k, \mu_{U_{ij}}^k]$ indicates the membership degree of alternative i with respect to criterion j assigned by the expert E_k , and $[v_{L_{ij}}^k, v_{U_{ij}}^k]$ indicates the non-membership degree of alternative i with respect to criterion j assigned by the expert E_k .

3.3.3 Steps of Pythagorean Fuzzy AHP

Step 1. Construct the compromised pairwise comparison matrix $R = (r_{jt})_{m \times m}$ with respect to experts' opinions.

Step 2. Find the differences matrix $D = (d_{jt})_{m \times m}$ between lower and upper points of the membership and non-membership functions using Eqs. (3.19) and (3.20):

$$d_{ijL} = \mu_{ijL}^2 - v_{ijU}^2 \quad (3.19)$$

$$d_{ijU} = \mu_{ijU}^2 - v_{ijL}^2 \quad (3.20)$$

Step 3. Find the interval multiplicative matrix $S = (s_{jt})_{m \times m}$ using Eqs. (3.21) and (3.22):

$$s_{ijL} = \sqrt{1000^{d_{ijL}}} \quad (3.21)$$

$$s_{ijU} = \sqrt{1000^{d_{ijU}}} \quad (3.22)$$

After the simulations, we determine 1000 as the best value of the base which makes all the relations among the elements of the matrix more explicit without compromising consistent relation. We ensure that 1000 is the best value of the base by comparing the relations between criteria in defuzzified and interval multiplicative matrix.

Step 4. Calculate the indeterminacy value $H = (h_{jt})_{m \times m}$ of the r_{jt} using Eq. (3.23):

$$h_{ij} = 1 - (\mu_{ijU}^2 - \mu_{ijL}^2) - (v_{ijU}^2 - v_{ijL}^2) \quad (3.23)$$

Step 5. Multiply the indeterminacy degrees with $S = (s_{jt})_{m \times m}$ matrix for finding the matrix of unnormalized weights $T = (\tau_{jt})_{m \times m}$ using Eq. (3.24):

$$\tau_{ij} = \left(\frac{s_{ijL} + s_{ijU}}{2} \right) h_{ij} \quad (3.24)$$

Here, inspired by Eqs. (3.18), (3.24) is developed.

Step 6. Find the priority weights w_i by using Eq. (3.25).

$$w_i = \frac{\sum_{j=1}^m w_{ij}}{\sum_{i=1}^m \sum_{j=1}^m w_{ij}} \quad (3.25)$$

3.3.4 Consistency

Consistency ratio (CR) is used to measure how consistent the judgments of experts are. Since the extensions of AHP with fuzzy sets appeared in the literature, a lot of calculation techniques have been introduced for the measurement of CR. Here, we apply the Saaty's classical consistency ratio process. We measure the consistency ratio by matching the linguistic terms with Saaty's scale and following the classical framework.

3.4 Application

The aim of this section is to illustrate our proposed method through a landfill site selection problem. We first present the problem definition, followed by evaluation criteria, problem solution, sensitivity and comparative analyses, respectively.

3.4.1 Problem Definition

The final step in the waste management is the disposal of waste in a manner that does not harm human health and the environment. This problem has been frequently

handled in the literature Al-Jarrah and Abu-Qdais (2006), Sumathi et al. (2008), Chang et al. (2008), Moeinaddini et al. (2010), Marin et al. (2012), Effat and Hegazy (2012), Gbanie et al. (2013) and Beskese et al. (2015). The combination of AHP and GIS has been widely employed for this purpose Siddiqui et al. (1996); Wang et al. (2009); Sener et al. (2011, 2010); Uyan (2014); Alavi et al. (2013); Vatalis and Manoliadis (2002); Sener et al. (2006); Gorsevski et al. (2012). Therefore, in this study, AHP method is integrated with Pythagorean fuzzy sets which is a quite novel set proposed by Yager (2013). The criteria employed in the literature for the evaluation of landfill site selection are diverse. These criteria and their definitions are provided in Section 3.4.2.

The construction and operation activities of the landfills started in 1994 in Istanbul for this purpose, and approximately 320 ha area is allocated to landfills since that date. There are three sanitary landfills in Istanbul where municipal waste is disposed of. These are Kömürcüoda, Odayeri and Seymen sanitary landfills. Kömürcüoda is located at Asian side of Istanbul, whereas Odayeri and Seymen are at European side. 16,000 tons/day waste that cannot be recovered in Istanbul are disposed to these landfills regularly as 10,500 tons and 5500 tons are sent to landfills in European and Asian side, respectively (URL-1).

As a result of urbanization, residential areas are rapidly growing and it is quite costly and time-consuming to transport solid waste collected from all over the city directly to the landfills. The concept of transfer stations has emerged to reduce these costs and save time. These stations are the intermediate processing centers where solid wastes of adjacent areas are collected, compressed and sent to disposal sites with larger vehicles. With the use of these stations, the number of vehicles in traffic traveling to the landfills is reduced and accordingly the effects of emissions from vehicle exhausts and air pollution can be diminished (Arslankaya et al. 2007). In Istanbul, there are eight waste transfer centers indicated in Figure 3.4: Hekimbaşı, Küçükbakkalköy, Aydınli, Şile, Baruthane, Yenibosna, Halkalı and Silivri (URL-2).



Figure 3.4 : Alternative landfill sites in Istanbul.

Although landfilling is not the first choice for waste disposal according to waste hierarchy, it is the most preferred disposal method in Istanbul as well since it is more costeffective. In this study, a new site will be determined for a landfill since waste generation and consequently need for landfill are constantly growing in Istanbul. Various criteria must be taken into account to construct and operate a landfill. Some of these parameters might even be in conflict, so landfill site selection is a multi-criteria decision-making problem. For instance, it is desired to locate a landfill close to waste source to reduce transportation costs. However, residents would object to siting a landfill close to their neighborhood due to odors, spread by wind and bad appearance.

Such conflicting criteriamake it difficult to decide. Moreover, changing conditions might make the current landfills unsuitable. For instance, new airport might be constructed close to landfills or urban settlements might expand and become closer to landfills. In such cases, current landfills can be no longer suitable and finding a new site for a landfill might be required.

3.4.2 Evaluation Criteria

Landfill site selection has been widely studied in the literature with various criteria. Soil, land use and proximity are the main decision factors in the study of Siddiqui et al. (1996) whereas Uyan (2014) categorized the factors as environmental, economic and social. In the study of Sener et al. (2011), evaluation criteria are grouped as

geological and tectonic, hydrological and hydrogeological, morphologic and social criteria. However, in the study of Banar et al. (2007), evaluation criteria are categorized as benefit, risk and cost criteria since the combination of BOCR and ANP methods is proposed in this study. The criteria listed in the literature include various sub-criteria. Lithology, lineament, surface water, aquifer, groundwater depth, aspect, elevation, slope, distance to roads and land use were used for the evaluation of landfill sites in the study of Sener et al. (2011). Nas et al. (2010) took the following sub-factors into consideration: proximity to municipal and local wells and irrigational canals, distance from transportation routes and rails, distance from archaeological sites, distance from urban areas, land use/land cover and land slope. Akbari et al. (2008) considered protection from strong winds, transportation issues, altitude, size and shape of landfill, public health, safety nuisance in the process of evaluation. Sener et al. (2006) utilized the following criteria for evaluation: topography, settlements, roads, railways, airport, wetlands, infrastructures, slope, geology, land use, floodplains, aquifers and surface water. As a result of this detailed review of the literature, the criteria given in the next section are selected to be considered in this study.

The evaluation criteria, in this study, are identified and classified into four main categories as (1) environmental impacts, (2) social factors, (3) economic conditions and (4) operational activities. The first main criterion involves the constraining sub-criteria that ensure the protection of the environment. The second category consists of sub-criteria related to society and urban life, whereas the third and fourth categories include sub-criteria related to cost and operation of the landfill, respectively.

3.4.2.1 Environmental Criteria

Groundwater depth Sanitary landfills are made impermeable to prevent leachate to get into groundwater; however, in order to ensure the safety of groundwater, base of the sanitary landfill must be at least 1 meter higher than the maximum level of natural groundwater. Moreover, it is issued in 1991 by Ministry of Environment and Forestry of Turkey (1991) that sanitary landfills cannot be located close to the water catchment areas. This criterion is taken into account in Siddiqui et al. (1996) and Sener et al. (2010) to select a suitable location for a landfill.

Land use Land use is an important sub-criterion, and it has been commonly employed in the literature for landfill location selection such as Abdullah et al. (2009), Wu et al.

(2013); Xu and Liao (2014); Ren et al. (2016); Mousavi et al. (2014); Onar et al. (2016) and Zhu et al. (2016). Cultivated and rocky lands are considered as unsuitable for landfill Sener et al. (2010), whereas forested and barren lands are qualified as the most suitable Gorsevski et al. (2012).

Elevation and slope Elevation and slope are important to construct and operate a landfill Gorsevski et al. (2012). Thus, in the literature, they have been widely utilized for landfill site selection Sener et al. (2011); Uyan (2014); Sener et al. (2006) and Gorsevski et al. (2012). Excavation cost is a significant economic criterion in landfill selection and depends on the topography because excavation cost increases along with the slope of the land Banar et al. (2007).

Odors nuisance Landfills can cause annoyance in neighboring urban areas because of odors released to the atmosphere. This annoyance increases at the places located near or downwind of the landfill. Odors pollution might negatively affect quality of life, human health and welfare Saral et al. (2009) . Vatalis and Manoliadis (2002) also utilized this criterion to select a suitable landfill site.

3.4.2.2 Social Criteria

Distance to urban settlements A minimum of 500 m distance from residential areas is determined by European legislation Gorsevski et al. (2012). In Turkey, landfills cannot be located in places with a distance of less than 1000 meters from the nearest settlement area. However, if there are obstacles such as hills, piles and afforestation around the landfill, local environmental boards with the approval of the Ministry, if necessary, may be allowed to site the landfill in places less than this distance (Turkey 1991).

Public reaction There might be public conflicts in siting a landfill which is an unwanted facility. Baban and Flannagan (1998) indicated that preferring a low-valued landfill causes less resistance and provides greater acceptance . Banar et al. (2007) also took this criterion into consideration.

Distance to historical and cultural sites A landfill should not be located on a site close to historical and cultural sites. A minimum of 500 m distance from such areas is considered necessary (Lin and Kao 2005). Uyan (2014), Vatalis and Manoliadis (2002) and Nas et al. (2010) utilized this criterion for landfill site selection.

3.4.2.3 Economic Criteria

Land cost Initial price of the land is an important factor to determine a suitable landfill site. Wang et al. (2012) and Banar et al. (2007) took land cost into account for this purpose.

Transportation cost The distance of alternative landfill sites to waste sources is taken into account to evaluate the transportation cost. The nearest alternative has the most advantageous position with respect to cost (Banar et al. 2007).

3.4.2.4 Operational Criteria

Distance to road Distance to road is crucial factor to select a landfill site because an increase in the distance does not only increase the cost of transportation but also it can make waste transportation difficult. Access to sanitary landfills must be possible under all kinds of weather conditions Sener et al. (2010), Turkey (1991). However, aesthetic issues should be taken into account and landfills should not be placed within 200 m of any major highways and city streets Nas et al. (2010).

Distance to waste source In order to decrease transportation cost of the waste, landfill should be located to waste sources. In the studies of Alavi et al. (2013), Vatalis and Manoliadis (2002) and Gorsevski et al. (2012), this criterion is taken into account.

Distance to airports In the study of Uyan (2014), minimum buffer zone between landfill sites and an airport is determined as 1000 m. Wang et al. (2009) and Sener et al. (2006) incorporated this criterion into evaluation process as well.

3.4.3 Solution

Landfilling is the most common waste disposal method used by Istanbul Metropolitan Municipality. The objective of our paper is to select the best landfill among several alternatives. These alternatives are evaluated with respect to four main criteria involving twelve sub-criteria. The hierarchy used in this study is provided in Figure 3.5. Five candidates are identified for alternative landfill sites in Istanbul: AL1-Arnautköy-Dursunköy, AL2-Çatalca-Çakıl, AL3-Sultangazi-Cebeci, AL4-Sultanbeyli-Battalgazi, AL5-Şile-Kömürcüoda.

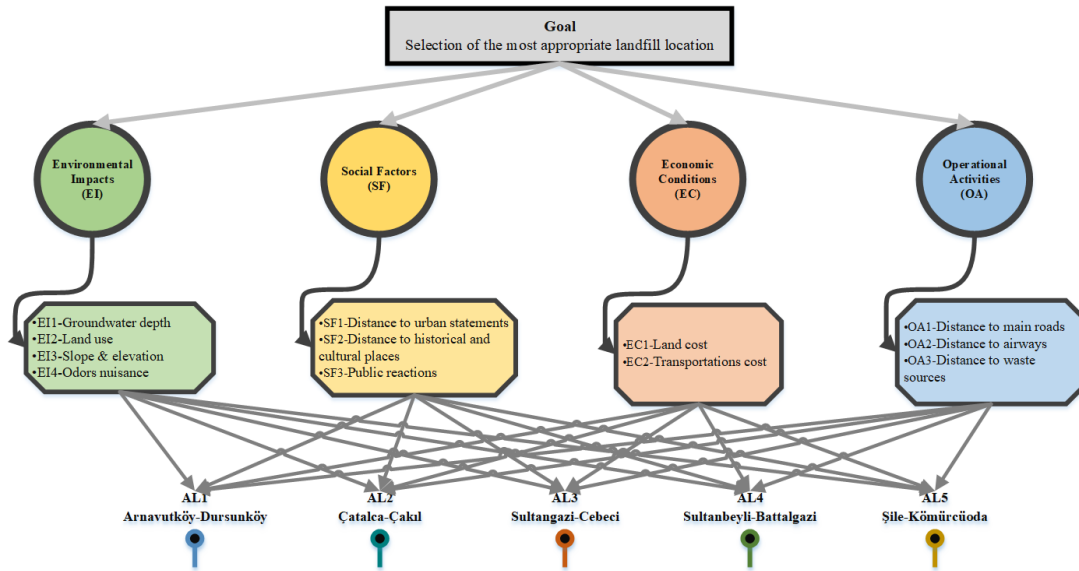


Figure 3.5 : Hierarchical structure of the problem.

