ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

GIS-BASED MULTI-CRITERIA DECISION ANALYSIS FOR OPTIMAL URBAN EMERGENCY FACILITY PLANNING

Ph.D. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

KENTSEL OPTİMAL ACİL DURUM TESİS PLANLAMASI İÇİN CBS TABANLI ÇOK KRİTERLİ KARAR ANALİZİ

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Penjani Hopkins NYIMBILI, a Ph.D. student of ITU Graduate School student ID 501172611, successfully defended the thesis entitled “GIS-BASED MULTI-CRITERIA DECISION ANALYSIS FOR OPTIMAL URBAN EMERGENCY FACILITY PLANNING”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family and friends,

FOREWORD

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To the rest of my remaining siblings, Dr Sulani NYIMBILI, Kelvin NYIMBILI and Kajipande NYIMBILI, may our Lord continue to guide, bless and sustain us in every area of our lives to achieve success and a long, healthy and joyful life ahead.

October 2022 Penjani Hopkins NYIMBILI
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ABBREVIATIONS

AHP : Analytical Hierarchy Process
ANOVA : Analysis Of Variance
BWM : Best-Worst Method
CI : Consistency Index
CR : Consistency Ratio
DEM : Disaster and Emergency Management
DEMATEL : Decision Making Trial and Evaluation Laboratory
DEF : Distance from Existing Fire Stations
DER : Distance to Earthquake Risk
DHM : Density of Hazardous Materials
DRR : Disaster Risk Reduction
EHM : Earthquake Hazard Map
EM-DAT : Emergency Events Database
FAHP : Fuzzy Analytical Hierarchy Process
GDM : Group Decision-Making
GIS : Geographic Information System
HAZTURK : Hazards Turkey
HPD : High Population Density
IMM : Istanbul Metropolitan Municipality
MADM : Multiple Attribute Decision-Making
MAGDM : Multiple Attribute Group Decision-Making
MCDA/M : Multi-Criteria Decision Analysis/Making
NFPA : National Fire Protection Association
PMR : Proximity to Main Roads
SA : Sensitivity Analysis
SDGs : Sustainable Development Goals
RI : Random Consistency Index
TUIK : Turkish Statistical Institute
UNISDR : United Nations International Strategy for Disaster Reduction
WBD : Wooden Building Density

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SUMMARY

The growing scale of urban fire risks especially in megacities of the world such as Istanbul in Turkey arises largely as a result of the confluence of varied contemporary developmental and demographic trends that include accelerated urbanization, rising urban population, and migration to cities and socio-economic factors such as inequalities. Increasing urban development pressure brings about an expansion in built-up and urban settlement areas, often without adequate and comprehensive urban planning policies and regulations. As a result of increased human activities and interactions, these places are increasingly exposed to fire risk. To improve decision-making, a better comprehension of these relationships and interconnections as part of the complexities of human systems and urban dynamics functioning across different levels, actors, stakeholders, sectors, and disciplines is needed to mitigate fire hazard risk in urban populations. Therefore, recent advances in geospatial sciences have prompted emergency planners and managers to demand vast volumes of geographical data in order to make complex decisions. Diverse stakeholders, multidisciplinary teams, and multiple criteria are all involved in making these complex decision-making procedures. GIS-based Multi-Criteria Decision-Analysis (MCDA) strategies can be used to improve the quality of decision-making by merging spatial data and value judgments to tackle such complex planning issues, which is the fundamental strength of using this approach. In this context, fire risk and emergency planning at the spatial scale of the urban environment is a complicated and interrelated decision-making process requiring many factors and transdisciplinary stakeholder interaction.

In this PhD thesis, GIS-based MCDA methods are applied to integrate the decision-makers' preferences with regard to solving such emergency planning problems of mitigating fire impacts and response action improvement by the optimization of new urban emergency and fire station site selection for the case of Istanbul province.

The main aim of this thesis is therefore to develop an integrated GIS and MCDA model for effectively planning new urban emergency and fire facilities in Istanbul province, to reduce the fire response times to within five minutes. In order to achieve the main objective, there are ten (10) sub-objectives namely: using MCDA methods such as fuzzy AHP, Entropy-AHP, Best-Worst Method (BWM) and Decision Making Trial and Evaluation Laboratory (DEMATEL) for model construction, comparison and validation of resultant weights; determination of influencing criteria for effective urban emergency facility planning; utilizing the *Delphi* technique to conduct surveys to capture the preferences of decision-makers (DMs), evaluation of the criteria weights based on pairwise comparisons from relevant experts/DMs using the GIS-based MCDA approaches; identification of the most essential criteria for urban emergency facility site selection from the experts' judgements; using GIS to process, analyse and produce raster suitability maps that identify the most viable areas for locating new urban emergency facilities; prioritization of proposed new fire and urban emergency facilities (from low to high) for planning their construction in a phased manner based on cost and resource limitations; comparison analysis of distinct opinions and preferences of two DM groups in the group decision-making (GDM) process, comprising of fire brigade employees and academic/professional experts; using GIS capabilities to conduct a *sensitivity analysis* (SA) to test the sensitivity and robustness of the constructed models based on the combination of criteria weights; investigation of the interdependencies and levels of interaction among the various criteria employed in the MCDA modelling process.

The thesis is, thus, comprised of three (3) papers addressing these ten sub-objectives. Istanbul province is determined as the case study area and six influencing criteria are identified with their respective weights evaluated, for each paper.

In the first paper, a hybrid model of the recently developed BWM integrated with GIS is proposed. In the study, a GDM framework is suggested to support the incorporation of divergent views of two DM groups consisting of academicians and fire brigade practitioners for the emergency facility planning decision problem. Meaningful inferences from the study are made from statistical tests such as *one-sample t-test*, *one-way ANOVA* and *Tukey's HSD test* to analyse the preferences of the expert groups. Further, in this research, a degree of consensus or reliability in the DM process is assessed by a statistical measure called *Kendall's coefficient of concordance, W*. According to the study, it is revealed that the density of hazardous materials (DHM) and high population density (HPD) are perceived to be the most important by the academician and fire brigade practitioner DM group, respectively. For both DM groups, the distance from earthquake risk (DER) is viewed to be the least important. Resultant raster suitability maps for both DM groups are produced for visualizing the BWM model.

In the second paper, the combination of AHP and Entropy methods with GIS is used for evaluating criteria weights both subjectively and objectively. In the study, the validation of the AHP-Entropy model is carried out on the criteria with the strongest influence on the decision outcome and spatially visualized using the *One-At-a-Time* (OAT) *Sensitivity Analysis* (SA) method. The study concludes that 28.1% of the case study area, or a third of the total area, is likely to be exposed to the risk of urban fires, necessitating the urgent planning of new urban emergency facilities to ensure adequate fire service coverage and protection.

In the third paper, an integrated approach using fuzzy AHP based on a triangular membership function and GIS is implemented. For this case, the resultant fuzzy AHP weights are obtained from surveys of 19 experts and are validated using another MCDA technique, called BWM. Research results identified the most significant criteria in urban fire station site selection as the density of hazardous material facilities (DHM), a high population density (HPD) and proximity to main roads (PMR) with corresponding weights of 33.3%, 24.4% and 15.2%, respectively. By a thorough analysis of the results, a total of 34 new urban fire stations were proposed in addition to the existing 121 fire stations for addressing the increasing demands of fire protection services by minimizing the response time to less than 5 minutes. In addition, a three-level prioritization analysis from low to high was performed on the 34 proposed fire stations to plan their construction in phases based on cost and resource availability.

Finally, the DEMATEL method is applied to examine the complex interrelationships and levels of influence among the criteria previously determined for optimally selecting new urban infrastructure for fire and emergency services in Istanbul as well as for model results validation of the BWM, AHP-Entropy and fuzzy AHP techniques applied. In this research, useful insights are generated by constructing an intelligible structural model visually in form of a *digraph* involving analysis of causal relationships among criteria and their directional influences as well as corresponding degrees of strength. The findings reveal that the high population density (HPD) is the most critical criterion followed by the density of hazardous materials (DHM) criterion in effectively planning new urban facilities for fire and emergency services and thus significantly influence and impact all the other criteria, while the distance to earthquake risk (DER) criterion does not influence any other criteria and consequently not essential in the planning procedure. The DEMATEL model results are used to validate the BWM, AHP-Entropy and fuzzy AHP model results in terms of levels of criteria significance and are therefore shown to be in high correlation. In this regard, these contextual relationships established from this research contribute toward an integrated fire risk mitigation policy formulation for planning new emergency facilities in urban environments through the engagement of all decision-makers across various backgrounds and disciplines.

KENTSEL OPTİMAL ACİL DURUM TESİS PLANLAMASI İÇİN CBS TABANLI ÇOK KRİTERLİ KARAR ANALİZİ

ÖZET

Hızla büyüyen kentsel çevrelerin artan karmaşıklığı, sosyo-ekonomik ve politik sistemlerin etkileşimi, sürdürülebilir risk yönetimi planlama stratejilerinin küresel aciliyetini ortaya koymakta, bu aciliyet, kentsel yangın riskini azaltma faaliyetleri için kapsamlı bir şekilde, dünya çapında yangına eğilimli, İstanbul gibi mega kentlerin birçoğunda giderek daha belirgin hale gelmektedir. İstanbul'da kaydedilen ve son zamanlarda artış gösteren itfai olaylar, büyük ölçüde enerji tüketimi ve insan faaliyetlerinden kaynaklanmakta, itfai olaylara müdahale süreleri uluslararası bir standart olan beş dakikanın üzerine çıkmakta, mevcut yangın riski göz önüne alındığında, ek kentsel yangın acil durum tesislerine olan acil ihtiyacın altı çizilmektedir.

2005 yılında yürürlüğe giren Hyogo Eylem Çerçevesi (2005-2015), afet riskinin azaltılması (DRR) ile sürdürülebilir kalkınma arasında kurulmuş bağlantıyı tanımlamaktadır. Afet risk azaltma stratejisi bu çerçevede sürdürülebilir kalkınmayı her düzeyde etkileyen sektörler arası bir aciliyet sorunu olarak kabul edilmektedir. Geniş anlamda, 2000 yılında Birleşmiş Milletler Binyıl Zirvesi'nden ortaya koyulan Binyıl Kalkınma Hedefleri, kentsel ortamlarda güvenliğin (yangın risklerine ve afetlere karşı korumayı içeren) önemini kabul etmektedir. Sürdürülebilir Kalkınma Hedefleri'nin (SKH'ler) 11. Hedefi, Sendai 2015-2030 Afet Riskini Azaltma Çerçevesine uygun olarak kapsamlı afet risk yönetimi için birleşik çok seviyeli planlama stratejileri oluşturarak şehirleri ve insan yerleşimlerini daha adil, güvenli, dayanıklı ve sürdürülebilir hale getirmeyi amaçlamaktadır. Sendai Çerçevesi, riskler ve tehlikeler yelpazesiyle bağlantılı daha kapsamlı sorunlarla başa çıkmak için Hyogo Eylem Çerçevesi'nin yerine geçen mekanizma olarak 2015 yılında tüm dünyadaki hükümetler tarafından onaylanmıştır. Hükümetler ve vatandaşlar gibi ilgili paydaşlar için ilgili teknolojik tehlikeleri ve yangınlar gibi riskleri azaltmak amacıyla politika yönü konusunda netlik sağlamaktadır. Sendai Çerçevesi, 2030 Sürdürülebilir Kalkınma Gündemi, Paris Anlaşması, Yeni Kentsel Gündem, Addis Ababa Eylem Gündemi ve İnsanlık Gündemi için afet riskinin azaltılması ve dayanıklılığın artırılması arasındaki bağlantıyı mantıksal olarak formüle etmek açısından bağlantı dokusunu oluşturmaktadır.

Bu açıdan bakıldığında, kentsel çevrenin mekansal ölçeğinde yangın risk ve acil durum planlaması, birçok faktör ve disiplinler arası paydaş etkileşimi gerektiren birbiriyle bağlantılı ve karmaşık bir karar verme süreci olmaktadır. Kentsel acil durum planlaması ve yangın riskinin azaltılması bağlamında, bu tez çalışması kapsamında, İstanbul, Türkiye'deki yeni kentsel yangın ve acil durum tesislerinin optimal planlaması için CBS tabanlı Çok Kriterli Karar Analizi (ÇKKA) tekniklerinin uygulanması önerilmektedir. İtfaiye, tıp, polis ve ambulans hizmetleri gibi kentsel acil durum hizmetlerinin dağıtımı, dikkatli tasarım ve yerleşim değerlendirmelerini gerektirmektedir. Deprem, sel ve toprak kayması gibi büyük afet ve krizlerde bu itfaiye

istasyonları aynı zamanda acil tıbbi iletişim ve bölge/bölge kontrol merkezi olarak da hizmet vermektedir. Sonuç olarak, bu tesislerin nereye kurulacağına karar vermek, uzmanların, karar vericilerin, idarenin ve acil müdahale personelinin yanı sıra karardan etkilenen yerel halk gibi diğer paydaşların işbirliğini gerektirmektedir. Bu nedenle, bu tezin temel amacı, İstanbul ilinde yeni kentsel acil durum ve yangın tesislerinin etkin bir şekilde planlanması için entegre bir CBS ve ÇKKA modeli geliştirmek, yangına müdahale sürelerini uluslararası standart olan beş dakikaya indirmektir.