These alternatives are evaluated through linguistic terms by experts. For instance, since elevation of AL2 is higher than AL4 (URL-3), AL2 is qualified as 'High Important (HI)' than AL4 with respect to this criterion. While assessing the potential of public reaction, population of the area is taken into account. All the steps to find the priority weights of the main criteria with respect to goal will be shown one by one. The fuzzy evaluation matrix relevant to the goal is given in Table 3.2.

Table 3.2 : Fuzzy evaluation matrix with respect to the goal in linguistic form.

Goal	EI	SF	EC	OA
EI	EI	BAI	AAI	HI
SF	AAI	EI	AAI	HI
EC	BAI	BAI	EI	AA
OA	LI	LI	BAI	EI

The pairwise comparison matrix $R = (r_{jt})_{m \times m}$ is constructed based on the experts' opinions given in Table 3.2. The pairwise comparison matrix is then obtained from Table 3.2 using the scale given in Table 3.1. The pairwise comparison matrix is provided in Table 3.3.

Table 3.3 : Importance of main criteria with respect to goal- R_{ik} .

Goal	EI	SF	EC	OA
EI	$([0.5, 0.5], [0.5, 0.5])$	$([0.35, 0.45], [0.55, 0.65])$	$([0.55, 0.65], [0.35, 0.45])$	$([0.65, 0.8], [0.2, 0.35])$
SF	$([0.55, 0.65], [0.35, 0.45])$	$([0.5, 0.5], [0.5, 0.5])$	$([0.55, 0.65], [0.35, 0.45])$	$([0.65, 0.8], [0.2, 0.35])$
EC	$([0.35, 0.45], [0.55, 0.65])$	$([0.35, 0.45], [0.55, 0.65])$	$([0.5, 0.5], [0.5, 0.5])$	$([0.55, 0.65], [0.35, 0.45])$
OA	$([0.2, 0.35], [0.65, 0.8])$	$([0.2, 0.35], [0.65, 0.8])$	$([0.35, 0.45], [0.55, 0.65])$	$([0.5, 0.5], [0.5, 0.5])$

Then, the difference matrix $D = (d_{jt})_{m \times m}$ between lower and upper values of the membership and non-membership functions is obtained using Eqs. (3.20) and (3.21) which are given in Table 3.4.

Table 3.4 : Matrix of difference between lower and upper values of the membership and non-membership functions.

Goal	EI		SF		EC		OA	
EI	0.000	0.000	-0.180	-0.220	0.180	0.220	0.383	0.518
SF	0.180	0.220	0.000	0.000	0.180	0.220	0.383	0.518
EC	-0.180	-0.220	-0.180	-0.220	0.000	0.000	0.180	0.220
OA	-0.383	-0.518	-0.383	-0.518	-0.180	-0.220	0.000	0.000

After this step, the interval multiplicative matrix $S = (s_{jt})_{m \times m}$ given in Table 3.5 is formed using Eqs. (3.22) and (3.23).

Table 3.5 : Interval multiplicative matrix.

Goal	EI		SF		EC		OA	
EI	1.000	1.000	0.537	0.468	1.862	2.138	3.748	5.974
SF	1.862	2.138	1.000	1.000	1.862	2.138	3.748	5.974
EC	0.537	0.468	0.537	0.468	1.000	1.000	1.862	2.138
OA	0.267	0.167	0.267	0.167	0.537	0.468	1.000	1.000

The matrix of unnormalized weights $T = (\tau_{jt})_{m \times m}$ given in Table 3.6 is calculated using determinacy values.

Table 3.6 : Matrix of unnormalized weights.

Goal	EI	SF	EC	OA
EI	1.000	0.402	1.600	3.402
SF	1.600	1.000	1.600	3.402
EC	0.402	0.402	1.000	1.600
OA	0.152	0.152	0.402	1.000

Finally, the priority weights provided in Table 3.7 are obtained using Eq. (3.25).

Table 3.7 : Priority weights of the main criteria.

EI	0.335
SF	0.398
EC	0.178
OA	0.089

Since how to obtain the weights is already explained on The matrix of main criteria with respect to goal, computations for Tables 3.8-3.23 are not given considering space constraints.

Table 3.8 : Evaluation of the sub-criteria with respect to environmental impact.

EI	EI1	EI2	EI3	EI4	W
EI1	EI	BAI	AAI	HI	0.338
EI2	AAI	EI	AAI	HI	0.401
EI3	BAI	BAI	EI	AAI	0.174
EI4	LI	LI	BAI	EI	0.087
CR = 0.06					

Table 3.9 : Evaluation of the sub-criteria with respect to social factors.

SF	SF1	SF2	SF3	W
SF1	EI	BAI	LI	0.143
SF2	AAI	EI	BAI	0.279
SF3	HI	AAI	EI	0.578
CR = 0.03				

Table 3.10 : Evaluation of the sub-criteria with respect to operational activities.

OA	OA1	OA2	OA3	W
OA1	EI	BAI	LI	0.148
OA2	AAI	EI	AI	0.329
OA3	HI	AI	EI	0.522
CR = 0.03				

Table 3.11 : Evaluation of the sub-criteria with respect to economic conditions.

EC	EC1	EC2	W
EC1	EI	BAI	0.346
EC2	AAI	EI	0.654
CR = 0.003			

Table 3.12 : Evaluation of the landfills with respect to groundwater depth.

EI1	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	VLI	BAI	AAI	LI	0.042
AL2	VHI	EI	CHI	CHI	AAI	0.643
AL3	AAI	CLI	EI	HI	BAI	0.087
AL4	BAI	CLI	LI	EI	VLI	0.021
AL5	HI	BAI	AAI	VHI	EI	0.206
CR = 0.079						

Table 3.13 : Evaluation of the landfills with respect to land use.

EI2	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	AI	BAI	HI	VHI	0.165
AL2	AI	EI	AI	VHI	CHI	0.336
AL3	AAI	AI	EI	CHI	CHI	0.451
AL4	LI	VLI	CLI	EI	AAI	0.032
AL5	VLI	CLI	CLI	BAI	EI	0.017
CR = 0.05						

Table 3.14 : Evaluation of the landfills with respect to slope and elevation.

EI3	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	AAI	LI	AAI	AAI	0.114
AL2	BAI	EI	CLI	BAI	AAI	0.066
AL3	HI	CHI	EI	HI	VHI	0.686
AL4	BAI	AAI	LI	EI	AAI	0.091
AL5	BAI	BAI	VLI	BAI	EI	0.043
CR = 0.09						

Table 3.15 : Evaluation of the landfills with respect to odors nuisance.

EI4	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	AI	AI	BAI	AAI	0.200
AL2	AI	EI	AI	BAI	AI	0.165
AL3	AI	AI	EI	BAI	AI	0.165
AL4	AAI	AAI	AAI	EI	AAI	0.323
AL5	BAI	AI	AI	BAI	EI	0.147
CR = 0.033						

Table 3.16 : Evaluation of the landfills with respect to distance to historical places.

SF1	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	AI	VHI	HI	LI	0.185
AL2	AI	EI	VHI	HI	LI	0.185
AL3	VLI	VLI	EI	BAI	CLI	0.020
AL4	LI	LI	AAI	EI	CLI	0.037
AL5	HI	HI	CHI	CHI	EI	0.573
CR = 0.077						

Table 3.17 : Evaluation of the landfills with respect to public reaction.

SF2	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	AI	VHI	HI	LI	0.228
AL2	AI	EI	VHI	HI	LI	0.228
AL3	VLI	VLI	EI	BAI	CLI	0.024
AL4	LI	LI	AAI	EI	LI	0.048
AL5	HI	HI	CHI	HI	EI	0.473
CR = 0.097						

Table 3.18 : Evaluation of the landfills with respect to distance to urban settlements.

SF3	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	AAI	CHI	CHI	BAI	0.422
AL2	BAI	EI	HI	HI	LI	0.084
AL3	CLI	LI	EI	AI	CLI	0.020
AL4	CLI	LI	AI	EI	CLI	0.020
AL5	AAI	HI	CHI	CHI	EI	0.453
CR = 0.049						

Table 3.19 : Evaluation of the landfills with respect to land cost.

EC1	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	BAI	HI	AAI	BAI	0.148
AL2	AAI	EI	VHI	HI	BAI	0.339
AL3	LI	VLI	EI	BAI	VLI	0.037
AL4	BAI	LI	AAI	EI	LI	0.072
AL5	HI	AAI	VHI	HI	EI	0.404
CR = 0.094						

Table 3.20 : Evaluation of the landfills with respect to transportation cost.

EC2	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	HI	VHI	VHI	AI	0.419
AL2	LI	EI	AAI	AAI	LI	0.080
AL3	VLI	BAI	EI	AI	VLI	0.042
AL4	VLI	BAI	AI	EI	VLI	0.042
AL5	AI	HI	VHI	VHI	EI	0.419
CR = 0.021						

Table 3.21 : Evaluation of the landfills with respect to distance to main roads.

OA1	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	LI	VLI	VLI	LI	0.034
AL2	HI	EI	AAI	AAI	AI	0.205
AL3	VHI	BAI	EI	AI	BAI	0.278
AL4	VHI	BAI	AI	EI	BAI	0.278
AL5	HI	AI	AAI	AAI	EI	0.205
CR=0.079						

Table 3.22 : Evaluation of the landfills with respect to distance to airports.

OA2	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	VHI	HI	HI	CHI	0.528
AL2	VLI	EI	BAI	BAI	HI	0.08
AL3	LI	AAI	EI	AI	VHI	0.186
AL4	LI	AAI	AI	EI	VHI	0.186
AL5	CLI	LI	VLI	VLI	EI	0.019
CR = 0.075						

Table 3.23 : Evaluation of the landfills with respect to distance to waste source.

OA3	AL1	AL2	AL3	AL4	AL5	W
AL1	EI	BAI	HI	AI	BAI	0.169
AL2	AAI	EI	VHI	AAI	HI	0.462
AL3	LI	VLI	EI	LI	BAI	0.048
AL4	AI	BAI	HI	EI	AI	0.18
AL5	AAI	LI	AAI	AI	EI	0.141
CR = 0.082						

According to the final scores given in Table 3.24, AL5 is the most preferred alternative.

Table 3.24 : Rank of the alternatives.

Alternatives	AL1	AL2	AL3	AL4	AL5
Final scores	0.253	0.24	0.143	0.06	0.305
Rank	2	3	4	5	1

3.4.4 Sensitivity

In this subsection, we apply one-at-a-time sensitivity analysis for the four main criteria. One-at-a-time sensitivity analysis is a measure of effectiveness due to changes in a single parameter (Canada 1980). The weights of these main criteria are changed gradually using each of the linguistic terms given in Table 3.1, and the scores of the alternatives are observed. Figure 3.6 indicates the results of the sensitivity analysis.

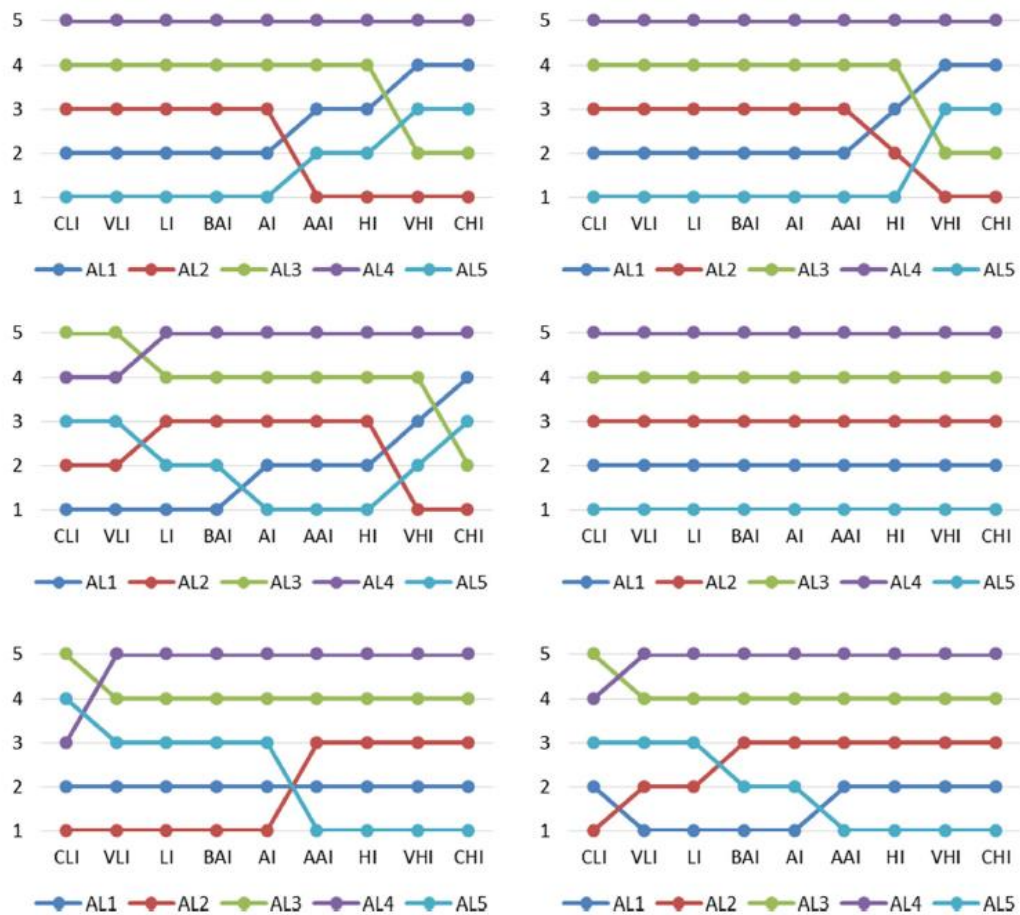


Figure 3.6 : One-at-a-time sensitivity analysis results.

After the changes on criterion environmental impacts with respect to criterion social factors, AL5 mostly remained in first rank but in weighting AAI, HI, VHI and CHI

AL2 become the first. Also, some changes in ordering relation occurred throughout. Similarly, after the changes on criterion environmental impacts with respect to economic conditions, almost identical changes have been observed. Unlike the others, after the changes on criterion environmental impacts with respect to criterion operational activities, AL1, AL5 and AL2 share the first rank in different weights. When we check the sensitivity on changes in criterion social factors with respect to criterion economic conditions, there is no impact on ranking in all variations of weights. Another sensitivity analysis has been applied on changes in criterion social factors with respect to criterion operational activities. By a majority AL2 in first rank and AL5 come after. Last analysis has been applied on changes in criterion economic conditions with respect to operational activities. In these sensitivity analyses, whichever linguistic terms are used, one of the alternatives AL1, AL2 and AL5 takes the first order.

According to these results, our proposed method's decisions are robust and reliable on the basis of one-at-a-time sensitivity analysis.

3.4.5 Comparison with Ordinary Fuzzy AHP and IVIF AHP

In this subsection, we compare our proposed PF-AHP method with Buckley's fuzzy AHP (Buckley 1985). Table 3.25 shows the scale for Buckley's fuzzy AHP. Here, we use the same pairwise matrices for a reliable comparison.

Table 3.25 : Scale of Buckley's fuzzy AHP.

Linguistic terms	Scale of Fuzzy Numbers
Exactly equal	(1, 1, 3)
Above average importance	(1, 3, 5)
High importance	(3, 5, 7)
Very high importance	(5, 7, 9)
Certainly high importance	(7, 9, 9)

Because of the space constraints, we only present the obtained results of Buckley's method. Table 3.26 gives the final solution of the Buckley's method.

Table 3.26 : Solution of Buckley's fuzzy AHP.

Alternatives	AL1	AL2	AL3	AL4	AL5
Weights	0.2235	0.2094	0.1778	0.1539	0.2353
Rank	2	3	4	5	1

Based on these rankings, the best alternative is AL5 in both ordinary fuzzy AHP and the proposed PF-AHP methods. When we compare the weights of alternatives, it is clearly seen that the weights obtained by Buckley's fuzzy AHP are quite close to each other. However, the differences between the weights of alternatives are more distinct in our proposed method, which is an advantage of PF-AHP. Additionally, we compared our method with Wu et al.'s (2013) interval-valued intuitionistic fuzzy AHP (IVIF AHP). The obtained results based on the scale provided in Table 3.27 are given in Table 3.28.

Table 3.27 : Scale of Wu et al.'s IVIF AHP.

Certainly low—CL	$\langle [0.1, 0.25], [0.65, 0.75] \rangle$
Very low—VL	$\langle [0.15, 0.3], [0.6, 0.7] \rangle$
Low—L	$\langle [0.2, 0.35], [0.55, 0.65] \rangle$
Below medium—BM	$\langle [0.25, 0.4], [0.5, 0.6] \rangle$
Exactly equal—EE	$\langle [0.5, 0.5], [0.5, 0.5] \rangle$
Above medium—AM	$\langle [0.5, 0.6], [0.25, 0.4] \rangle$
High—H	$\langle [0.55, 0.65], [0.2, 0.35] \rangle$
Very high—VH	$\langle [0.6, 0.7], [0.15, 0.3] \rangle$
Certainly high—CH	$\langle [0.65, 0.75], [0.1, 0.25] \rangle$

Table 3.28 : Solution of Wu et al.'s IVIF AHP.

AL1	AL2	AL3	AL4	AL5
0.2217	0.21741	0.1734	0.1699	0.2175
1	3	4	5	2

Wu et al.'s method replaces the best alternative AL5 with AL1. The rest of the ranking is the same as other two methods. When we examine the weights of alternatives, the same problem observed in Buckley's AHP which is very close alternative weights reappears in Wu et al.'s IVIF AHP method. This shows that our proposed method has more discriminatory power.

3.5 Conclusion

Pythagorean fuzzy sets are an extension of IFSs aiming that experts are not forced to assign membership and non-membership degrees whose sum must be at most 1. This provides a larger range of freedom to experts in expressing their opinions about the

vagueness and impreciseness of the considered problem. However, it brings a constraint such that squares sum of these degrees must be at most 1.

In this study, a Pythagorean fuzzy AHP method has been developed and applied to a landfill location selection problem. The proposed method has successfully evaluated the landfill location alternatives with respect to the considered criteria based on experts' compromised opinion. The developed defuzzification method for Pythagorean fuzzy sets is expected to be frequently used by other researchers since it efficiently reduces PFSs to crisp sets. A new scale for PFAHP has been also presented, which corresponds to the scale of crisp AHP when the developed defuzzification method is used.

The comparison with ordinary fuzzy AHP reveals that our proposed method produces consistent and informative outcomes involving more details about the uncertainty of decision-making environment. Sensitivity analyses show that the given decisions through the proposed method are robust against the changes in the main criteria weights.

For further research, we suggest that PF-AHP should be compared with hesitant fuzzy AHP, intuitionistic fuzzy AHP, or neutrosophic AHP. Alternatively, other types of PFSs such as singleton PFSs, triangular PFSs and trapezoidal PFSs can be employed instead of interval-valued PFSs in the developed PF-AHP method.

4 A NOVEL INTERVAL-VALUED NEUTROSOPHIC EDAS METHOD: PRIORITIZATION OF THE UNITED NATIONS NATIONAL SUSTAINABLE DEVELOPMENT GOALS³

In the traditional set theory, an element can belong to a set or not; in optimization, a solution is either feasible or not; and in Boolean logic, a statement can be true or false but nothing in between (Zimmerman, 2001). But in real life conditions, almost everything is not precise and is a matter of degree and cannot be defined by the traditional logic. In order to deal with this kind of uncertainty, Zadeh (1965) introduced the fuzzy sets theory. Since its first introduction in 1965, it has been extended to several fuzzy set variants. Type-n fuzzy set was developed by Zadeh (1975) for handling the uncertainty of the membership function in the fuzzy set theory. Interval-valued fuzzy sets (IVFSs) were introduced by Zadeh (1975), Grattan-Guinness (1975), Jahn (1975), and Sambuc (1975). Intuitionistic fuzzy sets (IFSs) were presented by Atanassov (1986) in order to better define a membership function with its membership and non-membership degrees including the hesitancy of decision makers. Hesitant fuzzy sets (HFSs), initially described by Torra (2010), are the extensions of regular fuzzy sets where a set of values are possible for the membership of a single element. Despite all these extensions, they may not sufficiently reflect decision-makers feelings to the definition of membership functions. Therefore, some new extensions are still required.

In order to surpass this insufficiency, Smarandache (1995) developed neutrosophic logic and neutrosophic sets (NSs) as an extension of intuitionistic fuzzy sets. The neutrosophic set is defined as the set where each element of the universe has a degree of truthiness, indeterminacy and falsity which are between $] - 0,1 + [$ the non-standard unit interval (Rivieccio, 2008). In the neutrosophic sets, uncertainty is represented as truth and falsity values where degrees of belongingness and non-belongingness and indeterminacy value where the factor incorporated as relativity or

³ This chapter is based on the paper “Karaşan, A., & Kahraman, C. (2018). A novel interval-valued neutrosophic EDAS method: prioritization of the United Nations national sustainable development goals. *Soft Computing*, 22(15), 4891-4906.

absoluteness. With this notation, neutrosophic sets do not only handle the uncertainty of the system but also reduce indecisiveness of inconsistent information. Thus, we can independently consider the truth and falsity values as membership and non-membership degrees and the indeterminacy value as the hesitancy degree.

EDAS method is relatively a new method proposed by Keshavarz Ghorabae et al. (2015). It aims to find the best solution by using two distance measures, namely the Positive Distance from Average (PDA) and the Negative Distance from Average (NDA). The best alternative is determined as the one with larger PDA and lower NDA. EDAS method is first time extended with neutrosophic sets to incorporate the advantages of these sets such as reflection of experts' relativity and absoluteness, and independency of the subsets of a neutrosophic set. This independency provides larger freedom to experts to assign the values of subsets. The proposed neutrosophic EDAS method involves all the advantages of neutrosophic sets over the other fuzzy set types.

Type-2 fuzzy sets have attracted attention of many researchers after they emerged in the literature. They have been widely used in image processing, fuzzy control applications, possibilistic clustering, and information granule formation. The reason why higher orders, or types, of fuzzy logic is used in the literature is to capture and represent more complex uncertainty. Rubio et al. (2017) presented an extension of the Fuzzy Possibilistic C-Means (FPCM) algorithm using Type-2 Fuzzy Logic Techniques in order to improve the efficiency of FPCM algorithm. Castillo et al. (2017) presented a literature review of applications using type-2 fuzzy systems in the area of image processing. They focused on image processing systems, which includes image segmentation, image filtering, image classification and edge detection. Tai et al. (2017) presented a literature review on recent applications of Type-2 fuzzy logic controllers (T2 FLC). To follow the developments in this field, we first review general T2 FLCs and the most well-known interval T2 FLS algorithms that have been used for control design. Certain applications of these controllers include robotic control, bandwidth control, industrial systems control, electrical control and aircraft control. Sanchez et al. (2015) presented a technique for forming type-2 fuzzy information granules. They give an approach toward a general base related to the theory of uncertainty-based information. Interval-valued fuzzy methods are the most preferred techniques since experts can better express their opinions through intervals instead of

exact numbers. Hence, we have proposed an interval-valued neutrosophic EDAS method.

United Nations are founded for maintaining worldwide security and peace, developing international relations and solving the problems related to economic, social, environmental, cultural, or humanitarian problems. In 2015, the foundation announced the sustainable development goals for the countries to achieve them for the next 15 years. The goals are very complicated and depend on many actors such as governments, the private sector, civil societies and of course, people. Here, we combine some of these goals since they have strong connections between each other and define the relevant criteria for scoring them.

In this study, an interval-valued neutrosophic EDAS method is developed and applied to the prioritization of the United Nations national sustainable development goals. This method is similar to distance based MCDM (Keshavarz Ghorabae et al., 2015) such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwan & Yoon, 1981) and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) (Opricovic, 1998). The criteria and alternatives are determined by an expert group and the weights of criteria and the scores of the decision matrices are aggregated by their opinions.

The rest of this paper is organized as follows. In Section 4.1, a literature review on MCDM methods with neutrosophic sets is given. In Section 4.2, the proposed methodology is given with its details. In Section 4.3, an application is given to examine its validity and robustness. The paper ends with the conclusion and suggestions for further research.

4.1 Literature Review: MCDM Methods with Neutrosophic Sets

Peng et al. (2014) proposed simplified neutrosophic ELECTRE III method and applied two practical examples to illustrate the practicality and effectiveness of the proposed approach. Ye (2013) studied a decision-making method which is composed of the weighted correlation coefficient or the weighted cosine similarity measure of single valued neutrosophic numbers (SVNNs). The proposed approach is applied to an illustrative example to demonstrate its applicability and effectiveness. Zhang et al. (2016) presented a novel ELECTRE IV method with interval-valued neutrosophic

numbers (IVNNs). Bausys et al. (2015) extended complex proportional assessment (COPRAS) method with SVNNS in their studies and applied it to the selection of location for a liquefied natural gas terminal. Ji et al. (2016) studied TODIM method with the extension of multi-valued neutrosophic sets (MVNSs). The proposed method is applied to an illustrative example to indicate its feasibility. Biswas et al. (2016) proposed TOPSIS method with its extension of SVNNS. Bausys & Zavadskas (2015) presented IVNS VIKOR method for the solution of the MCDM problems. A comparative analysis is conducted to demonstrate the applicability and the effectiveness of the proposed method. Peng et al. (2016) proposed an extension of ELECTRE III method with MVNNs for MCDM problems. The proposed model is applied to a numerical example to demonstrate and testify its validity and feasibility. Zavadskas et al. (2017) proposed neutrosophic Multi-Attribute Market Value Assessment (MAMVA) method and applied it to the sustainable market valuation of Croydon University Hospital. The results of the study indicate the effectiveness of the proposed approach for calculations of property market valuation. Karaşan & Kahraman (2017) proposed IVN EDAS method and applied to a multi-criteria and multi-expert supplier selection problem. Sensitivity and comparative analyses are conducted to check the robustness of the given decisions and proposed method. Otay & Kahraman (2017) employed an extended IVN TOPSIS method to evaluate Six Sigma projects with group decision making. Hu et al. (2017) extended VIKOR method with a new type of measurement function by using IVNNs to deal with the shortcomings in its normal version. The proposed method is applied to the doctor selection problem and the results of the problem, and conducted sensitivity analysis demonstrate the viability, and validity of the method. Peng et al. (2016) introduced probability multi-valued neutrosophic sets (PMVNSs) based on multi-valued neutrosophic sets and probability distribution and used it to extend QULIFLEX method. The proposed method is applied to an illustrative example concerning logistics outsourcing and its feasibility and validity were further verified by comparison with other existing methods. Ma et al. (2016) presented a cloud service interval-valued neutrosophic set (CIVNS) and designed its operators, with theoretical proofs provided. The problem of time-aware trustworthy service selection was solved as an MCDM problem with its extension with CIVNS. Ye (2014) defined the Hamming and Euclidean distances between interval neutrosophic sets (INSs) and proposed the similarity measures between INSs based on the relationship between

similarity measures and distances. Deli et al. (2016) proposed interval-valued bipolar fuzzy weighted neutrosophic set (IVBFWN-set) and applied to a real example to demonstrate the effectiveness of the proposed extension. Elhassouny & Smarandache (2016) extended TOPSIS method with neutrosophic sets and applied to an illustrative example to present its effectiveness. Ye (2014) introduced simplified neutrosophic sets (SNSs) and aggregation operators on these sets including weighted arithmetic and weighted geometric average operators.