Ana amaca ulaşmak için on (10) alt amaç belirlenmiştir:

- Model için bulanık AHP, Entropi-AHP, En İyi-En Kötü Yöntemi (BWM) ve Karar Verme Deneme ve Değerlendirme Laboratuvarı (DEMATEL) gibi ÇKKA yöntemlerini kullanmak, sonuç ağırlıklarının oluşturulması, karşılaştırılması ve doğrulanması;
- Etkili kentsel acil durum tesisi planlaması için ilgili kriterlerin belirlenmesi;
- Karar vericilerin (DM'ler) tercihlerini saptamak amacıyla Delphi tekniğininin kullanılması;
- CBS tabanlı ÇKKA yaklaşımlarını kullanarak ilgili uzmanların/DM'lerin ikili karşılaştırmalara dayalı olarak kriter ağırlıklarının değerlendirilmesi;
- Uzmanların yargılarından kentsel acil durum tesisi yeri seçimi için en temel kriterlerin belirlenmesi;
- Yeni kentsel acil durum tesislerinin planlanması amacıyla en uygun alanları belirleyen raster uygunluk haritalarının işlenmesi, analiz edilmesi ve üretimi için CBS'nin kullanılması;
- Maliyet ve kaynak sınırlamalarına dayalı olarak aşamalı bir şekilde acil durum tesislerinin inşa önceliklerini planlamak için önerilen yeni yangın ve kentsel acil durum tesislerinin (düşükten yükseğe) önceliklendirilmesi;
- İtfaiye çalışanları ve akademik/profesyonel uzmanlardan oluşan grup karar verme (GDM) sürecinde iki karar verici grubun farklı görüş ve tercihlerinin karşılaştırmalı analizi;
- Kriter ağırlıklarının kombinasyonuna dayalı olarak oluşturulmuş modellerin duyarlılığını ve sağlamlığını test etmek amacıyla duyarlılık analizlerinin (SA) yapılandırılması için CBS yeteneklerinin kullanılması;
- ÇKKA modelleme sürecinde kullanılan çeşitli kriterler arasındaki karşılıklı bağımlılıkların ve etkileşim seviyelerinin araştırılması.

Bu nedenle tez, bu on alt amacı ele alan üç (3) uluslararası makaleden oluşmaktadır. İstanbul ili, yaklaşık 960 mahalleden oluşan pilot alan olarak belirlenmiştir. Her bir makale için altı etki kriteri dikkate alınarak bu kriterlerin ağırlıkları saptanmıştır. Literatür tavsiyelerine ve uzman geri bildirimlerine dayanarak, yeni kentsel acil durum tesislerinin kapsamlı bir şekilde planlanması için bu en etkili altı kriter, kapsamlı bir tarama prosedürü sonuncunda seçilmiştir. Belirlenen kriterler sosyal boyutlarla, yerleşiklik, erişilebilirlik, risk ve güvenlik boyutlarını kapsamaktadır. Yüksek nüfus yoğunluğu (YNY), yangınların yoğun nüfuslu kentsel topluluk alanlarında meydana gelme olasılığının daha yüksek olması ve daha büyük bir yangın riski potansiyeli ve etkisi ile sonuçlanması nedeniyle dikkate alınması gereken ana faktörlerden biri olmaktadır. Bu durum, özellikle aşırı kalabalık yerleşim yerlerinde topluluklar tarafından güvenli olmayan elektrik, gaz vb. kullanımların artmasını sonuçlamakta, yangınlarla mücadelede anlık müdalaleleri zora sokmaktadır. Ahşap yapı yoğunluğu (ABY) kriteri, İstanbul kentinin Bizans döneminden beri zengin bir kültürel mirasa sahip olması ve yangın ve büyük kentsel yangınların yayılma riskini önemli ölçüde artıran eski ahşap yapı mimarisinden oluşması nedeniyle dikkate alınmaktadır. Ahşap bina envanteri yoğunluğunun yüksek olduğu yerleşim bölgelerinde, kentsel yangın riski potansiyeli daha yüksek olmakta, bu nedenle bu yerlerde yangın ve acil durum tesislerinin inşa edilmesine öncelik verilmesi gerekmektedir. Optimizasyonu sağlamak ve hizmet kapsama alanlarının çakışmasını önlemek için yeni kentsel acil durum tesislerinin mevcut acil durum ve yangın tesislerinden uzakta planlanması gerektiğinden, mevcut itfaiye istasyonlarından uzaklık (İİU) kriteri de dikkate alınmaktadır. Ana yol ağlarındaki sürüş süresi, topoloji ve karayolu trafik koşulları dikkate alınarak yeni hizmet alanı analizinde beş (5) dakikalık bir yangına müdahale süresi dikkate alınmaktadır. Kentsel alanlarda, özellikle sıkışık/yoğun merkezî iş bölgelerinde ve kötü planlanmış şehir altyapısına sahip yüksek bina yoğunluklu alanlarda, dar yollar itfaiye araçları ve yangınla mücadele ekipmanlarının erişimini sınırlamaktadır. Bu senaryo yangın riskini önemli ölçüde artırmakta ve acil müdahale sürelerinde gecikmelerle kurtarma ve tahliye çabalarını engellemektedir. Bu nedenle, ana yollara yakınlık (AYY) kriteri de modele dahil edilmiştir. Bu bağlamda, itfai olaylara daha kolay, etkin erişim sağlamak ve acil müdahale sürelerini iyileştirmek için yeni kentsel acil durum tesisleri ana karayolu ulaşım ağlarının yakınında, kalabalık alanlardan arındırılmış şekilde yerleştirilmelidir. İtfai olayların ana kaynaklarından biri, petrol ve gaz rafinerileri, petrol ve sıkıştırılmış gazlardan oluşan endüstriyel depo tesisleri kaynaklı yüksek derecede yanıcı olan kimyasal döküntüler olmakta, büyük alevlerin, patlamaların oluşmasıyla birlikte yangının yayılma riski artmaktadır. Bu nedenle, yüksek yoğunluklu tehlikeli madde içeren bu yüksek yangın riski alanlarında, dikkate alınması gereken kriterlerden biri olarak yeni acil durum tesislerine öncelik verilmelidir. İstanbul'un ağırlıklı olarak yoğun yerleşimli bina stoğundan oluşan büyük metropol alanı, kentin deprem risk bölgesinde yer alması nedeniyle tarihsel olarak deprem sonrasında çıkan yangınlardan kaynaklanan büyük itfai olaylara maruz kalmıştır. Bu nedenle, yeni kentsel acil durum tesisleri planlanırken İstanbul içinde yüksek sismik kapasiteye sahip bölgelerden kaçınılmakta, bu yüksek riskli alanlardan daha uzak yerler daha fazla tercih edilmekte, bu nedenle deprem riskine uzaklık (DER) kriteri dikkate alınmaktadır. Ayrıca, bir deprem sırasında iletişim ve karayolu ulaşım yollarının zarar görmesi itfaiye ve acil durum araçlarının acil durum bölgelerine erişimini engelleyecektir. Bu kriterlerin belirlenmesinden sonra, girdi kriter verileri işlenmekte ve 50 × 50 m^2 uzaysal hücre boyutu çözünürlüğünde ESRI ArcGIS 10.3 yazılımı kullanılarak vektör ve raster kriter harita katmanları şeklinde her bir alt bölge düzeyinde analiz edilmektedir. Ana CBS analizleri, her bir çalışma durumu için ön işleme, yeniden sınıflandırma ve ağırlıklı toplam bindirme işlemlerinden oluşmaktadır.

İlk makalede, yakın zamanda geliştirilen BWM'nin CBS ile entegre edilmiş bir hibrit modeli önerilmiştir. Çalışmada, acil durum tesis planlama karar problemi için akademisyenler ve itfaiye personelinden oluşan iki karar verici grubunun farklı görüşlerinin birleştirilmesini desteklemek için bir karar verme çerçevesi önerilmektedir. Uzman gruplarının tercihlerini analiz etmek için tek örneklem t testi, tek yönlü ANOVA ve Tukey HSD testi gibi istatistiksel testler uygulanarak çalışmadan anlamlı çıkarımlar yapılmıştır. Ayrıca, bu araştırmada, karar verme sürecinde bir dereceye kadar fikir birliği veya güvenilirlik, Kendall'ın uyum katsayısı, W olarak adlandırılan istatistiksel bir ölçü ile değerlendirilmektedir. Çalışmaya göre, TMD ve YNY'nin en önemli kriterler olarak algılandığı ortaya çıkmıştır. Her iki karar verici grubu için de DER en az önemli olarak görülmektedir. BWM modelini görselleştirmek için her iki karar verici grubu için elde edilen raster uygunluk haritaları üretilmektedir.

İkinci makalede, kriter ağırlıklarının hem öznel, hem de nesnel olarak değerlendirilmesi için AHP ve Entropi yöntemlerinin CBS ile kombinasyonu kullanılmıştır. Çalışmada, AHP-Entropi modelinin geçerliliği, karar çıktısı üzerinde en güçlü etkiye sahip olan kriterler üzerinde gerçekleştirilmekte ve Bir Zamanda Bir (OAT) Duyarlılık Analizi (SA) yöntemi kullanılarak uzamsal olarak görselleştirilmektedir. Çalışmada, vaka inceleme alanının %28,1'inin veya toplam alanın üçte birinin, kentsel yangın riskine maruz kalma olasılığının yüksek olduğu sonucuna varılmakta ve bu da yeterli itfaiye kapsamı ve koruma sağlamak için yeni kentsel acil durum tesislerinin acil olarak planlanmasını gerektirmektedir.

Üçüncü makalede, üçgen üyelik fonksiyonuna ve CBS'ye dayalı bulanık AHP'nin kullanıldığı bütünleşik bir yaklaşım uygulanmaktadır. Bu durumda, ortaya çıkan bulanık AHP ağırlıkları 19 uzmanın anketlerinden elde edilmekte ve BWM adı verilen başka bir ÇKKA tekniği kullanılarak doğrulanmaktadır. Araştırma sonuçları, kentsel itfaiye istasyonu yer seçiminde en önemli kriterleri sırasıyla %33,3, %24,4 ve %15,2 kriter ağırlıklarıyla TMD, YNY ve AYY olarak belirlemiştir. Sonuçların kapsamlı bir analizi ile, yangından korunma hizmetlerinin artan taleplerini yanıtlama süresini 5 dakikanın altına indirerek ele almak amacıyla mevcut 121 itfaiye istasyonuna ek olarak toplam 34 yeni kentsel itfaiye istasyonu önerilmektedir. Ayrıca, maliyet ve kaynak mevcudiyetine dayalı olarak inşaatlarını aşamalı olarak planlamak için önerilen 34 itfaiye istasyonunda düşükten yükseğe üç seviyeli bir önceliklendirme analizi yapılmıştır.

Son olarak, İstanbul'daki yangın ve acil servisler için yeni kentsel altyapının en uygun şekilde seçilmesi ve ayrıca BWM, AHP-Entropi ve bulanık model sonuçlarının doğrulanması için daha önce belirlenen kriterler arasındaki karmaşık karşılıklı ilişkileri ve etki düzeylerini incelemek için DEMATEL yöntemi uygulanmaktadır. Bu araştırmada, ölçütler arasındaki nedensel ilişkileri ve birbirileri arasında oluşan etkileşim derecelerini ve bunların ne ölçüde güçlü kurulduğunu belirlemek amacıyla *digraf* şeklinde görsel olarak anlaşılır bir yapısal model oluşturularak faydalı bilgiler üretilmektedir. Bulgular, yangın ve acil durum hizmetleri için yeni kentsel tesislerin etkin bir şekilde planlanmasında YNY'nin en kritik kriter olduğunu ve bunu TMD kriterinin takip ettiğini, bu nedenle diğer tüm kriterleri önemli ölçüde etkilediğini ortaya koymaktadır. DEMATEL model sonuçları, BWM, AHP-Entropi ve bulanık AHP model sonuçlarını kriter anlamlılık seviyeleri açısından doğrulamak için kullanılmakta ve bu nedenle diğer çalışmalarla yüksek korelasyon içinde olduğu gösterilmektedir. Bu bağlamda, bu araştırmayla kurulan bu bağlamsal ilişkiler, çeşitli altyapıya ve bilgi birikimine sahip tüm karar vericilerin katılımıyla kentsel ortamlarda yeni acil durum tesislerinin planlanması için entegre bir yangın riski azaltma politikası formülasyonuna katkıda bulunmaktadır.