4.2 Methodology

In this section, we propose interval-valued neutrosophic EDAS with its details. A new deneutrosophication technique for the interval-valued neutrosophic sets is proposed and the subtraction operation for interval-valued neutrosophic sets is developed.

4.2.1 Preliminaries

Definition 14 (Zhang et al., 2014). Let $x_j = \langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$, be a collection of interval-valued neutrosophic number (IVNN) where $j = 1, 2, \dots, n$ is the expert. Based on the weighted aggregation operators of IVNNs, the interval-valued neutrosophic weighted arithmetic average operator (INWAA) is given as below:

$$\text{INWAA}(x_1, x_2, \dots, x_n) = \sum_{k=1}^n y_k x_j,$$

where

$$\langle [1 - \prod_{k=1}^n (1 - T_j^L)^{y_k}, 1 - \prod_{k=1}^n (1 - T_j^U)^{y_k}], [\prod_{k=1}^n (I_j^L)^{y_k}, \prod_{k=1}^n (I_j^U)^{y_k}], [\prod_{k=1}^n (F_j^L)^{y_k}, \prod_{k=1}^n (F_j^U)^{y_k}] \rangle \quad (4.1)$$

and y_k is the weight vector of expert.

Definition 15. The deneutrosophication function of an IVNN which is given above is calculated as below:

$$\mathfrak{D}(x) = \frac{\left(\left(T_x^L * ((1 - I_x^L) + (1 - I_x^U)) \right) + \left(T_x^U * ((1 - I_x^L) + (1 - I_x^U)) \right) + \left((1 - F_x^L) * ((1 - I_x^L) + (1 - I_x^U)) \right) + \left((1 - F_x^U) * ((1 - I_x^L) + (1 - I_x^U)) \right) \right)}{8} \quad (4.2)$$

where $x = \langle [T_x^L, T_x^U], [I_x^L, I_x^U], [F_x^L, F_x^U] \rangle$.

Definition 16. A function is defined in the following to find the maximum between interval-valued neutrosophic set and zero.

$$Z(x_j) = \begin{cases} x_j & \text{if } \kappa(x_j) > 0 \\ 0 & \text{if } \kappa(x_j) \leq 0 \end{cases} \quad (4.3)$$

where $x_j = \langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$ and $0 = \langle [0,0], [1,1], [1,1] \rangle$.

Definition 17. Let X be a universe of discourse. An IVN set N in X is independently characterized by a truth-membership function $T_N(x)$, an indeterminacy-membership function $I_N(x)$, and a falsity-membership function $F_N(x)$ for each $x \in X$, where $T_N(x) = [T_{N(x)}^L, T_{N(x)}^U] \subseteq [0,1]$, $I_N(x) = [I_{N(x)}^L, I_{N(x)}^U] \subseteq [0,1]$, and $F_N(x) = [F_{N(x)}^L, F_{N(x)}^U] \subseteq [0,1]$, then they satisfy the condition $0 \leq T_N^L(x) + I_N^L(x) + F_N^L(x) \leq 3$. Thus, the IVNS N can be denoted as (Li et al., 2016):

$$N = \{ \langle x, [T_N^L(x), T_N^U(x)], [I_N^L(x), I_N^U(x)], [F_N^L(x), F_N^U(x)] \rangle | x \in X \} \quad (4.4)$$

We will denote Eq. (4.4) as $[T_N^L, T_N^U], [I_N^L, I_N^U], [F_N^L, F_N^U]$ for short.

Let $a = [T_a^L, T_a^U], [I_a^L, I_a^U], [F_a^L, F_a^U]$ and $b = [T_b^L, T_b^U], [I_b^L, I_b^U], [F_b^L, F_b^U]$ be two INNs, the relations of them are shown as below (Zhang et al., 2014):

1. $a^c = \langle [T_a^L, T_a^U], [1 - I_a^U, 1 - I_a^L], [F_a^L, F_a^U] \rangle$.
2. $a \subseteq b$ if and only if $T_a^L \leq T_b^L, T_a^U \leq T_b^U; I_a^L \geq I_b^L, I_a^U \geq I_b^U; F_a^L \geq F_b^L, F_a^U \geq F_b^U$.
3. $a = b$ if and only if $a \subseteq b$ and $b \subseteq a$.
4. $a \oplus b = \langle [T_a^L + T_b^L - T_a^L T_b^L, T_a^U + T_b^U - T_a^U T_b^U], [I_a^L I_b^L, I_a^U I_b^U], [F_a^L F_b^L, F_a^U F_b^U] \rangle$.
5. $a \otimes b = \langle [T_a^L T_b^L, T_a^U T_b^U], [I_a^L + I_b^L - I_a^L I_b^L, I_a^U + I_b^U - I_a^U I_b^U], [F_a^L + F_b^L - F_a^L F_b^L, F_a^U + F_b^U - F_a^U F_b^U] \rangle$.

Definition 18. Subtraction operation of two interval-valued neutrosophic sets is proposed as in Eq. (4.5):

$$x \ominus y = [T_x^L - T_y^U, T_x^U - T_y^L], [\text{Max}(I_x^L, I_y^L), \text{Max}(I_x^U, I_y^U)], [F_x^L - F_y^U, F_x^U - T_y^L] \quad (4.5)$$

where $x = \langle [T_x^L, T_x^U], [I_x^L, I_x^U], [F_x^L, F_x^U] \rangle$ and $y = \langle [T_y^L, T_y^U], [I_y^L, I_y^U], [F_y^L, F_y^U] \rangle$.

4.2.2 Interval-valued Neutrosophic EDAS Method

In this section, we use interval-valued neutrosophic sets in EDAS method to surpass of incompleteness, indeterminacy, and inconsistency information of the system. The steps of the extended method are as follows:

Step 1: Construct the IVN decision matrix (D_j) with regards to experts (j) , where the benefit and cost variables are b_{mn} and c_{mn} respectively. The columns are the

alternatives (n) and the rows are the criteria (m). The scale used to construct IVN decision matrix is given in Table 4.1.

Table 4.1 : Scale for IVN decision matrix.

Linguistic Terms		$\langle T, I, F \rangle$
CL	Certainly Low	$\langle [0.05, 0.2], [0.6, 0.7], [0.75, 0.9] \rangle$
VL	Very Low	$\langle [0.15, 0.3], [0.5, 0.6], [0.65, 0.8] \rangle$
L	Low	$\langle [0.25, 0.4], [0.4, 0.5], [0.55, 0.7] \rangle$
BA	Below Average	$\langle [0.35, 0.5], [0.3, 0.4], [0.45, 0.6] \rangle$
A	Average	$\langle [0.4, 0.6], [0.1, 0.2], [0.4, 0.6] \rangle$
AA	Above Average	$\langle [0.45, 0.6], [0.3, 0.4], [0.35, 0.5] \rangle$
H	High	$\langle [0.55, 0.7], [0.4, 0.5], [0.25, 0.4] \rangle$
VH	Very High	$\langle [0.65, 0.8], [0.5, 0.6], [0.15, 0.3] \rangle$
CH	Certainly High	$\langle [0.75, 0.9], [0.6, 0.7], [0.05, 0.2] \rangle$

Through the scale, IVN decision matrix with respect to Expert j is given in Table 4.2. In here, we use $x_{jmn} = \langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$ notation to express IVN number with respect to Expert j .

Table 4.2 : IVN decision matrix with respect to expert j .

Criterion	Type	AL_1	AL_2	...	AL_n
C_1	Linguistic Cost	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	...	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$
C_2	Numerical Cost	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	...	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
C_m	Linguistic Benefit	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$	...	$\langle [T_j^L, T_j^U], [I_j^L, I_j^U], [F_j^L, F_j^U] \rangle$

Step 2: Aggregate the decision matrix for obtaining average IVN decision matrix. We use Eq. (4.1) for aggregation operation. Aggregated IVN decision matrix (A) is constructed as in Table 4.3. In here, $x_{mn} = \langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$ notation is used to express aggregated IVN number.

Table 4.3 : Aggregated IVN decision matrix.

Criterion	Type	AL_1	AL_2	...	AL_n
C_1	Linguistic Cost	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$	...	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$
C_{12}	Numerical Cost	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$	...	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
C_m	Linguistic Benefit	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$	...	$\langle [T_A^L, T_A^U], [I_A^L, I_A^U], [F_A^L, F_A^U] \rangle$

Step 3: Construct the average solution matrix of criteria weights with regards to experts (j). The criteria weights are determined by Table 4.4. The weights are shown as follows:

$$W = [w_j]_{1 \times m} \quad (4.6)$$

where w_j is obtained by using Eq. (4.1).

Table 4.4 : Scale for weighting the criteria

Linguistic Term		<(T, I, F)>
CLI	Certainly Low Importance	<[0.05, 0.25], [0.6, 0.7], [0.75, 0.95]>
VLI	Very Low Importance	<[0.15, 0.35], [0.5, 0.6], [0.65, 0.85]>
LI	Low Importance	<[0.25, 0.45], [0.4, 0.5], [0.55, 0.75]>
BAI	Below Average Importance	<[0.35, 0.55], [0.3, 0.4], [0.45, 0.65]>
AI	Average Importance	<[0.4, 0.6], [0.1, 0.2], [0.4, 0.6]>
AAI	Above Average Importance	<[0.45, 0.65], [0.3, 0.4], [0.35, 0.55]>
HI	High Importance	<[0.55, 0.75], [0.4, 0.5], [0.25, 0.45]>
VHI	Very High Importance	<[0.65, 0.85], [0.5, 0.6], [0.15, 0.35]>
CHI	Certainly High Importance	<[0.75, 0.95], [0.6, 0.7], [0.05, 0.25]>

Step 4: Construct the matrix of average criteria weights (AV) with regards to scores that are determined in Table 4.3. The constructed criteria weight matrix is shown as below:

Table 4.5 : Average criteria weights with regards to scores.

Criterion	Type	Average Criteria Weights
C_1	Linguistic Cost	$\langle [T_{av}^L, T_{av}^U], [I_{av}^L, I_{av}^U], [F_{av}^L, F_{av}^U] \rangle$
C_{12}	Numerical Cost	$\langle [T_{av}^L, T_{av}^U], [I_{av}^L, I_{av}^U], [F_{av}^L, F_{av}^U] \rangle$
$\vdots$	$\vdots$	$\vdots$
C_m	Linguistic Benefit	$\langle [T_{av}^L, T_{av}^U], [I_{av}^L, I_{av}^U], [F_{av}^L, F_{av}^U] \rangle$

In here, $av_n = \langle [T_{AV}^L, T_{AV}^U], [I_{AV}^L, I_{AV}^U], [F_{AV}^L, F_{AV}^U] \rangle$ where the average weight of criteria x_{mn} with respect to scores taken from the decision matrix.

Step 5: Calculate the positive distance from average (PDA) and negative distance from average (NDA) according to benefit and cost criteria, respectively. As we mentioned above benefit and cost variables are shown as b_{mn} and c_{mn} .

$$PDA = [pda_{mn}]_{m \times n} \quad (4.7)$$

$$NDA = [nda_{mn}]_{m \times n} \quad (4.8)$$

where pda_{mn} and nda_{mn} denote the positive and negative distance performance value of the n^{th} alternative from average solution in terms of m^{th} criterion respectively.

$$pda_{mn} = \begin{cases} \frac{Z(x_{mn} \ominus av_n)}{\kappa(av_n)} & \text{if } m \in B \\ \frac{Z(av_n \ominus x_{mn})}{\kappa(av_n)} & \text{if } m \in C \end{cases} \quad (4.9)$$

$$nda_{mn} = \begin{cases} \frac{Z(av_n \ominus x_{mn})}{\kappa(av_n)} & \text{if } m \in B \\ \frac{Z(x_{mn} \ominus av_n)}{\kappa(av_n)} & \text{if } m \in C \end{cases} \quad (4.10)$$

Step 6: Calculate the weighted sum of positive and negative distances for all alternatives as follows:

$$sp_n = \sum_{j=1}^l (w_j \otimes pda_{mn}) \quad (4.11)$$

$$np_n = \sum_{j=1}^l (w_j \otimes nda_{mn}) \quad (4.12)$$

Step 7: Normalize the sp_n and np_n values. The normalize values of sp_n and np_n for all alternatives are calculated as follows:

$$nsp_n = \frac{sp_n}{\max(\kappa(sp_n))} \quad (4.13)$$

$$nsn_n = 1 - \frac{sn_n}{\max(\kappa(sn_n))} \quad (4.14)$$

Step 8: Calculate the appraisal score (as_n) for all alternatives as follows:

$$as_n = \frac{1}{2} (nsp_n \oplus nsn_n) \quad (4.15)$$

Step 9: Rank the alternatives according to the decreasing values of appraisal score (as_n).

4.3 Application

In this section, we apply our proposed model to prioritize United Nations sustainable development goals for Turkey to determine which goal they will start to invest firstly. In our application, we have 3 experts which have 0.42, 0.35, and 0.23 importance level, 15 goals to prioritize, 4 main-criteria and 15 sub-criteria to weight. For weighting procedure, we aggregate the 3 experts' opinions by using Eq. (4.1). After this procedure, we employ sub-criteria and their weights as inputs of neutrosophic EDAS method to prioritize the goals and give the final decision. The hierarchy of the application is given in Figure 4.1.

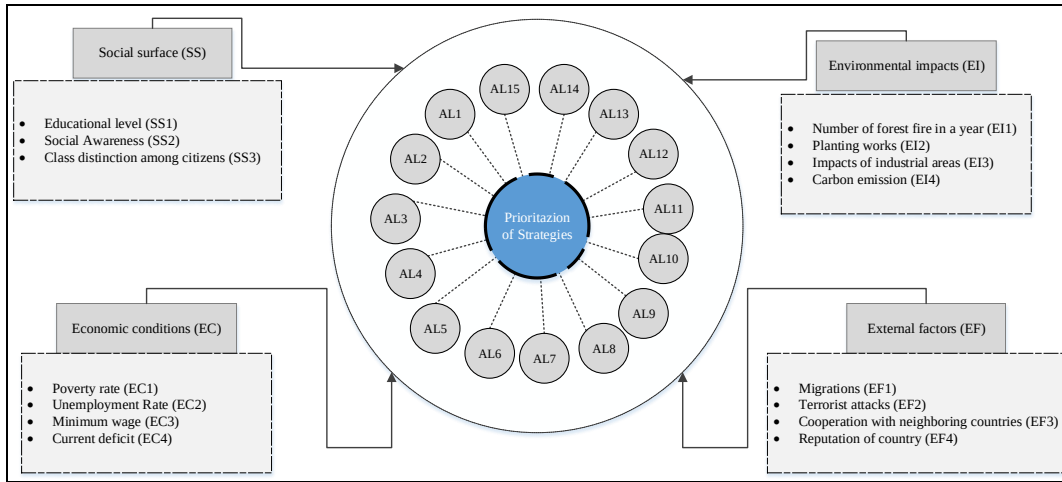


Figure 4.1 : Hierarchy of the proposed novel method.

4.3.1 Problem Definition

Due to Human Development Report 2016 of United Nations organization based on human development indicators, Turkey is 71st country in the world on the development ranking (Jahan, 2016). We investigate the country's situation with respect to United Nations national sustainable development goals and assign them as our strategies to prioritize based on the criteria that are listed in Section 4.3.2. These goals are Poverty (AL1), Sustainable agriculture (AL2), Promote healthy living (AL3), Quality of education (AL4), Gender equality (AL5), Access to water and sanitation (AL6), Sustainable energy (AL7), Unemployment (AL8), Sustainable industrialization and resilient infrastructure (AL9), Sustainable cities (AL10), Sustainable consumption and production patterns (AL11), Conserve and sustainably use the seas and marine resources (AL12), Sustainable management of nature (AL13), Promote peaceful and inclusive societies (AL14), Global partnership (AL15). We give brief descriptions of these goals below:

Poverty (AL1): In today's world, due to the unemployment, deficiencies in unionization, labor market problems, income inequality, fluctuations in economy, inflations, social and demographic impacts, rapid population growth, household structures, education level, discrimination, migrations, geographical and political issues are the main causes of poverty in a country. Due to the Human Development Report of 2016, one in five people in developing regions still live on less than \$1.25 a day, and there are millions more who make a little more than this daily amount, plus many people risk slipping back into poverty. On the other hand, according to the

purchasing power parity in Turkey, the poverty rate at the limit of \$4.3 and it is corresponding to 1.62% of the overall population (Sarica, 2016).

Sustainable agriculture (AL2): Agriculture, forestry, livestock, and fisheries sectors can provide nutritious food for all and generate decent incomes. Through years, Turkey trying to transform its status from a form of agricultural to an industrial country. In order not to be affected negatively in agriculture by this transformation, Turkey aims to increase the technological activities to get more products from the unit area or per animal. Due to the report of Republic of Turkey Ministry of Food, Agriculture, and Livestock, as a conclusion of precautions and allowances, records of the Republican history were broken in the livestock production in 2014 (Yazici, 2015).

Promote healthy living (AL3): This alternative is one of the key factors for sustainable development that provides a healthy life. In Turkey, despite the number of health personnel cannot meet health service demand and institutional requirement and the existence of ineffective legislation, with the implementation of social security reform most of the goals that are determined in 2015 are reached (Gümüş, 2016).

Quality of education (AL4): Quality of education is one of the most important factors that will bring the country to the level of contemporaries. Based on the OECD report; crowded classrooms, unsatisfactory schooling rates, waste of resources and time caused by failure or repetition of the grade, double shift education, integrated classrooms especially in rural areas, lack of equipment, lack of finance, problems related to the training, balanced distribution, economic conditions, social status and in-service training of teachers, review need of the curricula, and the educational material according to the changing and varying educational needs of society Turkey has many ways to get (OECD, 2007). Turkey aims to overcome these problems with new regulations and legislation.

Gender equality (AL5): Gender equality, women's empowerment, and equal access to primary education between girls and boys are the main factors that need to be resolved in today's world. In Turkey, protocols and agreements were signed and steps were taken to decrease women's deaths and necessary arrangements for women in business and social life led by the Family and Social Policy Ministry.

Access to water and sanitation (AL6): With the rapid increase of human population clean and accessible water is become a vital factor for who lived in the world today.

For Turkey, since it is a rich country with underground and surface water resources as it does not draw the clean water requirement. In order to be sustainable, many dam constructions are underway, and these operations also aim to meet the water needs of agriculture fields.

Sustainable energy (AL7): By way of technological advances we have become able to produce energy from almost everything today. To make it sustainable and reachable for all, we should also implement things on it for without damaging the environment and all living. Due to International Energy Agency, Turkey's energy policy has constantly improved to serve a growing economy and population, reduce rising import dependence and meet not only the country's development goals but also international environmental factors (IEA, 2016).

Unemployment (AL8): From the past to present, we see that all technological developments and new working areas are inadequate for the needs of growing human population for working and unemployment is an important factor to be addressed. As a result of this, today almost half the world's population still lives on the equivalent of about US\$2 a day. In Turkey for the March 2017, employment increased by 496 thousand people compared to the same period of the previous year and was 27 million 489 thousand persons, Nevertheless, the number of unemployed people aged 15 and over was an increase of 618 thousand in March of 2017 compared to the same period of the previous year, and totally 3 million 642 thousand.

Sustainable industrialization and resilient infrastructure (AL9): To achieving sustainable development and make it permanent, the infrastructure of cities and industrialization are key factors. Today, one of the biggest problems of the world, infrastructure, contains transport of people and goods, energy for residents and facilities, information and communication technology for all who lived in societies. Infrastructure and following industrial grants will contribute to the formation of planned industrialization in the regions determined in the investment program. For Turkey, Ministry of Science, Industry, and Technology prepared and implemented the 2016 Performance Program in the framework of the Strategic Plan covering the years 2013-2017. 5 strategic objectives, 44 strategic targets, 44 performance targets, and 151 performance indicators in 48 activities are observed (Aslan, 2016). On the other hand, industrialization in Turkey does not continue as an equal and simultaneous process in the regions. Most of these activities and objectives are encompassed only big cities.

As a result of these, 120 were rated "Target Achieved", 11 were considered "Reasonable" and 20 were considered "Improved". A percentage of success appears to be approximately 80% of overall.

Sustainable cities (AL10): With the better opportunities and influence of industrialization, cities are the center of productivity in almost every way like commerce, culture, science, and other developments. On the other hand, cities have many challenges such as congestion in pedestrian and vehicle traffic, insufficient employment opportunities that cannot meet the growing population's need, a shortage of adequate housing and declining infrastructure. For Turkey, as one of the countries experiencing a serious change in the meaning of urbanism and providing serious growth in the construction sector, there is a lot of work to do according to the 2016 annual report. According to report results, there needs to integrate enterprise data infrastructure with business processes, needs for the development of inter-institutional coordination capacity, and needs for further strengthening of the inspection capabilities for assigned positions.

Sustainable consumption and production patterns (AL11): Sustainable consumption and production are achieved with the efficient use of resource and energy. Its implementation helps to reach the economic goals of countries, reduce the overall cost of cities, and provides a better quality of life for all humankind. To apply this pattern, it needs cooperation with stakeholders of the supply chain in a range of the suppliers to the consumers and creation of awareness and education on green lifestyles. Through the eighteenth session of the Commission on Sustainable Development Views of Turkey on sustainable consumption and production reports in 2010, usage of natural resources should be planned considering the needs of future generations, protection-usage trade-off should be arranged, more production with to a lesser extent of scrap should be targeted, consistency and coherency between the industrial and environmental laws and regulations should be provided.

Conserve and sustainably use the seas and marine resources (AL12): Through the years, oceans, seas, lakes, and streams are vital formations of the world that make it habitable for all livings. In addition to meeting food needs, it is also greatly used in key areas such as trade and transport. In order to provide and improve the continuity of this formation, many studies are being carried out in the world today. In Turkey, it is planned to establish safe maritime navigation corridors, give high priority to allow

the aquacultural activities, strengthen the institutional capacity, based on statistical data fulfill the efficient resource management in the fishery sector (Unknown, 2016).

Sustainable management of nature (AL13): Management of nature is the most important factor for bridging the gap between regulations and enforcement in countries. In this system, forests are the key elements that combat climate change, protects biodiversity and the habitation of the native population. For Turkey, from the 2000s, major issues influencing the sustainability of natural resource contains weak capacity to implement the overall strategy for environmental management, forest resource planning and utilization systems do not adequately incorporate environmental and biodiversity conservation issues, unsustainable range and grazing resource management systems, lack of intersectoral coordination, particularly between conservation agencies and the Ministries responsible for regulation of tourism development, management of cultural heritage, and the use of water resources, lack of public awareness of the importance of Turkish biodiversity and the urgent need for effective conservation initiatives (Linn, 2000). Today, evaluating the effects of climate change and all activities in catchments on water quantity and quality, measures for saving water, combatting drought and preventing pollution are the most important issue of Ministry of Environment and Urbanization during the term between 2014-2018.

Promote peaceful and inclusive societies (AL14): Creating a peaceful and healthy society and being able to continue what is achieved is one of the most important goals of the countries. To reach this aim, policy makers construct a system that can provide justice for everyone, education for all level of citizens. Due to the Human Development Report of 2016 (Jahan, 2016) the human development index that demonstrates the level of prosperity in countries, Turkey has reached 0.767 point in 2016 and has a steady increase since 1990.

Global partnership (AL15): As a result of treaties and interstate agreements between countries, borders have begun to be overcome in today's world and many laws have been designed for global purposes. These partnerships aim to place the world and people at the center of actions that create prosperity. Turkey, one of the most important countries in the Middle East and a bridge in European trade traffic with Asia, has many advantages to serve for its and around people. Today, wars and conflicts in Middle East countries impressed not only the region but all of the world, since the migration

reached incredible dimensions. The actions of Turkey will determine the effect the peace and security of the region.

4.3.2 Evaluation Criteria

The evaluation criteria for the prioritization of the goals are given as below:

Social Surface (SS): Turkey has many ethnic origins and many differences in social backgrounds. Due to the wars that have taken place in the Middle East, a great immigrant influx occurred to the country. It is not only a transit point of freights and people between the West and East but also a bridge in the sense of life order at the same time. Hence, social surface is an important criterion while making decisions. Social surface can be divided into 3 sub-criteria which are *Educational level* (SS1), *Social awareness* (SS2), *Class distinction among citizens* (SS3). These sub-criteria have been determined to assess goals from different points of view, but as a whole, they are components of the *Social surface* criterion in the application.

Economic Conditions (EC): The most important issue in making an investment is its economic power. Most of the investments are realized in the construction sector, but the manufacturing sector has not yet gained a momentum in the international arena. This can be seen as a deficiency. Fluctuation in foreign exchange rates is another problem. When the experts determined the sub-criteria in this framework, they decided to divide *Economic conditions* into *Poverty rate* (EC1), *Unemployment rate* (EC2), *Minimum wage* (EC3), *Current deficit* (EC4) sub-criteria for the application.

Environmental Impacts (EI): Turkey, with its large water resources and forests, has not yet faced the problems of lack of water and food. The determined goals relevant to the environment will be an important step for the Turkey's prosperity in order to make a better trade-off between the industrialization, environmental impact, and environmental regulation. From this point of view, *Number of forest fire in a year* (EI1), *Planting works* (EI2), *Impacts of industrial areas* (EI3), and *Carbon emission* (EI4) determined as sub-criteria of *Environmental impacts* for the application.

External Factors (EF): The geographical location of Turkey and many treaties made in the past cause other countries to become arbiter in determining the purposes of the country as much as the rulers and the living people. Terrorist attacks that have been going on for many years and wars in the Middle East for the past 15 years have

significantly affected the country. Hence, this criterion can be divided into *Migrations* (EF1), *Terrorist attacks* (EF2), *Cooperation with the neighboring countries* (EF3), *Reputation of the country* (EF4) as sub-criteria for the evaluation of goals in the application.

In line with all these sub-criteria, we will apply IVN-EDAS method to prioritize United Nations national sustainable development goals for Turkey in this application.

4.3.3 Solution

Before starting the IVN-EDAS method, experts weighted the sub-criteria based in Table 4.4. The linguistic terms and their aggregated results based on interval-valued neutrosophic numbers are given in Table 4.6.

Table 4.6 : Aggregated weights of sub-criteria.