1. INTRODUCTION

The most urbanized province of Turkey with respect to economy and infrastructure is Istanbul. With a population of more than 15 million, this represents about 20% of Turkey’s total population (TUIK, 2019). However, of great concern, is the growing challenge of the high and rising number of fire and fire-related incidences experienced in Istanbul exacerbated by population increase as well as urban infrastructure expansion (largely attributed to urbanization). As stated in the 2016 annual report (IMM, 2016) of the Istanbul Metropolitan Municipality Department of Fire Brigade, 58, 666 fire incidents occurred with an average response time of more than five minutes. Since the year 1900, there have been over 2,391 recorded deaths caused by fires accounting for about 35.4% of all disasters within the related technological sub-group class of disasters affecting Turkey (EM-DAT, 2019). Fires, classified as technological hazards, can occur as a result of careless actions or misuse of flammable or explosive materials and also after the occurrence of large earthquakes due to structural and infrastructural damage. In such cases, the most vulnerable facilities are large oil refineries, factories, warehouses, electrical and natural gas lines (ISMEP, 2009). Fires triggered by an earthquake e.g. Girgin (2011) can even cause more devastation than the direct impacts of the initial hazards – earthquakes e.g. Korup (2010).

Against this background, the main goal of this research is motivated by the critical need to mitigate fire impacts and improve fire response action within the urban environment of Turkey, particularly in Istanbul. Often, the problems concerning fire risk in Istanbul range from poor quality or depreciation of structures and wooden buildings constructed a long time ago, to poor urban environment linked to human activities as well as uncontrolled urban growth and an inflexible planning system that is not responsive to the dynamics of the city. In this context, the approach to the prevention and mitigation of the fire risk problem must be applied holistically, i.e. incorporating social, cultural, economic, political and strategic issues. For effective mitigation and risk management, reliance on flexibility and various stakeholder participation in the decision-making process cannot be over-emphasized within the broader planning framework (Pektas, 2004). This has uncovered the urgent need to explore tools and methods that have emerged with advancements in the information technology fields, to enhance the urban planning process for disaster mitigation. In order to be more effective, the urban planning approach currently involves more complex decision-making and multiple stakeholders in a more participatory, rational and communicative way that complements modern planning theories.

Multi-criteria Decision Analysis (MCDA) techniques were first developed in the 1960s, to resolve difficulties in harmonizing diverse opinions among interest groups, evaluating complex problems (arising from the increasingly complex and large amounts of information to be processed) which have many criteria and conflicting objectives in the decision-making process (Afshari et al., 2016; Voogd, 1982; Zeleny, 1982). These competencies have motivated planners to integrate MCDA with other information technological (IT) planning tools such as geographical information system (GIS) (Belton & Stewart, 2002). Many MCDA methods exist and are present in numerous literature. Regardless of the method of choice, the common goal to be achieved is the evaluation and selection among many available alternatives based on large number and variety of criteria so as to acquire the most optimum and viable planning outcome through a systematic analysis procedure that overcomes the limitations of unstructured individual or group decision-making (Afshari et al., 2016; Bhushan & Rai, 2007; Vaidya & Kumar, 2006). Within the context of urban planning efforts, information associated with the state and dynamics of urban regions is multi-varied (incorporates scales, time, dependences, values, beliefs and objectives) and targets diverse interest groups drawing particular political dimensions. Therefore, to be relevant, the decision-making objectives and feasibility of agreed planning decisions must be considered in the planning process by contextualizing the factors that structure the decision to avoid unnecessary conflict (Prévil & Thériault, 2003). Methodologies and tools are therefore required to manage and analyse this kind of complex information, such as fire risk mitigation planning which is spatial.

This PhD research thereby proposes the use of GIS-based MCDA techniques for optimal selection of new fire stations in Istanbul required to lessen the fire response time to within five minutes. The significance of the research will be very critical in mitigating fire impacts and improving fire response action. GIS-based MCDA methods can be employed to enhance the quality of decision-making by integrating geographical data and value judgements (Jacek Malczewski, 2006). Planning of emergency facility locations is a complex process involving multiple sites to be considered, multiple criteria to be evaluated and multiple stages to be conducted.

In this thesis, application of the fuzzy extension of the MCDA method of Analytical Hierarchical Process (AHP), hence known as fuzzy AHP (Zadeh, 1965) integrated with GIS, is suggested to optimally site new fire station facilities for the case of Istanbul region. In addition, the reliability and consistency of the fuzzy AHP result were assessed and compared with other MCDA methods such as Best-Worst Method (BWM) (Rezaei, 2015) from the perspectives of two decision-maker (DM) groups in the multiple attribute group decision-making (MAGDM) approach, integrated Entropy-AHP (Saaty, 2008; Shannon, 1948) for evaluating criteria weights both subjectively and objectively and Decision-Making Trial and Evaluation Laboratory (DEMATEL) (Gabus & Fontela, 1973, 1976) for modelling the complex interrelationships of criteria previously determined. The validation of all these applied MCDA techniques was accomplished through a comparison of the criteria weights and importance levels as well as using the DEMATEL method for determining the most influential criteria from the interdependencies evaluated from each of the outlined MCDA techniques. The facility selection decision is terminated when the DMs provide their final recommendation for the most suitable sites with the analysis results from these procedures visualized via GIS in the form of raster suitability maps.

1.1 Research Motivation and Problem Statement

The World Bank estimates that, globally, 55% of the population resides in urban regions presently. It is estimated that by the year 2050, the urban population will more than double its current size (World Bank, 2020). Istanbul, straddling Europe and Asia is one of the megacities of the world having a population of 15,462,452 (constituting 18.49% of Turkey’s population) as of 2020 (TUIK, 2020) and is the commercial capital of Turkey accounting for more than a third of the GDP. The number of people living in Turkey's urban regions has risen steadily throughout the years, from 38.9% in 1971 to 76.1% in 2020, with an average annual growth rate of 1.38% (United Nations Population Division, 2020). This upsurge in the urban population resulting in the growing demand for increased access to socio-economic and infrastructure services has given rise to rapid urbanization challenges such as exposure and vulnerability to urban fire risk. It is vital to have enough coverage of fire and emergency facilities in the urban area to limit the risks of present and future fire hazard situations. In Istanbul province, most of the existing fire and emergency facilities are clustered around the densely populated regions of the predominantly built-up and industrialized zones with high exposure to urban fire risk. Urban fires can be dangerous to people, essential infrastructure, and the environment, resulting in injuries and deaths, as well as economic loss and pollution. Urban fires generally fall under the technological hazard cluster and can be triggered by natural (e.g. lightning strikes) and human-made activities (e.g. arson) emanating from technological or industrial situations such as accidents, unsafe operations, and damage to infrastructure (UN Office for Disaster Risk Reduction, 2019, 2020). Fires may also arise from secondary effects of natural hazard impacts such as earthquakes e.g. 1999 Kocaelli (AİGM, 1999) with devastating consequences due to structural and infrastructure damage. Large industries, warehouses, petroleum refineries, and electrical and gas utility lines are among the most vulnerable facilities (ISMEP, 2009). According to the Istanbul Metropolitan Municipality's annual report (IMM, 2016), the number of fires reported in Istanbul has been rising, with response times exceeding five minutes.

In this view, the situation analysis of the fire risk status from the latest statistics acquired from the Istanbul Metropolitan Municipality Fire Brigade Department (IMM Fire Department, 2020) for the year 2020 considered the causes of fires and the number of incidences. From these results, the sources and causes of the urban fires were generalised into 11 classes that included cigarettes, electrical (electrical contact, electricity, electrical appliances, electrical conduit box, transformer, overhead lines), children playing with fire (spark splash, candle tipping, flash fire and fire suspicion), intentional (deliberate), unknown, chimney and stove, increased heat/blaze, cooker hood/hoover and gas cooker, natural gas explosion (chemical substance fire, LPG explosion, explosion), gasoline flares/fuel oil for vehicles (LPG vehicle and fuel oil) and lightning. The total number of fire incidents registered for Istanbul in the year 2020 was 20,586. The highest cases emerged from cigarettes with 8,022 (39.0%), followed by electrical causes with 5,420 (26.3%). Children playing with fire-related causes also represented quite a high number with 1,946 (9.5%) as well as intentional/deliberate and unknown causes of fire incidences accounting for 1,553 (7.5%) and 1,444 (7.0%) cases, respectively. The lowest number of incidences were recorded from lightning causes with only 10 (0.1%) cases, closely followed by gasoline flares/fuel oil/LPG for vehicle causes with 57 (0.3%) and natural gas/LPG explosions with 87 (0.4%) cases. From the fire statistics examined, it can be observed that the high number of fire occurrences was largely related to energy consumption (electricity usage) and human activities such as smoking (cigarettes) and children playing with fire/flash fires.

The urgent need for additional urban emergency facilities is underlined in light of Istanbul's current fire risk condition. The thesis, therefore, establishes the research motivation which is to mitigate the growing challenge of rising fire impacts and fire-related incidences experienced in Istanbul province by the implementation of GIS-based Multi-Criteria Decision Analysis (MCDA) approaches for the enhanced planning procedure of new fire and emergency facilities, necessary to significantly reduce fire response time to under five minutes.

This thesis is comprised of three academic paper publications. The first paper considered the application of a recently developed MCDA technique known as the Best-Worst Method (BWM) (Rezaei, 2015) that integrated with GIS within a group decision-making (GDM) framework. Divergent views of two decision-maker (DM) groups were incorporated constituting academic-related professionals and fire brigade practitioners to resolve the complex planning decision problem of suitably siting urban fire and emergency facilities in Istanbul. DM preference and insightful inference analyses were derived from useful statistical tests such as *one-sample t-test*, *one-way ANOVA* and *Tukey's HSD test*. A statistical measure known as *Kendall's coefficient of concordance, W* was applied to determine the consensus level in the decision-making approach. The second paper utilizes a hybrid model that combines the Entropy (Shannon, 1948) method with AHP and GIS for the evaluation of criteria weights both subjectively as well as objectively with regard to assessing urban fire risk and optimal areas for planning new fire and urban emergency sites. The model was validated by applying the *one-at-time* (OAT) sensitivity analysis (SA) method on the criteria having the largest influence on the planning decision result and visualised spatially in a GIS environment. In the third paper, the MCDA approach of fuzzy AHP (Zadeh, 1965) combined with GIS was used to determine the best location for new fire station facilities in the Istanbul region. The fuzzy AHP solution design was adopted to better simulate the inherent ambiguity in decision-makers' (DMs) preferences, resulting in more accurate planning judgments. The fuzzy AHP result was evaluated and compared to other MCDM methods such as the Best-Worst Method (BWM) (Rezaei, 2015) to assess its reliability and consistency.

This thesis research is significant in mitigating the increasing fire risk impacts in Istanbul negatively affecting the sustainable development of the urbanized region owing to the prevailing fire risk situation (IMM Fire Department, 2020) and fire incidences surpassing 58,000 experienced with average response times exceeding five minutes (IMM, 2016). The suggested methodology of the use of GIS-based Multi-Criteria Decision Analysis (MCDA) has been implemented in this study for land-use suitability analysis of selecting new emergency facilities in Istanbul province. The utilization of these techniques has been motivated by the need to enhance GIS capabilities for decision-making and planning (Sugumaran & Degroote, 2010). The GIS-MCDA integrates geographic data (input maps) and preferences of experts or decision-makers (DMs) to be processed into a decision (output) map (Malczewski, 1999; Malczewski & Rinner, 2015; Malczewski & Rinner, 2015). GIS-based suitability modelling assessments of the generated final suitability map outputs indicate favourable locations for planning new emergency facilities distributed around the most densely populated and industrial zones of Istanbul as well as depict exposure to urban fire risk requiring urgent remedial action.

The effectiveness of the use of these GIS-based MCDA approaches has been established from the generated suitability maps, statistical measures, criteria interdependencies and model validations using the DEMATEL method. These decision outputs could be used by decision-makers, planners and policy-makers to reliably and comprehensively plan for the necessary fire protection and emergency services as well as in solving spatial emergency facility location problems within the context of planned future urban growth.

1.2 Research Questions

It is evident that there is a critical need for planning mitigation efforts in relation to the prevailing urban fire risk situation in Istanbul province. The growing challenge of rising fire and fire-related incidences is experienced with delayed fire response times exceeding the international standard of five minutes. GIS-based MCDA techniques are therefore presented in this study to improve the planning choice of where new urban fire and emergency facilities should be located in order to minimize fire response time to under five minutes. However, from the many available methods, the most appropriate MCDA techniques should be evaluated with regard to ease of development and integration with GIS, applicability to the decision problem, criteria inputs to the models, their respective weights/influences and spatial decision outputs (in form of raster suitability maps), model accuracy, consistency and reliability. From this perspective, the primary research questions for this thesis have been formulated as follows.

a) "Which criteria are most ideal for developing the framework for GIS-based MCDA approaches?"

b) "Which criteria under evaluation have the most and least influence in terms of their respective weights on the planning outcome for the urban fire and emergency facility site selection process?"

c) "Which of the MCDA methods is appropriate for this study? How do these methods compare in terms of the model accuracy, consistency and reliability as well as suitability map outputs?"

d) "What are the data processing and analysis procedures involved in the GIS and MCDA modelling processes?"

e) "Where are the identified and recommended optimal locations for the new urban fire and emergency facilities in Istanbul? Can these sites be prioritized in terms of cost and resource constraints?"

f) "Have any other variables been considered in the GIS-based MCDA model analyses results such as day-time population dynamics e.g. influx of migrants and tourists in the highly urbanized regions of Istanbul that could affect emergency facility planning decisions?"

g) "To what extent has the group decision-making (GDM) process been examined in achieving consensus in the collaborative urban planning process by various stakeholders from inter-disciplinary fields that include actual fire brigade practitioners?"

h) “Have the inter-relationships and level of interaction among the various criteria used in the MCDA process been thoroughly investigated?”

1.3 Research Aim and Objectives

The underlying aim of this PhD research is to develop an integrated GIS and MCDA model for optimally planning new fire stations in Istanbul province required to reduce the fire response time to five minutes or less. In achieving this goal, other research objectives to be realized include:

a) Model construction, comparison and validation of resultant weights using MCDA methods such as fuzzy AHP, Entropy-AHP, BWM and DEMATEL.

b) Determination and identification of influencing factors/criteria for effective urban emergency facility planning and siting.

c) Using the *Delphi technique*, conducting surveys through the use of a questionnaire to capture the preference evaluations of decision-makers (DMs) with the requisite urban emergency planning knowledge and experience (to include academic/professional experts and fire brigade practitioners).

d) Evaluation of the criteria weights using the GIS-based MCDA method premised on pairwise comparisons from the relevant experts/DMs.

e) Identification of the most important criteria for urban emergency facility site selection from the DMs’ assessments.

f) Using GIS for processing, analysis and final production of raster suitability maps showing areas most feasible for locating new emergency facilities.

g) Prioritization analysis (from low, medium to high) of the proposed new fire and emergency facilities for planning their construction in a phased approach based on cost and resource constraints.

h) Comparison analysis of different viewpoints and preferences of two DM groups in the group decision-making (GDM) process, comprised of fire brigade personnel and academic/professional related experts.

i) Performing a sensitivity analysis to test the sensitivity and robustness of the developed models, based on the combination of the criteria weights by use of GIS capabilities.

j) Investigation of the inter-relationships and level of interaction that exist among the various criteria used in the MCDA modelling process.

1.4 Research Contribution and Publications

The potential of the use of multi-criteria evaluation in a GIS-based suitability modelling framework that augments the complex urban planning and decision-making processes can be demonstrated in this PhD research by mapping the optimal distribution of new urban emergency facility locations to mitigate the increased risk of fires and the occurrence of fire-related incidences in Istanbul province. The contribution of this research by the implementation of GIS-based MCDA techniques is critical in reducing fire impacts and boosting emergency fire action among urban planners, decision-makers and policy-makers. In this regard, three research papers were published and each of the three publications delved into various issues related to GIS-based MCDA modelling approaches for effectively planning new urban fire and emergency facilities.

The first research publication presented a conceptual framework for a multiple attribute group decision-making (MAGDM) process coupled with a recently developed Best-Worst Method (Rezaei, 2015) and GIS that intended to achieve a consensus solution incorporating divergent views of two decision-maker (DM) groups for determining ideal weights for new optimal urban fire and emergency facility sites. Inferential statistics were applied to the DM preferences that included a *one-sample t-test, one-way ANOVA, Tukey's HSD test, Kendall's coefficient of concordance, W, Kappa*. This research is novel in that, it reveals new information on various thoughts and views of these clusters of DMs both from an academician and practitioner standpoint on the criteria significance and how this affects the overall planning result for locating the best fire station and emergency facilities. Exploring the link between these two DM clusters of preference judgements can aid in gaining a better understanding of GDM procedures and their interconnections with group consensus and social aspects. Furthermore, the novelty in the study is that these preferences in criteria weights are modelled in a GIS to produce two separate composite raster suitability maps for new emergency facility locations in Istanbul, each representing the academic-related professionals and fire brigade practitioners.

The second paper deals with the inherent weakness of subjective-based weighting in most MCDA methods such as AHP by integrating with the Entropy method to eliminate human interference in the weighting process, thereby evaluating the criteria weights objectively. The study is significant because it applied a hybrid AHP-Entropy GIS-based model, using a combined subjective and objective weighting procedure to achieve more accurate weight measures for resolving the planning problem of suitably siting new urban emergency facilities in Istanbul. The study is unique since the final criteria weights from both AHP and Entropy are integrated and used as input in GIS modelling and analysis functions to produce raster suitability maps showing recommended areas of new urban fire facilities. Due to inherent uncertainties and other exogenous factors in the input data beyond the DM's control, the study incorporates sensitivity analysis (SA) in the methodology, to determine if a solution is retained, thus significantly contributing to a more accurate planning decision outcome. In this context, the study brings out the novelty, by using the spatial SA approach to be able to geographically visualize and analyse the weight sensitivity ranges in a *one-at-a-time* (OAT) method via raster pre-processed composite raster suitability maps.

The novelty of the third research paper publication is that it explores fuzzy set theory to model the vagueness of human expressions that arise from linguistic imprecision when capturing DM preferences by proposing the GIS-based fuzzy AHP methodology in contrast to the conventional AHP procedures. This study approach contributes to better and more accurate decision-making results by overcoming the problems of uncertainty. In this manner, the uncertainties of DMs are modelled using possibility distributions called *fuzzy membership functions* as opposed to the use of crisp values in expressing linguistic judgements. Moreover, the reliability of the study methodology was assessed using a more recently developed MCDA technique known as the Best-Worst Method (Rezaei, 2015). Furthermore, the study uniquely contributes to the overall planning process by elaborately recommending actual sites for the construction of new fire facilities in Istanbul from the generated raster suitability maps across low, medium and high levels of priority. This prioritization scheme is based on cost and resource constraints as well as other special planning considerations.

1.5 Research Theme and Structure

The research themes of this thesis are structured based on the three publications which are SCI-Expanded articles as follows:

Chapter 1: consists of the introduction, research motivation and problem statement, research questions, research aim and objectives, research contribution and publication sub-sections.

Chapter 2: presents the journal article entitled “Comparative Evaluation of GIS-Based Best-Worst Method (BWM) for Emergency Facility Planning: Perspectives from Two Decision-Maker Groups”.

Chapter 3: presents the journal article entitled “A Hybrid Approach Integrating Entropy-AHP and GIS for Suitability Assessment of Urban Emergency Facilities”.

Chapter 4: presents the journal article entitled “GIS-Based Fuzzy Multi-Criteria Approach for Optimal Site Selection of Fire Stations in Istanbul, Turkey”.

Chapter 5: presents the model results validation of the applied MCDA techniques using the DEMATEL method.

Chapter 6: presents the conclusion of this study and recommendations for further research.

2. COMPARATIVE EVALUATION OF GIS-BASED BEST-WORST METHOD (BWM) FOR EMERGENCY FACILITY PLANNING: PERSPECTIVES FROM TWO DECISION-MAKER GROUPS[1]

2.1 Abstract

Nowadays, organizational decisions are made collectively in decision groups to achieve more meaningful and impactful outcomes, ranging from product design, policy and strategy formulation and resource allocation. This research, therefore suggests a group decision-making (GDM) approach utilizing a recently developed MCDM method known as Best-Worst Method (BWM) in combination with GIS for planning suitable areas for new emergency facilities in Istanbul. Using two decision-maker (DM) groups consisting of academic-related professionals and fire brigade practitioners, the BWM method was used to evaluate the associated weights and preference rankings of six pre-selected criteria, derived from pairwise comparisons of the best and worst criterion for each DM. The preference criteria of the two DM groups were examined to deepen the understanding of the varying perceptions about the level of influence of the criteria from a theoretical and practical view as well as to reflect a real-case scenario in typical GDM problems where group agreement or reliability is assessed by consensus using Kendall's coefficient of concordance, W.

The BWM results were compared for model validation with the AHP and found to be reliable and consistent. Further, from statistical tests conducted, it was inferred that criteria C_4 (Density of Hazardous Materials) and C_1 (High Population Density) were perceived to be the most important by the academician and fire brigade practitioner DM group, respectively. For both DM groups, criterion C_6 (Distance from Earthquake

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[1] This chapter is based on the article: Nyimbili, P. H., Erden, T., 2021: Comparative evaluation of GIS-based best–worst method (BWM) for emergency facility planning: perspectives from two decision-maker groups, Natural Hazards, 105(1), 1031-1067. doi: https://doi.org/10.1007/s11069-020-04348-3

Risk) was viewed to be the least important. Resultant raster suitability maps for both DM groups were produced for visualizing the BWM model.

Keywords: Best-worst method (BWM); group decision-making (GDM); geographic information system (GIS); multi-criteria decision-making (MCDM); analytical hierarchy process (AHP); emergency facility planning

2.2 Introduction

The most urbanized province of Turkey in terms of economy and infrastructure is Istanbul. With a population exceeding 15 million, this is proportional to almost 20% of Turkey's total population (TUIK, 2019). However, of great concern, is the challenge of soaring fire incidences experienced in Istanbul exacerbated by population growth as well as urban infrastructure expansion (largely attributed to urbanization). As stated in the 2016 annual report (IMM, 2016) of the Istanbul Metropolitan Municipality Department of Fire Brigade, 58, 666 fire incidents occurred with an average response time of more than five minutes.

From this perspective, the main goal of this research is motivated by the critical need to mitigate fire impacts and improving fire response action within the urban environment of Turkey, particularly Istanbul. An urgent need arises to explore tools and methods that have emerged with advancements in the information technology fields, to enhance the urban planning process for disaster mitigation (Erden, 2012). To be more effective, the urban planning approach presently involves more complex decision-making and multiple stakeholders in a rather participatory, rational and communicative way that complements modern planning theories, ensuring sustainability.

Multi-criteria Decision-Making (MCDM) techniques were first developed in the 1960s, to resolve difficulties in harmonizing diverse opinions among interest groups, evaluating complex problems which have many criteria and conflicting objectives in the decision-making procedure (Afshari et al., 2016). The key benefit of integrating MCDM with geographical information systems (GIS) is the ability of GIS to manage, analyse and present geographic data in the form of maps to support decision-making. The map outputs can be utilized as a basis for discussion and review of decision problems which may result in the clarification as well as the optimal selection of decision alternatives (Malczewski & Rinner, 2015). Regardless of the MCDM method of choice, the common goal to be achieved is the evaluation and selection among many available alternatives based on a large number and variety of criteria to acquire the most viable planning outcome. This is achieved through a systematic analysis procedure that overcomes the limitations of an unstructured individual or group decision-making (Afshari et al., 2016; Bhushan & Rai, 2007; Vaidya & Kumar, 2006). Within the context of urban planning efforts, information associated with the state and dynamics of urban regions is multi-varied (i.e. consisting of scales, time, dependences, values, beliefs and objectives) and targets diverse interest groups drawing particular political dimensions. Therefore, to be relevant, the decision-making objectives and feasibility of agreed planning decisions must be considered in the planning process by contextualizing the factors that structure the decision to avoid unnecessary conflict (Prévil & Thériault, 2003). In this view, methodologies, and tools are indeed required to manage and analyse this kind of complex information, which is spatial in nature, for urban emergency facility planning and fire risk mitigation in this study.

This research thereby proposes the use of GIS-based MCDM techniques for optimal selection of new urban fire stations and emergency facilities in Istanbul, required to lessen the fire response time to within five minutes. The significance of the research will be very vital in mitigating fire impacts and improving fire response action. GIS-based MCDM models can be applied to improve the quality of decision-making by merging spatial data and expert value judgements (Malczewski, 2006). In this paper, a recently developed MCDM technique called Best-Worst Method (BWM) (Rezaei, 2015) integrated with GIS, was suggested to optimally site new fire station facilities for the case of the Istanbul region. The spatial location of suitable areas for fire stations is an intricate procedure that requires careful analysis of many influencing and conflicting criteria. Six criteria were identified from a range of social/demographic, built environmental, spatial/accessibility and risk and safety variables based on relevant literature, expert opinion, and international norms. Thereafter, the BWM method through group decision-making (GDM) approach, was applied to determine the subjective weights of the criteria from the preference evaluations of two groups of decision-makers (DMs) composed of academic-related professionals and fire brigade practitioners. These criteria weights were ultimately used as input in GIS to resolve the selection problem that resulted in the production of two raster suitability maps representative of both DM groups. The GIS capabilities provided the necessary aid in the decision-making process for analysis and visualization of the developed BWM model.

The research outcome would make an important contribution to the literature and field of urban emergency facility location as few studies have applied this proposed model. Further, the BWM model result is tested by comparison with the AHP in terms of determined criteria weights, reliability and consistency. This study, additionally, explores the BWM preference criteria evaluations of two DM groups comprising of academicians/professionals and fire brigade personnel who have the requisite knowledge and experience in emergency management and planning. The findings of this analysis, would provide one of the first-ever investigations and generate new insights into the different perspectives and opinions of these groups of DMs about the level of importance of criteria and how this impacts the overall planning outcome for siting optimal fire station and emergency facilities. Understanding the link in the preference evaluations between these two groups of DMs will help to gain a deeper understanding of GDM processes and intersections with group consensus and social perspectives.