	SS1	SS2	SS3	EC1	EC2	EC3	EC4	EI1	EI2	EI3	EI4	EF1	EF2	EF3	EF4
DM1	VHI	HI	AI	CHI	VHI	HI	AI	LI	VLI	CLI	HI	HI	VHI	LI	AAI
DM2	CHI	AAI	AAI	VHI	HI	HI	AAI	BAI	LI	LI	BAI	LI	VHI	HI	HI
DM3	VHI	AI	HI	VHI	CHI	HI	BAI	BAI	BAI	BAI	AI	BAI	CHI	VHI	VHI
Aggregated weights of sub-criteria	<[0.69, 0.9], [0.59, 0.7], [0.1, 0.31]>	<[0.48, 0.69], [0.29, 0.42], [0.31, 0.52]>	<[0.46, 0.66], [0.22, 0.35], [0.34, 0.54]>	<[0.7, 0.91], [0.6, 0.71], [0.09, 0.3]>	<[0.65, 0.86], [0.54, 0.65], [0.14, 0.35]>	<[0.55, 0.75], [0.44, 0.56], [0.25, 0.45]>	<[0.41, 0.61], [0.21, 0.33], [0.39, 0.59]>	<[0.31, 0.51], [0.38, 0.49], [0.49, 0.69]>	<[0.24, 0.44], [0.46, 0.57], [0.56, 0.76]>	<[0.2, 0.4], [0.49, 0.61], [0.6, 0.8]>	<[0.45, 0.66], [0.29, 0.42], [0.34, 0.55]>	<[0.41, 0.62], [0.42, 0.53], [0.38, 0.59]>	<[0.68, 0.88], [0.58, 0.69], [0.12, 0.32]>	<[0.47, 0.69], [0.47, 0.58], [0.31, 0.53]>	<[0.54, 0.74], [0.41, 0.53], [0.26, 0.46]>

As the first step, constructed IVN decision matrix (D_j) is given in Table 4.7.

Table 4.7 : Decision matrix with respect to experts.

Expert 1																
Criteria	Type	AL 1	AL 2	AL 3	AL 4	AL 5	AL 6	AL 7	AL 8	AL 9	AL1 0	AL1 1	AL1 2	AL1 3	AL1 4	AL1 5
SS1	Benefit	H	H	VH	BA	AA	CL	A	VH	CL	VL	CH	AA	CL	AA	CL
SS2	Benefit	H	BA	H	BA	CH	CL	H	L	CL	CH	H	H	CL	H	CL
SS3	Cost	L	CH	CL	VL	VL	A	CL	L	CL	CH	VH	H	BA	H	BA
EC1	Cost	H	VH	VL	H	CH	CH	VL	CL	CL	VL	VL	A	VH	CH	VH
EC2	Cost	CH	H	H	L	CL	VL	L	A	VL	H	CH	CH	CL	VH	BA
EC3	Benefit	AA	AA	A	A	AA	CL	A	VH	VH	L	CL	VL	CL	H	BA
EC4	Cost	AA	H	CL	VL	BA	CH	BA	CL	CL	A	AA	CL	BA	CL	VH
EI1	Cost	CH	H	BA	CH	VL	L	VH	BA	CL	VL	BA	CH	VH	VL	H
EI2	Benefit	AA	CH	VH	CL	A	CL	H	BA	CH	CL	CH	CL	CH	H	L
EI3	Cost	AA	CH	A	A	AA	CH	CL	VH	A	CL	VL	CL	CH	VH	H
EI4	Cost	VH	CH	CL	VH	BA	CL	VL	H	VL	AA	BA	VH	A	A	H
EF1	Cost	CH	VH	VH	VH	CL	A	VL	H	CH	L	VH	BA	A	A	A
EF2	Cost	H	VH	CL	CL	VL	H	VH	L	CL	CL	CH	H	VH	A	CH
EF3	Benefit	BA	VL	BA	CL	AA	H	CL	A	AA	VL	AA	BA	CH	A	VL
EF4	Benefit	CH	CL	BA	CH	AA	H	CL	VL	BA	CH	L	VH	H	AA	BA
Expert 2																
SS1	Benefit	H	H	CH	BA	AA	CL	A	VH	CL	VH	CL	VL	VL	BA	CH
SS2	Benefit	H	BA	H	BA	CH	VL	H	L	VL	L	VL	VH	CL	VL	VL
SS3	Cost	VH	CH	CL	VL	VL	A	CL	L	VL	L	VL	VH	VL	H	VH
EC1	Cost	H	AA	VL	H	VH	VH	CL	VL	CH	VL	L	VH	CH	L	VL
EC2	Cost	AA	H	CH	L	VL	CL	L	A	BA	A	CL	AA	VL	A	BA
EC3	Benefit	AA	BA	VL	A	BA	CL	A	CH	H	AA	CH	CL	VH	CH	CL
EC4	Cost	AA	VH	VL	CL	AA	VH	BA	CL	VL	A	CL	VL	H	CL	VL
EI1	Cost	AA	H	AA	CH	VL	L	VH	AA	A	AA	A	VH	VL	A	VH
EI2	Benefit	VH	AA	CH	CL	A	CL	AA	AA	VH	CL	VH	VL	CL	L	BA
EI3	Cost	AA	VH	VH	L	AA	CH	CL	VH	A	CL	VL	BA	CH	H	AA
EI4	Cost	AA	VH	CL	VH	A	CL	VL	H	VL	CH	VL	AA	CL	VL	A
EF1	Cost	AA	A	CH	BA	CL	BA	CH	CL	A	BA	A	VL	AA	A	AA
EF2	Cost	AA	H	AA	CH	VL	CL	L	VL	CH	H	AA	CL	AA	VH	CL
EF3	Benefit	VH	AA	CH	CL	A	CL	VL	CH	CL	VL	A	CH	CL	H	H
EF4	Benefit	AA	VH	VH	L	AA	L	A	BA	AA	A	AA	CL	VL	BA	VH
Expert 3																
SS1	Benefit	A	H	VH	BA	AA	CL	A	VH	CL	VL	CH	CL	CH	H	VL
SS2	Benefit	A	VH	H	BA	CH	CL	H	VL	CL	CH	H	CL	CH	VH	H
SS3	Cost	VL	VH	CL	VL	VL	A	CL	L	CL	CH	VH	VH	A	A	H
EC1	Cost	AA	CL	VL	H	CH	CH	VL	CL	VH	A	A	BA	A	BA	AA
EC2	Cost	CH	VH	VH	VL	CL	VL	VL	A	BA	A	BA	H	VH	A	CH
EC3	Benefit	A	VL	L	A	AA	CL	A	CH	H	VH	A	CH	CL	A	CH
EC4	Cost	VL	VH	CL	VL	A	VH	BA	CL	VL	CH	A	VL	VH	BA	CL
EI1	Cost	AA	H	BA	CH	VL	CL	VH	BA	A	VH	VL	VH	CL	VH	BA
EI2	Benefit	L	AA	VH	CL	A	CL	VH	A	CH	CL	CH	A	CL	VH	A
EI3	Cost	VH	CH	CH	A	AA	CH	CL	VH	BA	CL	VL	CL	AA	BA	H
EI4	Cost	AA	CH	CL	H	BA	CL	VL	H	VL	A	BA	L	CL	L	BA

Table 4.7 (continued) : Decision matrix with respect to experts.

Expert 3																
EF1	Cost	L	A	AA	AA	VL	AA	CH	CL	VL	L	H	CH	H	H	H
EF2	Cost	CL	VL	A	VH	VL	BA	A	BA	A	VL	VL	CL	CH	L	AA
EF3	Benefit	BA	CH	VL	H	BA	VL	A	BA	H	A	AA	BA	VH	BA	CL
EF4	Benefit	VH	CL	A	AA	VH	A	L	L	BA	A	H	BA	H	VL	A

As a second step, constructed IVN decision matrix (D_j) is given in Table 4.8. We will only present the calculations of AL1 and AL15 in Table 4.8 and Table 4.9 because of the space constraints. The results of Steps 4 and 5 are given in Table 4.9.

Table 4.8 : Aggregated decision matrix.

Criteria		AL1	...	AL15
SS1	Benefit	<[0.88, 0.92], [0.44, 0.54], [0.32, 0.41]>	...	<[0.91, 0.97], [0.13, 0.23], [0.28, 0.51]>
SS2	Benefit	<[0.88, 0.92], [0.44, 0.54], [0.32, 0.41]>	...	<[0.65, 0.75], [0.2, 0.31], [0.58, 0.7]>
SS3	Cost	<[0.89, 0.93], [0.29, 0.4], [0.4, 0.51]>	...	<[0.91, 0.94], [0.34, 0.45], [0.31, 0.41]>
EC1	Cost	<[0.88, 0.93], [0.42, 0.52], [0.32, 0.42]>	...	<[0.76, 0.84], [0.28, 0.39], [0.35, 0.46]>
EC2	Cost	<[0.9, 0.96], [0.18, 0.29], [0.1, 0.28]>	...	<[0.84, 0.91], [0.35, 0.47], [0.27, 0.44]>
EC3	Benefit	<[0.83, 0.88], [0.52, 0.62], [0.4, 0.49]>	...	<[0.62, 0.81], [0.2, 0.32], [0.32, 0.52]>
EC4	Cost	<[0.82, 0.88], [0.44, 0.55], [0.45, 0.55]>	...	<[0.73, 0.82], [0.2, 0.3], [0.41, 0.53]>
EI1	Cost	<[0.88, 0.94], [0.25, 0.38], [0.17, 0.34]>	...	<[0.91, 0.95], [0.33, 0.44], [0.29, 0.39]>
EI2	Benefit	<[0.9, 0.94], [0.34, 0.45], [0.34, 0.44]>	...	<[0.79, 0.85], [0.47, 0.58], [0.48, 0.56]>
EI3	Cost	<[0.85, 0.9], [0.4, 0.51], [0.34, 0.44]>	...	<[0.85, 0.9], [0.43, 0.53], [0.33, 0.43]>
EI4	Cost	<[0.86, 0.91], [0.34, 0.45], [0.3, 0.4]>	...	<[0.84, 0.88], [0.49, 0.59], [0.36, 0.45]>
EF1	Cost	<[0.87, 0.94], [0.24, 0.36], [0.18, 0.36]>	...	<[0.84, 0.89], [0.51, 0.61], [0.37, 0.45]>
EF2	Cost	<[0.83, 0.88], [0.31, 0.43], [0.41, 0.52]>	...	<[0.68, 0.86], [0.14, 0.26], [0.21, 0.42]>
EF3	Benefit	<[0.9, 0.94], [0.36, 0.47], [0.34, 0.44]>	...	<[0.83, 0.89], [0.26, 0.37], [0.51, 0.63]>
EF4	Benefit	<[0.89, 0.95], [0.21, 0.32], [0.14, 0.3]>	...	<[0.9, 0.94], [0.38, 0.49], [0.33, 0.42]>

The calculations of Steps 7-9 are given in Table 4.10.

Table 4.9 : Results of steps 4 and 5.

		Average Solution (AV)		AL1	...	AL15		AL1	...	AL15
SS 1	Bene fit	<[0.77, 0.86], [0.29, 0.4], [0.39, 0.52]>	Positive distance from AV	<[0.05, 0.15], [-1.01, -0.77], [-1.3, -1.08]>	...	0	Negative distance from AV	0	...	<[0.08, 0.23], [-0.13, 0.25], [-1.15, -0.27]>
SS 2	Bene fit	<[0.77, 0.85], [0.28, 0.39], [0.4, 0.52]>		<[0.03, 0.08], [-0.46, -0.35], [-0.59, -0.49]>	...	0		0	...	<[-0.11, -0.08], [-0.23, 0.07], [0.1, 0.44]>
SS 3	Cost	<[0.74, 0.83], [0.28, 0.39], [0.45, 0.56]>		0	...	<[-0.5, 0.2], [0.38, 0.55], [-0.04, -0.42]>		<[-0.56, 0.18], [0.44, 0.44], [0.22, -0.31]>	...	<[0, 0], [0.22, 0.35], [0.34, 0.54]>
EC 1	Cost	<[0.79, 0.87], [0.26, 0.37], [0.37, 0.49]>		0	...	<[-0.51, 0.07], [0.4, 0.44], [0.02, -0.32]>		<[-0.37, 0.16], [0.26, 0.47], [0.08, -0.37]>	...	<[0, 0], [0.6, 0.71], [0.09, 0.3]>
EC 2	Cost	<[0.77, 0.85], [0.31, 0.42], [0.39, 0.51]>		0	...	<[-0.49, 0.15], [0.35, 0.58], [0, -0.39]>		<[-0.69, 0.21], [0.55, 0.77], [0.14, -0.57]>	...	<[0, 0], [0.54, 0.65], [0.14, 0.35]>
EC 3	Bene fit	<[0.79, 0.87], [0.33, 0.43], [0.38, 0.5]>		<[-0.04, 0.02], [-0.4, -0.29], [-0.54, -0.44]>	...	0		0	...	<[-0.16, -0.05], [0, 0.28], [-0.22, 0.23]>
EC 4	Cost	<[0.69, 0.8], [0.27, 0.38], [0.49, 0.61]>		0	...	<[-0.72, 0.06], [0.58, 0.45], [-0.1, -0.3]>		<[-0.41, 0.13], [0.28, 0.4], [0.19, -0.28]>	...	<[0, 0], [0.21, 0.33], [0.39, 0.59]>
EI 1	Cost	<[0.83, 0.88], [0.31, 0.42], [0.36, 0.47]>		0	...	<[-0.48, 0.19], [0.37, 0.53], [0.07, -0.42]>		<[-0.56, 0.18], [0.43, 0.66], [0.13, -0.47]>	...	<[0, 0], [0.38, 0.49], [0.49, 0.69]>
EI 2	Bene fit	<[0.74, 0.84], [0.26, 0.37], [0.39, 0.52]>		<[0.06, 0.1], [-0.54, -0.43], [-0.55, -0.44]>	...	0		0	...	<[-0.01, 0], [0.24, 0.44], [0.38, 0.69]>
EI 3	Cost	<[0.79, 0.87], [0.28, 0.39], [0.37, 0.49]>		0	...	<[-0.37, 0.14], [0.26, 0.48], [0.02, -0.37]>		<[-0.4, 0.14], [0.28, 0.47], [0.18, -0.35]>	...	<[0, 0], [0.49, 0.61], [0.6, 0.8]>
EI 4	Cost	<[0.73, 0.82], [0.31, 0.41], [0.44, 0.55]>		0	...	<[-0.35, 0.13], [0.23, 0.5], [-0.05, -0.39]>		<[-0.53, 0.17], [0.39, 0.58], [0.21, -0.45]>	...	<[0, 0], [0.29, 0.42], [0.34, 0.55]>
EF 1	Cost	<[0.8, 0.87], [0.34, 0.44], [0.34, 0.46]>		0	...	<[-0.3, 0.13], [0.18, 0.45], [0.03, -0.36]>		<[-0.61, 0.19], [0.47, 0.68], [0.1, -0.47]>	...	<[0, 0], [0.42, 0.53], [0.38, 0.59]>
EF 2	Cost	<[0.78, 0.87], [0.25, 0.36], [0.38, 0.51]>		<[-0.04, 0.02], [-0.58, -0.46], [-0.48, -0.36]>	...	0		0	...	<[-0.13, 0], [0.26, 0.49], [-0.49, 0]>
EF 3	Bene fit	<[0.77, 0.86], [0.31, 0.42], [0.39, 0.52]>		<[0.05, 0.09], [-0.58, -0.45], [-0.6, -0.48]>	...	0		0	...	<[-0.02, 0.02], [0.1, 0.34], [0.03, 0.4]>
EF 4	Bene fit	<[0.82, 0.88], [0.34, 0.44], [0.37, 0.49]>		<[0.01, 0.08], [-0.78, -0.65], [-0.85, -0.67]>	...	0		0	...	<[0.01, 0.05], [0.07, 0.32], [-0.21, 0.17]>

Table 4.10 : Neutrosophic results of the application.