The current paper is organized into the remaining subsections as follows. The next subsection provides a review of the literature on emergency management and facility planning issues and the background on BWM's relevant applications. Subsection 2.4 outlines the proposed methodology, GDM process, and its implementation, followed by the BWM results, analysis, and discussion of the two groups of DMs compared with the AHP for validation, GIS analysis and production of suitability maps for comparison in subsection 2.5. Finally, the study conclusions are clarified in subsection 2.6.

2.3 Background and Related Works

The selection of suitable areas for emergency facilities is affected by many influencing factors and has a finite number of alternative locations, thereby representing a typical Multi-Attribute Decision-Making (MADM) problem, which falls under the class of MCDM methods. For such MADM decision-problems, the method for determining the criterion weight and that for the ranking of alternatives are crucial in realizing optimal outcomes. Generally, criterion weight determination methods are categorized into subjective and objective weighting methods (Wu et al., 2019). The subjective weighting method evaluates the weights based on preference judgements from associated experts, such as the Analytical Hierarchical Process (AHP) (Saaty, 1980). The AHP is based on pairwise comparisons that take a long time to evaluate and whose pairwise comparison matrix lacks consistency (Wu et al., 2019).

Recently, a new MCDM technique called Best-Worst Method (BWM) was developed by (Rezaei, 2015, 2016) that uses fewer pairwise comparison matrices thereby less time to implement and has better consistency than existing subjective weighting methods such as AHP (Salimi & Rezaei, 2018; Wu et al., 2019). BWM evaluates several alternatives to select the best alternative (s) with respect to pairwise comparisons between each of the two criteria (best and worst, identified by the decision-maker) and the other criteria (Rezaei, 2015). As demonstrated by Rezaei (2015), the BWM technique can be applied to efficiently and reliably solve multi-criteria problems and has fewer comparison data (BWM needs to have $2n - 3$ comparisons while for AHP, as an example, $n(n-1)/2$ comparisons are required). Therefore, the BWM does not need complete pairwise comparison matrices, is easy to implement and saves lesser time compared to alternative MCDM methods (Suhi et al., 2019).

Considering all these advantages over other MCDM methods such as AHP, ANP, and SMART, scholars have recently applied the BWM method in facility location and site selection research fields. Pamucar et al. (2017) proposed a hybrid GIS-MCDM model in Serbia, that applied rough BWM and rough MAIRCA methods to determine the criteria weights for input into the GIS resulting in the production of the final map for selecting the most suitable locations for wind farms. Another hybrid BWM-EDAS model was applied by Özmen & Aydoğan (2020) for the logistics centre location problem in Kayseri, Turkey. BWM was used for calculating the weights of each criterion and sub-criteria and distance from average solution (EDAS), in the final stage, for ranking alternative logistics centre areas according to these criteria. The main evaluation factors for optimal logistics centre location included land, market, social, transportation, environmental effects, costs, risk and safety, national stability and international operation and management. Kheybari et al. (2019) suggested the BWM method for selecting suitable locations for a bioethanol facility in Iran. The researchers synthesized many criteria that affect the optimal location of a biofuel facility across only three main criteria using the sustainability approach namely: social, economic and environmental, thus simplifying the problem resolution and model application for optimal site selection. Other related works were conducted by Zolfani et al. (2019) for hotel site selection in Iran based on a proposed BWM and Weighted Aggregated Sum Product Assessment (WASPAS) approach; You et al. (2016) for selection of a culture centre in China by integrating modifications of BWM with ELECTRE III; and Stević et al. (2017) for selection of rail wagons for internal regional transportation across Bosnia and Herzegovina by proposing a rough BWM and rough Simple Additive Weighting (SAW) approach.

So far, as reviewed in the literature, few studies to date have applied the BWM method for facility location and site selection. The present study, therefore, contributes to the literature by proposing the use of the hybrid GIS-based BWM model for two decision-maker (DM) groups to more reliably and efficiently select new fire station facility areas for a case study region of Istanbul province, Turkey not previously considered in (Erden & Coskun, 2010; Penjani Hopkins Nyimbili & Erden, 2020a). Further, with reference to the prior work done by Erden & Coskun (2010) where combined AHP and GIS methods were applied for fire station location in Istanbul city, this study presents an improvement in the methodology for overcoming the drawbacks of the AHP usage.

2.4 Research Methodology

The urban emergency facility location problem of selecting new fire station sites is spatial in nature and involves an elaborate process involving multiple and conflicting criteria, data analysis and evaluation of many alternatives to achieve optimal results. The most influencing factors that affect the decision-making (DM) process were identified and abstracted from social/demographic, built environment, risk and safety, and spatial considerations as part of the criteria screening procedure.

The construction of the model proposed in this study was based on an integration of GIS and BWM methodology. Through a series of steps outlined in the subsequent sub-sections, the BWM method was applied using a group decision-making (GDM) approach to determine the subjective weights of the identified criteria from preference judgements of two different groups of decision-makers (DMs) comprising academic-related professionals and fire brigade personnel. Survey questionnaires based on the BWM were designed and filled-in by respondents representing a total of nineteen DMs and experts using a 9-point scale. An objective method, based on the consistency index of the individual decision matrices determined from the BWM was used to derive the weights of the experts (Koksalmis & Kabak, 2019). The weight coefficients of the criteria for individual DMs were calculated by using the BWM optimization model and the arithmetic means was later on used to aggregate the weight for each criterion. These criteria weights were used as input into GIS and applied on processed and re-classified criteria map layers through a weighted sum analysis to produce two final raster suitability maps for each DM group that showed the optimal areas for the new fire station and emergency facilities. Integrating GIS into the BWM model provided the requisite support in the spatial decision-making problem of siting new fire station locations, because of the GIS' inherent capabilities to handle spatial data and its powerful visualization and analysis tools. Figure 2.1 presents the general proposed approach used in this study procedure.

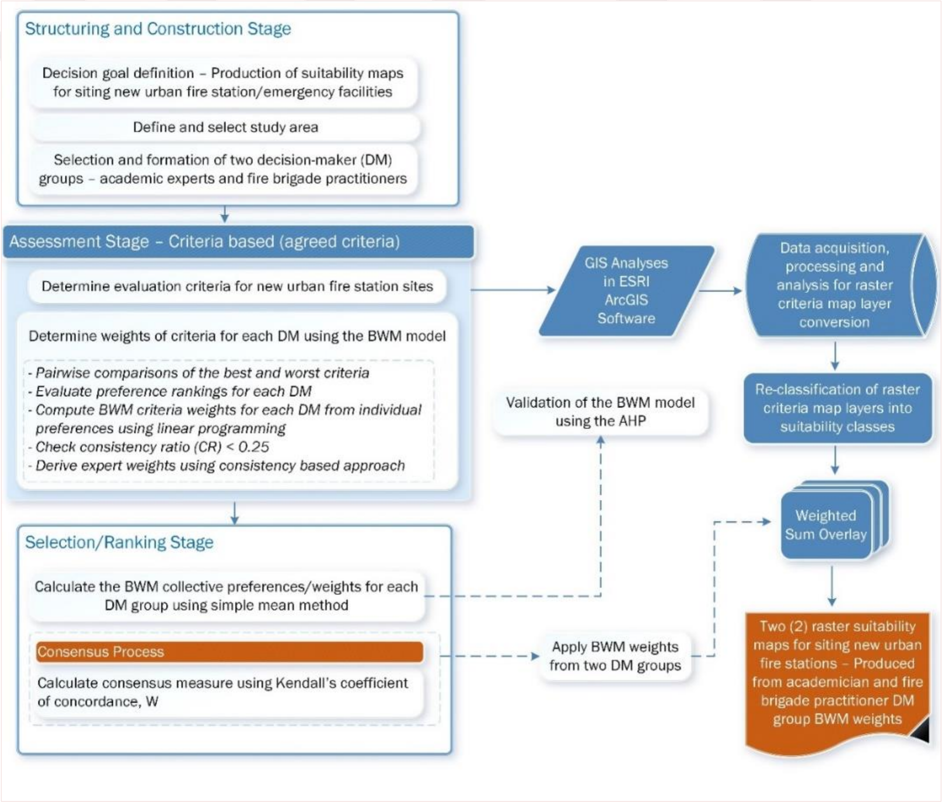


Figure 2.1: Proposed group decision-making (GDM) framework based on the BWM-GIS model.

2.4.1 Case study

The most densely populated and industrialized province of Turkey is Istanbul. With a population of about 15,067,724 as of 2018, the province stretches over an estimated total area of 5, 343.02 km^2 (TUIK, 2019). Due to increasing population and infrastructural expansion, there has been a rising number of fire incidences in Istanbul as registered in the annual report of the Istanbul Metropolitan Municipality (IMM, 2016) with the period it took to arrive at these locations of fire incidents exceeding five minutes.

Considering this situation, the research is proposed for optimally planning new areas for the fire station and emergency facilities to reduce the fire response time to five minutes or less, acceptable by international standards (Dong et al., 2018; NFPA, 2010; Wang, 2019; Yao et al., 2019). The research outcome underscores the importance of mitigating impacts of fire risk as well as improving the fire response activities as part of disaster and emergency management (DEM). To achieve the research objectives, this study covered the whole extent of Istanbul province, comprising of about 960 sub-districts as depicted in Figure 2.2.

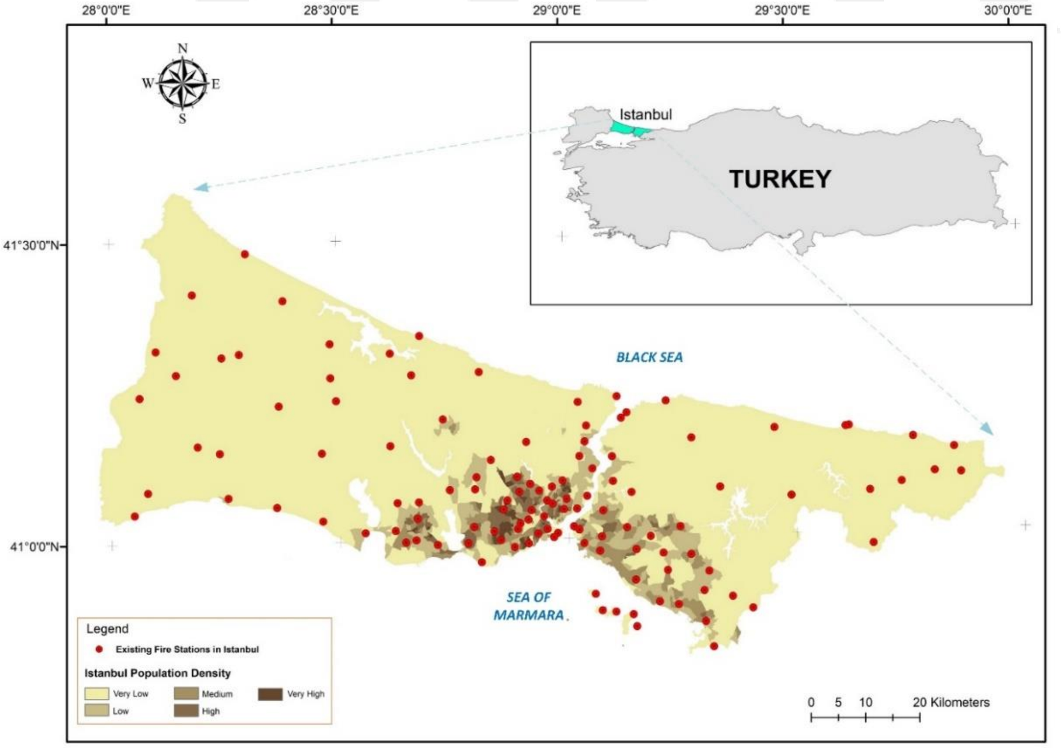


Figure 2.2: Map of Istanbul province showing existing fire stations and population density.

The population density ranges up to 1,333.2 people per hectare (ha) with a larger concentration of existing fire and emergency facilities located in the densely populated metropolitan areas of Istanbul. Within these urbanised regions, the high population density is associated with a high risk of fires resulting from increased socio-economic, tourism, infrastructure expansion and commercial activities. The fire departments are engaged in the key function of fire prevention and suppression to minimize loss of life and property. Additional services include ambulance, emergency rescue and recovery activities such as in the event of automobile accidents, disasters that include floods, earthquakes, landslides, etc.

2.4.2 BWM

The Best-worst method (BWM), recently introduced by Rezaei (2015), is a subjective weighting, pairwise comparison-based multi-criteria decision-making (MCDM) technique. BWM was selected for use in this research because it has the following advantages over other MCDM methods of requiring the use of fewer comparison data, therefore has better consistency in pairwise comparisons, achieving more reliable weight results, being easy to understand and revise by decision-makers for increased consistency (Rezaei, 2015, 2016; Rezaei et al., 2018). Since introduced, BWM has been applied in many recent studies covering wide domain areas such as location and site selection (Kheybari et al., 2019; Özmen & Aydoğan, 2020), mining (Ajrina et al., 2018), energy (van de Kaa et al., 2019; Zhao et al., 2018), manufacturing (Moktadir et al., 2018), supply chain (Liu et al., 2018a), transportation (Stević et al., 2017), environment (Liu et al., 2018b), water management (Chitsaz & Azarnivand, 2017; Nie et al. 2018a, 2018b), risk assessment (Torabi et al., 2016), emergency routes evaluation (Mei et al., 2018), search problem (Sotoudeh-Anvari et al., 2018), technology selection (Ren, 2018; Ren et al., 2017), piping selection (Safarzadeh et al., 2018) and materials selection (Zolfani & Chatterjee, 2019).

In this study, the BWM was applied to evaluate the criteria weights $(w_1, w_2, \ldots, w_n)$ for optimally planning locations of the new fire station and emergency facility areas for fire response mitigation in Istanbul province, using the following outlined steps (Rezaei, 2015, 2016):

1) Identify and select the set of decision criteria for analysis $\{c_1, c_2, \ldots, c_n\}$.

2) Determine the best (B) and the worst (W) criteria.

3) Determine preference via a pairwise comparison between the best criterion B, and all the other criteria. In this step, decision-makers (DMs) evaluate their preference, using a number between 1 and 9 (a 9-point scale with two extremes, where for pairwise comparison of i and j, 1 implies i is equally as important as j, and 9 implies i is extremely more important than j).

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn}) \tag{2.1}$$

is the resulting Best-to-Others vector of comparisons, where a_{Bj} indicates the preference of best criterion B over the worst criterion j and clearly, $a_{BB} = 1$.

4) Determine the preference of all the other criteria over the worst criterion W. In this step, DMs evaluate their preference using the 9-point scale.

$$A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T, \tag{2.2}$$

is the resulting Others-to-Worst vector of comparisons, where a_{jW} indicates the preference of criterion j over the worst criterion W and clearly, $a_{WW} = 1$.

5) Compute the optimal weights $(w_1, w_2, \dots, w_n)$. Given each pair of W_B / W_j and W_j / W_W, the optimal weight obtained is $W_B / W_j = a_{Bj}$ and $W_j / W_W = a_{jW}$. These conditions for all j are satisfied by finding a solution where the maximum absolute differences $|W_B / W_j - a_{Bj}|$ and $|W_j / W_W - a_{jW}|$ for all j is minimized. Based on the concept of minimizing the maximum deviation, this is translated to the following constructed mathematical model to determine the optimal weights:

$$min\, max_j \, \{|W_B / W_j - a_{Bj}| \text{ and } |W_j / W_W - a_{jW}|\},$$

subject to,

$$Sum_j\, W_j = 1$$

$$W_j \geq 0, \text{ for all } j, \tag{2.3}$$

Conversion of the model in Eq. (2.3) to a linear programming form is as presented below:

$$
\begin{aligned}
& \min \xi \\
& \text{subject to,} \\
& |W_B / W_j - a_{Bj}| \leq \xi, \text{ for all } j \\
& |W_j / W_W - a_{jW}| \leq \xi, \text{ for all } j \\
& Sum_j\, W_j = 1 \\
& W_j \geq 0, \text{ for all } j\,,
\end{aligned}
\tag{2.4}
$$

Solving the linear programming problem in Eq. (2.4), the unique solution of optimal weights $(w_1, w_2, \dots, w_n)$ and ξ^* are obtained. To check the consistency of the BWM pairwise comparisons, the following formula is applied:

$$Consistency\ Ratio = \xi^* / \ Consistency\ Index \tag{2.5}$$

The consistency index uses maximum possible values of ξ^* and can be retrieved from Table 2.1.

Table 2.1: Consistency index (CI) table.

a$_{BW}$	1	2	3	4	5	6	7	8	9
Consistency index (max ξ)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Observably, the smaller the value of ξ^*, the lower the consistency ratio and the more reliable the comparisons and vice versa. The bigger the ξ^*, the higher the consistency ratio resulting in less reliable comparisons.

2.4.3 Criteria selection

Screening of the criteria for selecting suitable fire station sites is a crucial process in the research procedure of the proposed model. The most influencing factors affecting the selection process were identified across social/demographic, built environment, spatial/accessibility, and risk/safety variables. After a thorough evaluation and analysis, six specific criteria were selected based on a review of a project report relating to fire station locations in Istanbul (IMM, 1989), and as suggested by Johnston (1999) and Gay & Siegel (1987) that the criteria should comprise population density, distances between fire stations and distinct hazards (Erden & Coskun, 2010). From these influencing factors and other considerations, within the framework of achieving a comprehensive planning process, the criteria selected and adopted were described in Table 2.2.

Table 2.2: Criteria selection assessment.

Variables	Selected criteria	Description	Effect
Social/ Demographic	High population density (HPD)	Highly populated areas are most at risk of fires and risk impact is very high, hence prioritized for fire station locations	+
Built environment	Wooden building density (WBD)	Built-up areas consisting of wooden buildings increase the risk of fire spread and impact, hence are prioritized for fire station construction	+
Spatial/ Accessibility	Distance from existing fire stations (DEF)	Fire stations should be constructed away from the serviced areas of the already existing fire stations	-
	Proximity to main roads (PMR)	Fire stations should be located in areas with easy access to main roads and transport routes for easy and faster reach to fire incident areas	+
Risk and Safety	Density of hazardous materials (DHM)	Areas with facilities having the presence of hazardous materials such as liquid petroleum gas (LPG) and compressed gases, oil stations, etc. increase the risk of fires, explosions and spread and therefore should be prioritized for locating fire stations	+
	Distance to earthquake risk (DER)	Istanbul is prone to the occurrence of natural hazards such as earthquakes, which cause structural and infrastructural damage to facilities. Fire station facilities should, therefore, be constructed away from high earthquake risk areas to lessen the risk of infrastructural damage due to earthquakes.	-

Once the criteria were determined, the subjective evaluation of the defined criteria for optimal fire station locations was undertaken by decision-makers (DMs) as part of the BWM procedure through a group decision-making (GDM) process, as elaborated in the next sub-section. Worldwide, natural disasters continue to pose a very serious threat to millions of people, their livelihood and significant losses both to human lives, the environment and infrastructure worth billions of dollars (USD) in value.

2.4.4 Group decision-making (GDM) and decision-maker (DM) selection

There are two main classifications of group decision-making (GDM) or collaborative decision-making, called process and content-oriented approaches. Process-oriented approaches relate to the process of making group decisions with the main goal being the generation of new ideas to understand and structure the problem. While content-oriented approaches focus on the content of the problem and attempt to find an optimal solution within given social or group constraints or objectives (Kabak & Ervural, 2017). There are three classes of content-oriented approaches namely: implicit (or Social choice theory) and explicit multi-attribute evaluation, and game theory approaches. Among these three categories, the interest of this research is directed towards the explicit multiple attribute evaluation, which refers to multiple attribute decision-making (MADM) with multiple decision-makers and is therefore called multi-expert or multiple attribute group decision-making (MAGDM). The term MADM is synonymously used with MCDM, referring to ‘‘multiple attributes’’ and ‘‘multiple criteria’’, to describe the multiple and conflicting criteria that are characteristic of decision environments (Kabak & Ervural, 2017). MADM becomes MAGDM with the involvement of multiple DMs and where criteria are explicitly provided as well as the alternatives relating to the criteria (Kabak & Ervural, 2017). In this regard, the research proposed a MAGDM process that aimed at arriving at a group satisfactory solution of determining optimum weights for suitable fire station facility locations. The study was based on the input of two DM groups drawn from both academic-related professionals and fire brigade personnel with relevant knowledge and experience in emergency and planning activities.

The conceptual framework for the MAGDM process proposed for use in this study was based on a literature analysis and adaptation from Kabak & Ervural (2017). Three main stages of the MAGDM process included: structuring and construction, assessment and selection/ranking stage, as earlier illustrated in Figure 2.1.

Within the structuring and construction stage, the MAGDM problem was structured by first understanding and defining the decision objective which was to locate suitable areas for the fire station and emergency facilities in Istanbul. This was followed by selecting two groups of DMs for criteria assessment that included academic-related professionals and fire brigade practitioners who have the requisite knowledge and experience within the scope of emergency planning.

The assessment stage, applying the criteria-based assessment approach, was conducted where the criteria were explicitly described and an agreed set of criteria was used by the DMs. From a survey of literature and various information sources, the evaluation criteria and constraints for the decision goal were determined. Applying the Delphi technique, questionnaires were designed to acquire the preference evaluations of the DM groups. The criteria weights were thereafter calculated according to their importance regarding the decision problem via pairwise comparisons of the Best-Worst Method (BWM) technique, representing the preferences and judgements of the DMs. A quantitative method using the consistency index of each DM was applied to derive the objective weights of the respective DMs (Koksalmis & Kabak, 2019). The DMs' individual preferences were computed, initially, and then aggregated.

Finally, in the selection/ranking stage, a calculation of the collective preference ordering (of the criteria weights) was done based on the results of the assessment stage for all the DMs' across both groups of the DMs' evaluations, separately. A simple arithmetic mean was used as an aggregation operator and for ranking in this process.

After the preference orderings of the DMs were evaluated, collectively, and in both groups separately, a consensus process was undertaken. This process was necessary to determine whether these results could be consolidated as the final weights of the fire station site selection goal and the design criteria for developing the BWM assessment model. For this determination, an overall measure of the consensus degree in the DMs' rankings, using *Kendall's coefficient of concordance, W* (Kendall, 1938), was proposed to be computed. Kendall's W is a meaningful measure of correlation/association for evaluating the degree of agreement between three or more sets of ranks on a given number of subjects/objects (Kendall, 1938; Sheskin, 2003). The possible values of W may fall between 0 and +1 (inclusive of both 0 and +1). If the value of $W = 1$, that indicates complete agreement among sets of ranks and if value of $W = 0$, there is no pattern of agreement (Kendall, 1938; Lee & Chan, 2008; Sheskin, 2003). The weights of the criteria determined from each of the DMs' preference evaluations were converted into the total number of DMs that formed the sets of ranks required for computing the Kendall’s W. The Kendall’s W for the rankings of evaluated criteria weights were calculated to determine the level of agreement among the DMs in each of the two DM groups. Kendall’s W is a ratio of the variance of the sums of the ranks for the subjects or objects divided by the maximum possible value that can be calculated for the variance of the sums of the ranks (for the relevant values of m and n) (Sheskin, 2003), summarized in Eq. (6).

$$W = \left(\frac{S}{m^2 n \,(n^2-1)/12} \right) \tag{2.6}$$

where,

S is the variance of the sums of the ranks for the subjects (i.e. the variance of the $\sum R_j$ values),

m is the number of decision-makers (DMs), relative to their rankings of the n subjects (criteria, in this study case).

The closer the value of W is to 1, denotes a high degree of agreement among the DMs in respect of how they rank the six criteria under evaluation.

Applying the BWM model, an interview of the two groups of DMs was undertaken to obtain their preference judgments regarding the decision problem of optimizing the selection of suitable fire station locations and for determining the related criteria weights. The premise upon which the two DM groups that have requisite knowledge and experience in related emergency planning services were chosen was the need to incorporate both academician/researcher-professionals and actual practitioners to gain both an inside knowledge and outside perspective view, objectively. In the survey, face-to-face interviews of the DMs using the adapted *Delphi method* were conducted.

The respondents were asked to indicate which criteria they deemed the most and least important to be used in the BWM for the determination of the weights and associated preference rankings. Additional statistical tests such as one-sample t-test, one-way ANOVA and Tukey's HSD test were used to analyse and make inferences about the DM group preferences. A total of nineteen experts were interviewed and information about their profile, background, and expertise was specified for each group of DMs in the subsequent sub-sections.

2.4.4.1 Academic-related professionals

A pool of ten academic-related professionals was selected for conducting the survey used in the BWM weight determination process. The background of these experts spanned planning, geomatics and industrial engineering fields with over 10 years' related experience in academics, research, and industry. All the DM experts have been involved in disaster and emergency planning activities and projects in Istanbul. Two of the DMs have Federal Emergency Management Agency (FEMA) certifications and are therefore well-recognised as emergency planning experts. Summary information of the experts' profiles and their corresponding weights were presented in Table 2.3.

2.4.4.2 Fire brigade personnel

Nine DMs working in the fire service stations and departments of Istanbul were selected to be interviewed for the BWM weight determination procedure. The fire brigade practitioners, all having more than 10 years' related experience, comprised personnel working as research, planning and coordinators, sectional heads, supervisors and firefighters. A summary of the background information about the DMs and their respective weights were provided in Table 2.4.

Table 2.3: Summary profile and weights of academician DMs.