	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8
<i>sp</i>	<[0.04, 0.33], [0, 0], [0, 0]>	<[-0.01, 0.29], [0, 0], [0, 0]>	<[0.09, 0.39], [0, 0], [0, 0]>	<[-0.55, -0.09], [0, 0], [0, 0]>	<[-0.24, 0.08], [0, 0], [0, 0]>	<[-3.54, -1.76], [0, 0], [0, 0]>	<[-0.3, -0.05], [0, 0], [0, 0]>	<[-0.06, 0.26], [0, 0], [0, 0]>
<i>nsp</i>	<[0.37, 2.72], [0, 0], [0, 0]>	<[-0.12, 2.4], [0, 0], [0, 0]>	<[0.78, 3.22], [0, 0], [0, 0]>	<[-4.52, -0.75], [0, 0], [0, 0]>	<[-1.95, 0.69], [0, 0], [0, 0]>	<[-29.19, -14.49], [0, 0], [0, 0]>	<[-2.46, -0.43], [0, 0], [0, 0]>	<[-0.46, 2.11], [0, 0], [0, 0]>
<i>np</i>	<[-4.22, 0.62], [0, 0], [0, 0]>	<[-5.44, 0.67], [0, 0], [0, 0]>	<[-6.23, 0.21], [0, 0], [0, 0]>	<[-4.38, 0.38], [0, 0], [0, 0]>	<[-4.52, 0.19], [0, 0], [0, 0]>	<[-5.09, 0.34], [0, 0], [0, 0]>	<[-5.31, 0.06], [0, 0], [0, 0]>	<[-4.01, 0.19], [0, 0], [0, 0]>
<i>nsn</i>	<[-4.07, 1.75], [1, 1], [1, 1]>	<[-5.53, 1.8], [1, 1.01], [1, 1]>	<[-6.47, 1.25], [1, 1], [1, 1]>	<[-4.25, 1.46], [1, 1], [1, 1]>	<[-4.42, 1.23], [1, 1], [1, 1]>	<[-5.11, 1.41], [1, 1], [1, 1]>	<[-5.37, 1.07], [1, 1], [1, 1]>	<[-3.8, 1.23], [1, 1], [1, 1]>
<i>as</i>	<[-1.85, 2.23], [0.5, 0.5], [0.5, 0.5]>	<[-2.82, 2.1], [0.5, 0.5], [0.5, 0.5]>	<[-2.85, 2.24], [0.5, 0.5], [0.5, 0.5]>	<[-4.38, 0.35], [0.5, 0.5], [0.5, 0.5]>	<[-3.18, 0.96], [0.5, 0.5], [0.5, 0.5]>	<[-17.15, -6.54], [0.5, 0.5], [0.5, 0.5]>	<[-3.92, 0.32], [0.5, 0.5], [0.5, 0.5]>	<[-2.13, 1.67], [0.5, 0.5], [0.5, 0.5]>
	AL9	AL10	AL11	AL12	AL13	AL14	AL15	
<i>sp</i>	<[-1.28, -0.44], [0, 0], [0, 0]>	<[-0.27, 0.1], [0, 0], [0, 0]>	<[-0.26, 0.27], [0, 0], [0, 0]>	<[-1.21, -0.39], [0, 0], [0, 0]>	<[-0.82, -0.08], [0, 0], [0, 0]>	<[-0.1, 0.21], [0, 0], [0, 0]>	<[-0.36, 0.19], [0, 0], [0, 0]>	
<i>nsp</i>	<[-10.53, - 3.66], [0, 0], [0, 0]>	<[-2.23, 0.81], [0, 0], [0, 0]>	<[-2.16, 2.19], [0, 0], [0, 0]>	<[-9.99, -3.18], [0, 0], [0, 0]>	<[-6.79, -0.64], [0, 0], [0, 0]>	<[-0.85, 1.71], [0, 0], [0, 0]>	<[-2.95, 1.59], [0, 0], [0, 0]>	
<i>np</i>	<[-5.25, 0.29], [0, 0], [0, 0]>	<[-3.78, 0.44], [0, 0], [0, 0]>	<[-4.25, 0.26], [0, 0], [0, 0]>	<[-5.15, 0.54], [0, 0], [0, 0]>	<[-4.8, 0.4], [0, 0], [0, 0]>	<[-3.63, 0.41], [0, 0], [0, 0]>	<[-3.56, 0.52], [0, 0], [0, 0]>	
<i>nsn</i>	<[-5.3, 1.35], [1, 1], [1, 1]>	<[-3.53, 1.52], [1, 1], [1, 1]>	<[-4.09, 1.31], [1, 1], [1, 1]>	<[-5.18, 1.65], [1, 1], [1, 1]>	<[-4.75, 1.47], [1, 1], [1, 1]>	<[-3.35, 1.49], [1, 1], [1, 1]>	<[-3.27, 1.62], [1, 1], [1, 1]>	
<i>as</i>	<[-7.92, -1.16], [0.5, 0.5], [0.5, 0.5]>	<[-2.88, 1.17], [0.5, 0.5], [0.5, 0.5]>	<[-3.13, 1.75], [0.5, 0.5], [0.5, 0.5]>	<[-7.59, -0.77], [0.5, 0.5], [0.5, 0.5]>	<[-5.77, 0.42], [0.5, 0.5], [0.5, 0.5]>	<[-2.1, 1.6], [0.5, 0.5], [0.5, 0.5]>	<[-3.11, 1.61], [0.5, 0.5], [0.5, 0.5]>	

We finally present the ranks and the deneutrosophicated appraisal scores of the alternatives in Table 4.11.

Table 4.11 : Deneutrosophicated appraisal scores and ranks of the alternatives.

	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9	AL10	AL11	AL12	AL13	AL14	AL15
$\$_{as}$	0.173	0.035	0.049	-0.38	-0.15	-2.83	-0.32	0.067	-1.01	-0.09	-0.05	-0.92	-0.54	0.062	-0.06
Rank	1	5	4	11	9	15	10	2	14	8	6	13	12	3	7

Through these calculations, *Poverty* (AL1), *Unemployment* (AL8), *Promote peaceful and inclusive societies* (AL14), *Promote healthy living* (AL3), and *Sustainable agriculture* (AL2) goals are determined as most important United Nations national sustainable development goals for Turkey, respectively. When we examined the results, it can be clearly seen that *Poverty* (AL1) is the most important issue and the government must take precautions and promote the investments to prevent and reduce it.

4.3.4 Sensitivity Analysis

Sensitivity analysis is conducted in order to measure the robustness of the results obtained from the applied method. The structure that we use for the sensitivity analysis is given in Table 4.12. By using this structure, the effects of the changes on alternative ranks are observed.

Table 4.12 : Developed pattern for the sensitivity analysis.

Pattern		Sets with respect to criteria			
		Set 1	Set 2	...	Set m
Test Variables	CLI	Ranks	...	...	Ranks
	LI	⋮	...	⋮	⋮
	AI	⋮	...	⋮	⋮
	HI	⋮	...	⋮	⋮
	CHI	Ranks	...	...	Ranks

The conducted sensitivity analysis is one-at-a-time sensitivity analysis and it has been applied for 75 cases which their results are given in Figure 4.2. For example, each linguistic term in test variables and its corresponding numerical value is assigned to SS1. Then, IVN-EDAS method's steps are re-run and ranks are re-determined. This procedure is applied to all sub-criteria.

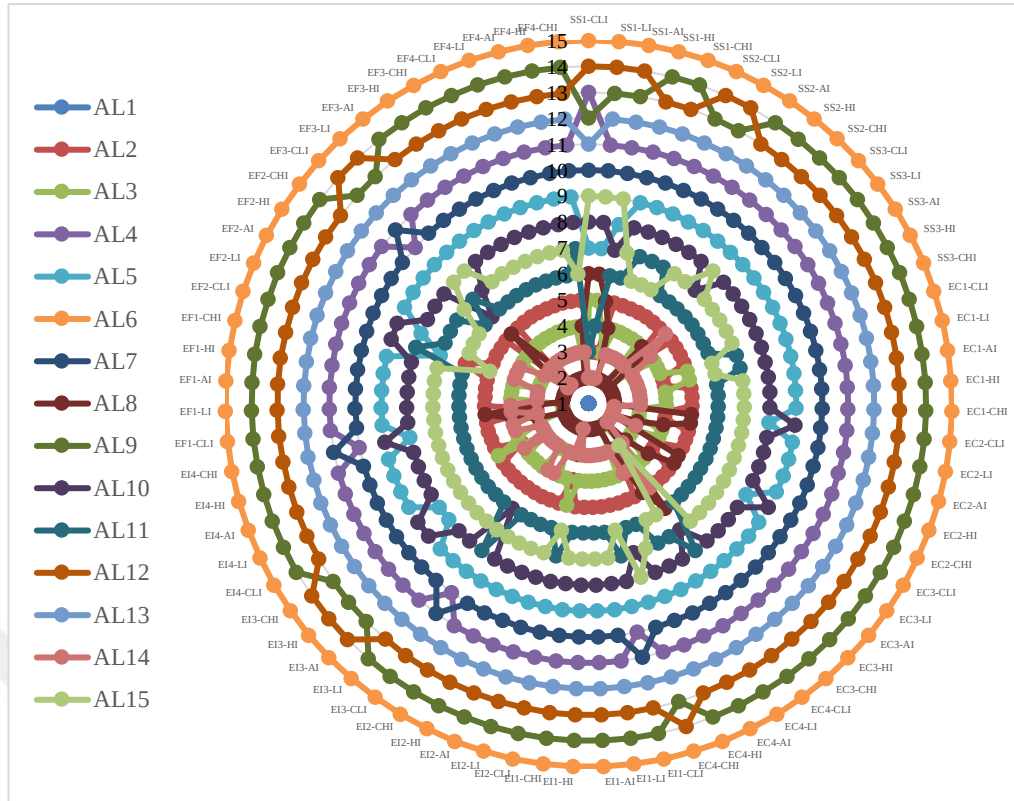


Figure 4.2 : Results of the sensitivity analysis.

When all the indicators are examined, it is seen that at certain intervals each criterion has an effect on the ranking of many alternatives and the appraisal scores of all the alternatives. When we increase or decrease the importance of the criterion, the order of a decreasing alternative does not increase, or order of an increasing alternative does not decrease. Also, the best alternative remained same in all tests. This concludes that our proposed method's decisions are robust.

4.3.5 Comparison with Intuitionistic Fuzzy TOPSIS

The proposed method is compared with the interval-valued intuitionistic fuzzy (IVIF) TOPSIS (Park et al., 2011). Before comparison, the scales that are used for IVN-EDAS are converted to intuitionistic fuzzy numbers form which are given in Tables 4.13 and 4.14. We simply remove the indeterminacy factor and take membership and non-membership functions as truth and falsity. All the expert opinions have no relativeness now.

Table 4.13 : Scale of weighting the criteria for IVIF TOPSIS.

Linguistic Term	IVIF number
Certainly Low Importance- CLI	$\langle [0, 0.15], [0.7, 0.85] \rangle$
Very Low Importance- VLI	$\langle [0.1, 0.25], [0.6, 0.75] \rangle$
Low Importance- LI	$\langle [0.2, 0.35], [0.5, 0.55] \rangle$
Below Average Importance- BAI	$\langle [0.3, 0.45], [0.4, 0.55] \rangle$
Average Importance- AI	$\langle [0.5, 0.5], [0.5, 0.5] \rangle$
Above Average Importance- AAI	$\langle [0.4, 0.55], [0.3, 0.45] \rangle$
High Importance- HI	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$
Very High Importance- VHI	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$
Certainly High Importance- CHI	$\langle [0.7, 0.85], [0, 0.15] \rangle$

Table 4.14 : Scale of scoring the alternatives for IVIF TOPSIS.

Linguistic Term	IVIF number
Certainly Low - CL	$\langle [0, 0.15], [0.7, 0.85] \rangle$
Very Low - VL	$\langle [0.1, 0.25], [0.6, 0.75] \rangle$
Low - L	$\langle [0.2, 0.35], [0.5, 0.55] \rangle$
Below Average - BA	$\langle [0.3, 0.45], [0.4, 0.55] \rangle$
Average - A	$\langle [0.5, 0.5], [0.5, 0.5] \rangle$
Above Average - AA	$\langle [0.4, 0.55], [0.3, 0.45] \rangle$
High - H	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$
Very High - VH	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$
Certainly High - CH	$\langle [0.7, 0.85], [0, 0.15] \rangle$

Table 4.15 shows the individual assessments of each decision maker transformed from IVN values to IVIF values together with the aggregated assessments for the criteria.

Table 4.15 : Aggregation of assessments of the criteria for IVIF TOPSIS.

	DM1	DM2	DM3	Aggregated
SS1	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$	$\langle [0.7, 0.85], [0, 0.15] \rangle$	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$	$\langle [0.638, 0.791], [0, 0.209] \rangle$
SS2	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.4, 0.55], [0.3, 0.45] \rangle$	$\langle [0.5, 0.5], [0.5, 0.5] \rangle$	$\langle [0.467, 0.539], [0.285, 0.415] \rangle$
SS3	$\langle [0.5, 0.5], [0.5, 0.5] \rangle$	$\langle [0.4, 0.55], [0.3, 0.45] \rangle$	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.467, 0.53], [0.339, 0.444] \rangle$
EC1	$\langle [0.7, 0.85], [0, 0.15] \rangle$	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$	$\langle [0.646, 0.798], [0, 0.202] \rangle$
EC2	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.7, 0.85], [0, 0.15] \rangle$	$\langle [0.595, 0.727], [0, 0.25] \rangle$
EC3	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$
EC4	$\langle [0.5, 0.5], [0.5, 0.5] \rangle$	$\langle [0.4, 0.55], [0.3, 0.45] \rangle$	$\langle [0.3, 0.45], [0.4, 0.55] \rangle$	$\langle [0.424, 0.507], [0.397, 0.493] \rangle$
EI1	$\langle [0.2, 0.35], [0.5, 0.55] \rangle$	$\langle [0.3, 0.45], [0.4, 0.55] \rangle$	$\langle [0.3, 0.45], [0.4, 0.55] \rangle$	$\langle [0.26, 0.41], [0.439, 0.55] \rangle$
EI2	$\langle [0.1, 0.25], [0.6, 0.75] \rangle$	$\langle [0.2, 0.35], [0.5, 0.55] \rangle$	$\langle [0.3, 0.45], [0.4, 0.55] \rangle$	$\langle [0.185, 0.336], [0.513, 0.627] \rangle$
EI3	$\langle [0, 0.15], [0.7, 0.85] \rangle$	$\langle [0.2, 0.35], [0.5, 0.55] \rangle$	$\langle [0.3, 0.45], [0.4, 0.55] \rangle$	$\langle [0.148, 0.3], [0.547, 0.66] \rangle$
EI4	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.3, 0.45], [0.4, 0.55] \rangle$	$\langle [0.5, 0.5], [0.5, 0.5] \rangle$	$\langle [0.438, 0.505], [0.315, 0.445] \rangle$
EF1	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.2, 0.35], [0.5, 0.55] \rangle$	$\langle [0.3, 0.45], [0.4, 0.55] \rangle$	$\langle [0.363, 0.464], [0.323, 0.455] \rangle$
EF2	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$	$\langle [0.7, 0.85], [0, 0.15] \rangle$	$\langle [0.626, 0.778], [0, 0.222] \rangle$
EF3	$\langle [0.2, 0.35], [0.5, 0.55] \rangle$	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$	$\langle [0.421, 0.541], [0.251, 0.392] \rangle$
EF4	$\langle [0.4, 0.55], [0.3, 0.45] \rangle$	$\langle [0.5, 0.55], [0.2, 0.35] \rangle$	$\langle [0.6, 0.75], [0.1, 0.25] \rangle$	$\langle [0.487, 0.607], [0.202, 0.36] \rangle$

After the calculations, results of the IVIF TOPSIS are given in Table 4.16.

Table 4.16 : Results of the IVIF TOPSIS.

	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9	AL10	AL11	AL12	AL13	AL14	AL15
s_j^*	2.611	3.402	1.664	2.791	1.685	3.379	2.133	1.726	2.02	2.442	2.26	3.1	3.236	2.4529	3.123
s_j^-	2.599	1.809	3.547	2.42	3.526	1.833	3.078	3.485	3.19	2.768	2.95	2.11	1.974	2.7582	2.087
cc_j	0.498	0.347	0.681	0.464	0.677	0.352	0.591	0.669	0.61	0.531	0.57	0.4	0.378	0.5293	0.401
Rank	9	15	1	10	2	14	5	3	4	7	6	11	13	8	12

The results demonstrate that AL1, AL2 and AL14 no longer one of the best goals and the best goal is AL3. Since the effects of indeterminacy are no longer available, this changes the results.

4.4 Conclusion

EDAS has been extensively used for MCDM problems in the literature for 2 years. Intuitionistic and type-2 fuzzy extensions of this method have been successfully applied to the solutions of various decision-making problems. However, these extensions do not consider the indeterminacy degree of experts. In this study, an IVN-EDAS method is proposed and applied to the prioritization of the United Nations national sustainable development goals. The importance of the criteria is aggregated by using aggregation operator and the scores of the alternatives with respect to these criteria based on experts' opinions by using IVN-EDAS. According to obtained results from the proposed method, *Poverty* (AL1), *Unemployment* (AL8), *Promote peaceful and inclusive societies* (AL14), *Promote healthy living* (AL3), and *Sustainable agriculture* (AL2) goals are determined as most important United Nations national sustainable development goals for Turkey, respectively. The conducted sensitivity analysis demonstrates that proposed method is robust and reacts all alterations in the criteria weights. Also, the comparative analysis shows that indeterminacy is a very important factor and when it is dismissed, the results considerably change. This condition reveals that the neutrosophic sets are very useful for the environment where indeterminacy and hesitancy are at excessive levels.

For further research, the other types of neutrosophic sets such as, simplified neutrosophic sets, triangular neutrosophic sets, or trapezoidal neutrosophic sets can be used instead of interval-valued neutrosophic sets in the developed neutrosophic EDAS method. Also, the proposed deneutrosophication technique and the subtraction operation can be extended other types of neutrosophic sets. Other extensions of ordinary fuzzy sets such as type-2 fuzzy sets, hesitant fuzzy sets, Pythagorean fuzzy sets, and orthopair fuzzy sets can be replaced with neutrosophic sets for comparative purposes.

5 CONCLUSION AND FURTHER WORK SUGGESTIONS

Multi-criteria decision-making (MCDM) methods are decision-making techniques that are widely used in the literature and can be diversified according to deterministic, stochastic, and probabilistic data types. The concept may involve several main criteria and sub-criteria which some of which are tangible or intangible. These criteria can be represented by a hierarchical structure indicating the relationships between them. Alternatives are the other components of the concept, which are solution opportunities for the addressed problem. Through that, experts or decision-makers evaluate the alternatives with respect to criteria to find the most appropriate solution. But, based on the complexity of the constructed decision-making structure and uncertainties in the available data, ordinary MCDM methods may be inefficient to represent the input data in their mathematical operations. Therefore, in this thesis, we aim to extend multi-criteria decision-making problems to offer applicable methodologies, which generate meaningful solutions, for the decision-making area by involving types of uncertainties based on the available data. Through that, three novel methodologies are introduced to the literature.

The first paper is introduced an integrated interval-valued intuitionistic fuzzy DEcision MAKing Trial and Evaluation Laboratory (DEMATEL)- Analytical Network Process (ANP)- Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodology presented in Section 2. The proposed methodology applied to a real-case study considering freight village location selection. First, the extended DEMATEL technique is used to determine the relationship between the evaluation criteria. Then, based on the relationship matrix, the network of the criteria is constructed. A supermatrix is constructed after calculating the local weights of the criteria by using the pairwise comparison matrices. Finally, the convergence of the normalized supermatrix, the limit matrix is obtained, and the final weights of the criteria are determined. Then, freight village location alternatives in Istanbul are evaluated by using the extended TOPSIS method. Finally, the results are analyzed by applying comparative analyses to yield the methodology's verification and validation.

Comparative analysis is carried out by considering the ordinary Simple Additive Weighting (SAW) method's results.

The second paper consists of a novel interval-valued Pythagorean fuzzy Analytical Hierarchy Process (AHP) method presented in Section 3. The proposed method is used in a real-case study evaluating landfill site selection. First, the method's inputs are gathered using a scale consisting of linguistic terms and their corresponding interval-valued Pythagorean fuzzy numbers. Next, the developed method is applied to a landfill site selection problem for Istanbul. Finally, the results are analyzed by applying both sensitivity and comparison analyses for verification and validation. The sensitivity analysis is carried out by considering a one-at-a-time concept based on the different simulations. Comparison analyses are conducted by using the results of the ordinary fuzzy AHP and interval-valued intuitionistic fuzzy AHP methods.

The third paper consists of a novel interval-valued neutrosophic EDAS method presented in Section 4. The proposed method is applied to prioritize the United Nations' national sustainable development goals. First, the method considers a scale, which consists of linguistic terms and corresponded interval-valued neutrosophic numbers. Then the proposed method is applied to prioritize the United Nations national sustainable development goals for the Turkey case by using three experts evaluations. Finally, the results are analyzed by applying both sensitivity and comparison analyses for verification and validation. The sensitivity analysis is carried out by considering a one-at-a-time concept based on the different simulations. Comparison analysis is conducted by using the results of the interval-valued intuitionistic fuzzy TOPSIS.

Therefore, novel fuzzy multi-criteria decision-making methods are introduced to the literature and then applied to real case studies to offer a meaningful solution for the problem, which aims to show the proposed methodologies' applicability. Then the results are analyzed by using sensitivity and comparison analyses to validate and verify the proposed methodologies. As a result, we believe that the proposed methodologies can be efficient decision-making tools for the different application areas that involve uncertainty. Through that, managers or researchers can use them to generate meaningful and applicable solutions for their problems. Furthermore, for further problems, the proposed techniques can be applied to situations where to prioritize innovative technologies such as unmanned aerial vehicles' technology selection and

risk analyses of the emerged systems such as autonomous vehicle driving systems risk assessments.

Based on the above conclusions, following suggestions and implications can be stated:

For constructing the scales (in each method of the three papers), computing with words concept is used. Computing with Words (CWW), a concept that is used to operate the data defined with natural language to represent the uncertainty of human-based knowledge, is introduced by Zadeh (Zadeh, 1999). In this concept, the linguistic terms are used to label the natural language in a dataset, which may contain imprecise, indeterminant, incomplete information with hesitant thoughts (Nguyen et al., 2014). In our proposed methodologies, experts are both imprecise and at a level of indeterminant while evaluating the system. Moreover, since some part of the evaluations is fully dependable on subjective information gathering impeccable data, which is precise and complete with no indeterminacy, is not possible. Thus, linguistic scales for each applied method are constructed, which aims to deal with the mentioned situations during the evaluations. There are three main components during the scale construction: the lowest linguistic term, mid-one, and highest linguistic term with corresponding fuzzy concepts and their numbers. Based on the discussions, intermediate linguistic terms are also determined to provide a large domain area for the evaluations. In the determination of the neutrosophic numbers, it is observed that experts have difficulty while assigning the intermediate linguistic terms. The reason for it can be explained as follows: Consider a chart that belongs to a population with normal distribution. Most of the values are spread around the average value, and as it gets closer to the smallest and largest values, the number of values that can be assigned or that exist are decreased. Therefore, for an expert who wants to assign a value that is close to the average one, many values can be picked from the poll. Similar to that, for an evaluation, which is the highest rate, there are only a few possible choices. Therefore, in our scale for the neutrosophic sets, the indeterminacy value is increased when the linguistic terms are close to the average value.

For such a complex decision-making structure that we used in Section 2, one of the most crucial assumptions is considering the system based on dependent criteria with each other, or the criteria have no dependency, which means no effect on one to another. Again, for such a complex decision-making structure that is given in Section 2, considering the criteria have no dependency between each other is unrealistic and

does not reflect the system characteristics well. Through that, to reveal the relation between the criteria, applying a systematic, quantitative approach promises meaningful outcomes, which improves the results of the application. In our application, the intuitionistic fuzzy DEMATEL approach has been conducted for this phase to determine the relationships among the criteria.

Another essential step for an assessment problem is to determine the weights of the evaluation criteria. Since the considered structure can be network-based as in Section 2 or hierarcycal as in Section 3, the ANP and AHP methods are extended with intuitionistic and Pythagorean fuzzy sets for the calculations, respectively. The most challenging phase of the both method is collecting the data, which is gathered by the experts' evaluations of the pairwise comparison matrices. The difficulty for this phase is ensuring consistency, which is proof of the validation of the evaluations. Moreover, when the dimension of the comparison matrix is increased, the consistency condition becomes difficult to maintain. Since the most advantageous side of ANP/AHP is dividing the whole problem into sub-problems, we offer the researcher/managers that dividing the considered problem into sub-problems as much as possible.

Since the most important objective for a methodology is to provide a meaningful result, applied techniques should reflect the aim of the target. When the literature is examined, one of the most efficient techniques for a ranking problem is distance-based assessment. But, the disadvantage of this method is that may occur a deviation in one indicator in the ideal solution powerfully affects the results. In our thesis, TOPSIS method extended with intuitionistic fuzzy sets and EDAS method extended with neutrosophic sets have been applied for the solutions.

For further works, since the proposed techniques' applicability and sensitivity are proven by the sensitivity and comparative analyses, they can be applied different decision-making problems to obtain useful solutions.

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