Experts	**Background**	**Position**	**Expertise**	**Expert Weights (%)**
DM_1	Academia/ Geomatics Engineering	Associate Professor, Researcher	Disaster and Emergency Management Planning, MCDM Methods, GIS Planning	12.7
DM_2	Academia/ Geomatics Engineering	Professor, Researcher	Disaster and Emergency Management Planning, Spatial Planning, GIS	16.4
DM_3	Academia/ Geomatics Engineering	Professor, Researcher	Disaster and Emergency Planning Expert, GPS and Engineering Surveying, GIS	18.2
DM_4	Academia/ Geomatics Engineering	Professor, Researcher	Disaster and Emergency Management Planning, GIS Planning, MCDM Methods	10.9
DM_5	Academia/ Geomatics Engineering	Professor, Researcher	Disaster and Emergency Management Planning, Cartography, GIS	9.1
DM_6	Academia / Geomatics Engineering	Professor, Researcher	Disaster and Emergency Management Planning, GIS, Cartography	7.3
DM_7	Industry/ Urban and Regional Planning	Professor, Regional Planner	Urban Planning and Development, GIS, Disaster and Emergency Planning Expert	5.5
DM_8	Academia/ Industrial Engineering	Associate Professor, Researcher	Emergency Planning, Operations Research, MCDM Techniques	14.5
DM_9	Academia/ Geomatics Engineering	Assistant Professor, Researcher	Disaster and Emergency Management Planning, GIS, Spatial Planning	3.6
DM_{10}	Industry/ Urban and Regional Planning, Geomatics Engineering	Planner – Istanbul Metropolitan Municipality (IMM) Earthquake and Soil Investigation Directorate	Disaster and Emergency Management Planning, Urban and Regional Planning, GIS, Spatial Planning	1.8

Table 2.4: Summary profile and weights of fire brigade personnel DMs.

Experts	Background	Position	Expertise	Expert Weights (%)
DM_{11}	Fire Service Industry	Research and Planning Coordinator	Fire service, disaster, and emergency planning, research and planning	8.9
DM_{12}	Fire Service Industry	Research and Planning Coordinator	Fire service, disaster, and emergency planning, research and planning	2.2
DM_{13}	Fire Service Industry	Sectional Head	Fire service management, supervision, planning, coordination	6.7
DM_{14}	Fire Service Industry	Supervisor	Fire service supervision, fire service delivery, fire-fighting, coordination	15.6
DM_{15}	Fire Service Industry	Firefighters	Fire-fighting, emergency service delivery, search and rescue (SAR)	11.1
DM_{16}	Fire Service Industry	Firefighters	Fire-fighting, emergency service delivery, search and rescue (SAR)	4.4
DM_{17}	Fire Service Industry	Firefighters	Fire-fighting, emergency service delivery, search and rescue (SAR)	13.3
DM_{18}	Fire Service Industry	Firefighters	Fire-fighting, emergency service delivery, search and rescue (SAR)	20.0
DM_{19}	Fire Service Industry	Firefighters	Fire-fighting, emergency service delivery, search and rescue (SAR)	17.8

2.4.5 Data collection

In this study, the criteria were determined and subjectively evaluated by two groups of experts through a group decision-making (GDM) process using the BWM technique to calculate the final optimal weights to be used as input into ESRI ArcGIS software. Thereby, resulting in the production of raster suitability maps for suitably siting additional fire station facilities covering the whole of Istanbul province. Six criteria were determined, from the approach outlined in subsection 2.4.3, and most of the related data were acquired in the form of vector-based polygon data layers and converted to raster format at a cell resolution of 50 x 50 m^2 for further processing and analysis in a GIS environment, leading to the generation of final raster suitability maps after applying the weighted sum analysis function. Table 2.5 below shows the criteria, layer format, description and source of the data collected for GIS modelling in ESRI ArcGIS 10.3 software.

Table 2.5: Criteria data source, description and processing.

Criteria Layer	Data Format	Description	Data Source
HPD	Excel, Raster	Population density from population data for the year 2017, calculated by dividing the number of people over the respective sub-district area in hectares (ha).	Turkish Statistical Institute (TUIK, 2019)
PMR	Polygon, Raster	Updated main road network data was used to create multiple ring buffer analysis of incremental distance values of 60m, 120m, 180m, 240m, and 300m.	Istanbul Metropolitan Municipality (IMM)
DEF	Point, Polygon, Raster	Digitized point locations of 121 existing fire stations and updated road network data were used for running a network analysis in GIS for service areas determination within a fire response time of 5 minutes.	Istanbul Metropolitan Municipality (IMM) fire department database website
DHM	Excel, Raster	Records of facility locations containing most recent and comprehensive records of hazardous materials such as liquid petroleum gas (LPG), compressed gases, natural and processed gases/oils, oil stations, other chemicals substances.	Istanbul Metropolitan Municipality (IMM)
WBD	Raster	Computation of ratio of wooden buildings to the total number of buildings in each sub-district of Istanbul.	Istanbul Metropolitan Municipality (IMM)
DER	Raster	Istanbul earthquake hazard map resampled to cell resolution of 50 x 50 m^2 for calculating the distance from areas exposed to earthquake risk.	HAZTURK Project (Karaman et al., 2008)

2.5 Results and Discussion

This section discussed the research results from the determination of the criteria weights, related statistical tests including Kendall’s W for consensus measurement, comparative analysis using the analytical hierarchy process (AHP) for validating the BWM model, GIS analyses, production and comparison of two suitability maps for each DM group visualizing the optimal locations for establishing fire station facilities in Istanbul.

2.5.1 BWM results

The best-worst method (BWM) results of the questionnaire responses from both the academicians and fire brigade personnel decision-maker (DM) groups were analysed in terms of the pairwise comparisons, preference rankings and the weights of the criteria. Excerpts of pairwise comparisons for each case of one of the experts from the academician (DM$_1$) and fire brigade personnel (DM$_{11}$) groups were shown in Tables 2.6 and 2.7.

Table 2.6: Excerpt from BWM pairwise evaluation of academic expert (DM1).

Best-to-Others (BO)	**C$_1$** (HPD)	**C$_2$** (PMR)	**C$_3$** (DEF)	**C$_4$** (DHM)	**C$_5$** (WBD)	**C$_6$** (DER)
(a) Best Criterion: **C$_4$ (DHM)**	*1*	*4*	*4*	*1*	*3*	*6*

Others-to-Worst (OW)	Worst Criterion: **C$_6$** (DER)
(b)	
C$_1$ (HPD)	*5*
C$_2$ (PMR)	*3*
C$_3$ (DEF)	*3*
C$_4$ (DHM)	*6*
C$_5$ (WBD)	*5*
C$_6$ (DER)	*1*

Table 2.7: Excerpt from BWM pairwise evaluation of fire brigade personnel (DM11).

Best-to-Others (BO)	**C$_1$** (HPD)	**C$_2$** (PMR)	**C$_3$** (DEF)	**C$_4$** (DHM)	**C$_5$** (WBD)	**C$_6$** (DER)
(a) Best Criterion: **C$_1$** (HPD)	*1*	*4*	*7*	*2*	*6*	*7*

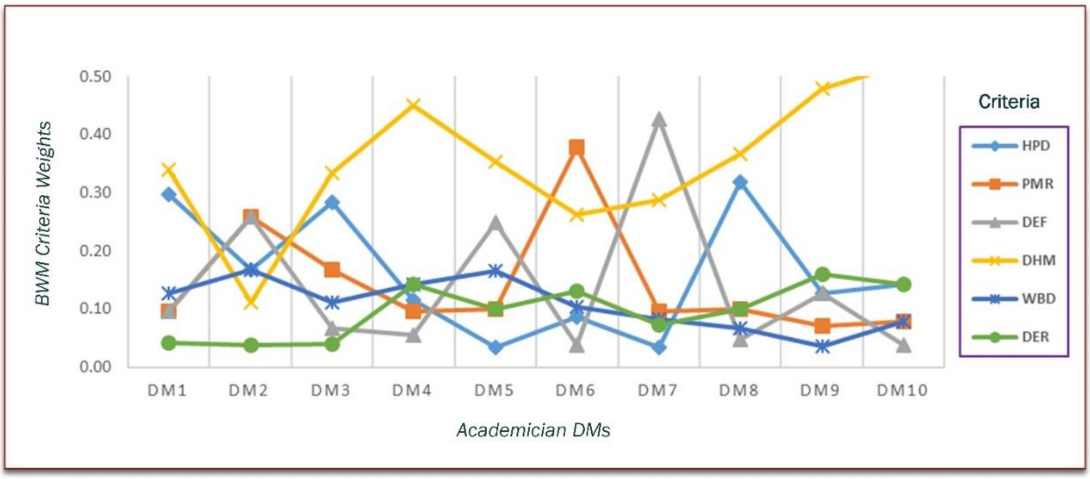
Others-to-Worst (OW)	Worst Criterion: **C$_3$** (DEF)
(b)	
C$_1$ (HPD)	*7*
C$_2$ (PMR)	*3*
C$_3$ (DEF)	*1*
C$_4$ (DHM)	*5*
C$_5$ (WBD)	*4*
C$_6$ (DER)	*3*

From the perspective of expert DM$_1$ (from the academicians' group), the density of hazardous materials (DHM) criterion was selected as the best, while the distance from earthquake-prone areas (DER) was considered as the worst criterion (Table 2.6). Table 2.7 reflected the fire brigade personnel's (DM$_{11}$'s) viewpoint where the high population density (HPD) criterion was chosen as the best while the distance to existing fire stations (DEF) was viewed as the worst criterion. Frequencies of the most and least important criteria preference ratings from the BWM weight coefficients calculated for each of the academicians and fire brigade personnel DM groups were shown in Table 2.8.

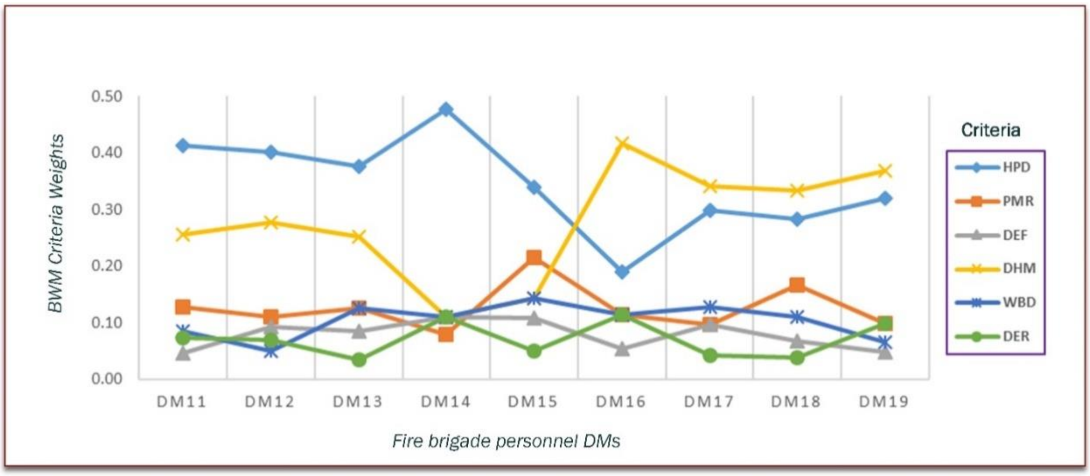
Table 2.8: Frequencies of the most and least important criteria preference ratings from BWM weights for each DM group.

Criteria	**Most important**		**Least important**	
	Academicians	*Fire brigade personnel*	*Academicians*	*Fire brigade personnel*
C$_1$ (HPD)	-	***5***	*2*	-
C$_2$ (PMR)	*1*	-	-	*1*
C$_3$ (DEF)	*2*	-	***4***	*3*
C$_4$ (DHM)	***7***	*4*	-	-
C$_5$ (WBD)	-	-	*1*	*1*
C$_6$ (DER)	-	-	*3*	***4***
Total no. of respondents	*10*	*9*	*10*	*9*

This showed the number of times the criteria were rated by each DM as the most and least important across the associated DM groups. From the academicians DM group, the most and least important criteria were DHM (with 7 out of the total 10 DMs) and DEF (with 4 DMs) respectively, while for the fire brigade personnel DM group, HPD criterion (with 5 out of the total 9 DMs) was the most important and DER, the least important criterion (with 4 DMs). The BWM weight coefficients calculated for each of the individual DMs in both the academician and fire brigade practitioner DM groups were illustrated in Figure 2.3.



(a)



(b)

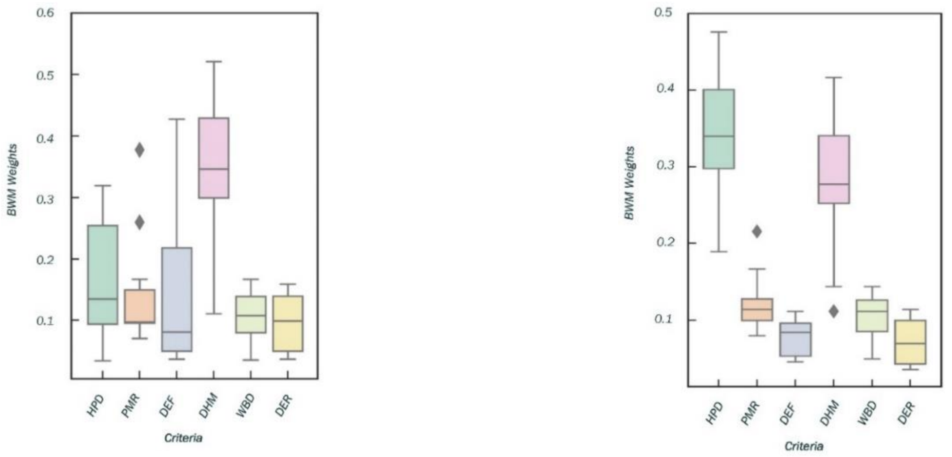
Figure 2.3: BWM criteria weights for each individual DM's preference in both DM groups: **(a)** Academician DMs; **(b)** Fire brigade personnel DMs.

In the academician DM group, the highest weight coefficient value of 0.4793 was computed for the DHM criterion by DM_9 and the lowest value of 0.0348 was calculated for the HPD criterion by DM_5. Whereas, in the fire brigade practitioner DM group, the HPD criterion weight value of 0.4762 by DM_{14} was the highest while 0.0354 was the lowest weight value determined for the DER criterion by DM_{13}. These preferences from the respondents were used as input for the BWM model to compute the final weights. Table 2.9 shows the summary statistics of the aggregated final BWM weights (tabulated in the mean column) for each of the academician and fire brigade practitioner DM groups. Additionally, the criteria weight rankings, minimum, maximum and standard deviation (s.d.) values were computed.

Table 2.9: Summary statistics of aggregated final BWM weights for each DM group.

Criteria	**BWM (weights)**									
	Academicians DM group					*Fire brigade personnel DM group*				
	Mean	*Rank*	*Min*	*Max*	*s.d.*	***Mean***	*Rank*	*Min*	*Max*	*s.d.*
C_1 (HPD)	***0.1608***	***2***	*0.0348*	*0.3193*	*0.1053*	***0.3441***	***1***	*0.1894*	*0.4762*	*0.0844*
C_2 (PMR)	***0.1439***	***3***	*0.0708*	*0.3775*	*0.0994*	***0.1261***	***3***	*0.0794*	*0.2155*	*0.0416*
C_3 (DEF)	***0.1403***	***4***	*0.0368*	*0.4273*	*0.1302*	***0.0783***	***5***	*0.0454*	*0.1111*	*0.0256*
C_4 (DHM)	***0.3504***	***1***	*0.1111*	*0.5211*	*0.1180*	***0.2775***	***2***	*0.1111*	*0.4167*	*0.1008*
C_5 (WBD)	***0.1082***	***5***	*0.0357*	*0.1667*	*0.0433*	***0.1038***	***4***	*0.0493*	*0.1436*	*0.0308*
C_6 (DER)	***0.0964***	***6***	*0.0370*	*0.1593*	*0.0468*	***0.0703***	***6***	*0.0354*	*0.1136*	*0.0312*
CR	*0.1195 < 0.25 (acceptable)*					*0.1016 < 0.25 (acceptable)*				

The consistency ratio (CR) was also calculated for each of the DM groups and determined to be acceptable (less than 0.25). From the final weight ranking results, the criteria were ranked in the following order for the academician DM group: $C_4 \succ C_1 \succ C_2 \succ C_3 \succ C_5 \succ C_6$ and for the fire brigade practitioner DM group: $C_1 \succ C_4 \succ C_2 \succ C_5 \succ C_3 \succ C_6$. The academician DM group viewed DHM (C_4) and DER (C_6) as the most and least important criteria respectively, while the fire brigade practitioner DM group considered HPD (C_1) as the most important criterion for optimal fire station facility location. In both DM groups, DER (C_6) was perceived as the least important criterion. Figure 2.4 compared the box plots with the associated BWM weight (mean) value distributions for each of the DM groups.



(a) **(b)**

Figure 2.4: Box plots of BWM criteria weight distributions for each DM group; **(a)** Academician DMs; **(b)** Fire brigade personnel DMs.

For a more thorough analysis to establish whether the criteria weight values within each DM group differed significantly, a statistical measure called the *one-sample t-test* was carried out.

2.5.1.1 One-sample t-test

To determine if there was a significant difference in the weight comparisons across the criteria, a *one-sample t-test* was performed. Assuming that each criterion was equally important, the weights for each criterion were assigned a value of 0.1667. This value was assumed to be the population mean and used as the test value in the one-sample t-test evaluation to ascertain if a significant difference existed between the weights of the criteria and the 0.1667 value. The results in Table 2.10 indicated for the academician DM group that C_1 (HPD), C_2 (PMR) and C_3 (DEF) criteria weights were not significantly different from the 0.1667 equal average weight since the corresponding significance values (sig.) or *p*-values were greater than 0.05 (alpha value). Thus, the null hypothesis (H_0) stating that the mean of differences is zero was accepted to be true.

Table 2.10: One-sample t test.

Criteria	**Academicians DM group**						**Fire brigade personnel DM group**					
					95% confidence interval						*95% confidence interval*	
	t	*df*	*Sig. (2-tailed)*	*Mean diff.*	*Lower*	*Upper*	*t*	*df*	*Sig. (2-tailed)*	*Mean diff.*	*Lower*	*Upper*
C$_1$ (HPD)	-0.1774	9	0.8631	-0.0059	-0.0812	0.0694	6.3066	8	0.0002	0.1774	0.1125	0.2422
C$_2$ (PMR)	-0.7254	9	0.4866	-0.0228	-0.0939	0.0483	-2.9284	8	0.0190	-0.0406	-0.0726	-0.0086
C$_3$ (DEF)	-0.6411	9	0.5375	-0.0264	-0.1196	0.0668	-10.3607	8	0.0000	-0.0884	-0.1081	-0.0688
C$_4$ (DHM)	4.9222	9	0.0008	0.1837	0.0993	0.2681	3.2973	8	0.0109	0.1108	0.0333	0.1883
C$_5$ (WBD)	-4.2748	9	0.0021	-0.0585	-0.0895	-0.0276	-6.1303	8	0.0003	-0.0629	-0.0866	-0.0393
C$_6$ (DER)	-4.7437	9	0.0011	-0.0703	-0.1038	-0.0368	-9.2615	8	0.0000	-0.0964	-0.1204	-0.0724

There was, however, a significant difference from the equal weight value for the remaining C_4 (DHM), C_5 (WBD) and C_6 (DER) criteria weights, since the respective significance values were less than 0.05 (alpha) and therefore the null hypothesis (H_0) was rejected. Within the fire brigade personnel DM group, the one-sample t-test results showed that all the six criteria weights were significantly different from the equal mean weight value of 0.1667 since the associated *p*-values for each criterion were less than 0.05 (alpha). These results provided new insight into the level of importance attached to the criteria for suitable fire station location studies. The criteria are not equally weighted (i.e. not homogeneous); therefore, every criterion has a different level of importance correlated by the assignment of relevant weight values.

Having established using the one-sample t-test that there were significant differences in the weight values for each DM group, a *one-way analysis of variance* (ANOVA) statistical test was conducted to determine if there was an overall significant difference between any of the criteria weights across the DM groups.

2.5.1.2 One-way ANOVA

A *one-way analysis of variance* (ANOVA) test was performed to check if there was an overall significant difference between the evaluated weights of the fire station selection criteria within both the academician and fire brigade personnel DM groups. The null hypothesis (H_0) of the comparisons stated that there was no significant difference between any of the weights of criteria for each DM group and the alternate hypothesis (H_1), to be tested, stated that there was a significant difference between the criteria. The results in Table 2.11 for both DM groups show that there was a significant difference in criteria weights.

Table 2.11: One-way ANOVA.

Weights	**Academicians DM group**					**Fire brigade personnel DM group**				
	Sum of Squares	*df*	*Mean Square*	*F*	*Sig.*	*Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
Between Criteria	*0.4336*	*5*	*0.0867*	*9.3055*	*0.00000195*	*0.5980*	*5*	*0.1196*	*33.2445*	*0.000000000000017*
Within Criteria	*0.5032*	*54*	*0.0093*			*0.1727*	*48*	*0.0036*		
Total	*0.9369*	*59*				*0.7707*	*53*			

The null hypothesis (H_0) was therefore rejected in favour of the alternative hypothesis (H_1) as the significance value (sig.) or *p*-value in both DM groups was less than 0.05 (alpha value). This analysis tells us that there was an overall significant difference in at least two criteria mean values but does not however show us exactly where the differences lie within the criteria comparisons. To locate and uncover these specific differences between the criteria means in both DM groups, a post-hoc statistical test called *Tukey's Honest Significant Difference* (HSD) test was applied.

2.5.1.3 Tukey's HSD test

The *Tukey's Honest Significant Difference* (HSD) post-hoc test was applied after the determination of the overall significance of results using ANOVA. Tukey's HSD test was used to find out which specific criteria means were different from each other by comparing all the possible pairs of mean values in both DM groups. Only the results of the Tukey test that indicated a significant difference in the paired comparisons of the criteria means were shown in Table 2.12.

Table 2.12: Tukey's HSD test.

					95% confidence interval	
(i) *criterion*	***(j)*** *criterion*	*Mean Difference (**i-j**)*	*Std. Error*	*Sig.*	*Lower Bound*	*Upper Bound*
Academicians DM						
C_4 *(DHM)*	***C_1*** *(HPD)*	*0.189609*	*0.043*	*0.000719*	*0.0621*	*0.3172*
	C_2 *(PMR)*	*0.206503*	*0.043*	*0.000192*	*0.0789*	*0.3341*
	C_3 *(DEF)*	*0.210101*	*0.043*	*0.000144*	*0.0825*	*0.3377*
	C_5 *(WBD)*	*0.242230*	*0.043*	*0.000010*	*0.1147*	*0.3698*
	C_6 *(DER)*	*0.253970*	*0.043*	*0.000004*	*0.1264*	*0.3815*
Fire brigade personnel DM						
C_1 *(HPD)*	***C_2*** *(PMR)*	*0.217955*	*0.028*	*0.000000*	*0.1340*	*0.3019*
	C_3 *(DEF)*	*0.265793*	*0.028*	*0.000000*	*0.1819*	*0.3497*
	C_5 *(WBD)*	*0.240289*	*0.028*	*0.000000*	*0.1564*	*0.3242*
	C_6 *(DER)*	*0.273728*	*0.028*	*0.000000*	*0.1898*	*0.3576*
C_4 *(DHM)*	***C_2*** *(PMR)*	*0.151386*	*0.028*	*0.000034*	*0.0675*	*0.2353*
	C_3 *(DEF)*	*0.199224*	*0.028*	*0.000000*	*0.1153*	*0.2831*
	C_5 *(WBD)*	*0.173720*	*0.028*	*0.000002*	*0.0898*	*0.2576*
	C_6 *(DER)*	*0.207159*	*0.028*	*0.000000*	*0.1232*	*0.2911*

Within the academician DM group, there was a significant difference observed in the paired comparisons between criterion C_4 (DHM) and all the other five criteria. Since the significance value (*p*-value) was less than 0.05 (alpha value) for all the five paired criteria comparisons, the null hypothesis (H_0) was rejected in favour of the alternative hypothesis (H_1) that states that all the combinations of the five paired criteria means were significantly different. The results showed that the C_4 (DHM) criterion was assigned a weight value that was so much higher and significantly different from all the criteria indicating its stronger influence and importance over all the other criteria. For the fire brigade personnel DM group, there was a significant difference in the weight values when the C_1 (HPD) and C_4 (DHM) criteria were each paired with the C_2 (PMR), C_3 (DEF), C_5 (WBD) and C_6 (DER) criteria indicated by the significance values that were less than 0.05 (alpha value). There was, however, no significant difference between the C_1 (HPD) and C_4 (DHM) criteria pairs. These findings indicated that both the C_1 (HPD) and C_4 (DHM) criteria were assigned significantly higher weight values that had the strongest influence and importance over all the other criteria but when compared to each other, neither had any significant influence over the other.

2.5.1.4 Kendall’s coefficient of concordance, W

The final BWM weights were computed for both the academician and fire brigade personnel DM groups from which the criteria rankings were obtained (Table 2.9). An analysis of the measure of agreement among the DMs in both the academician and fire brigade groups as well as the mean rankings of the criteria weights were evaluated using *Kendall’s coefficient of concordance*, *W*. The null hypothesis (H_0) that the distributions of the weights for the criteria were the same was rejected at a significance level of 0.05 for both DM groups and the results of the analysis were shown in Table 2.13.

Table 2.13: Kendall’s coefficient of concordance, W.

Criteria	*Academicians DM group*				*Fire brigade personnel DM group*			
	Mean Rank	*Std. Deviation*	*Minimum*	*Maximum*	*Mean Rank*	*Std. Deviation*	*Minimum*	*Maximum*
C_1 (HPD)	*3.60*	*1.647*	*2*	*6*	*1.44*	*0.527*	*1*	*2*
C_2 (PMR)	*3.60*	*1.269*	*1*	*5*	*3.67*	*1.130*	*2*	*6*
C_3 (DEF)	*4.05*	*2.108*	*1*	*6*	*5.06*	*1.054*	*3*	*6*
C_4 (DHM)	*1.60*	*1.265*	*1*	*5*	*1.78*	*0.972*	*1*	*4*
C_5 (WBD)	*4.05*	*0.943*	*3*	*6*	*4.17*	*1.000*	*3*	*6*
C_6 (DER)	*4.10*	*1.663*	*2*	*6*	*4.89*	*1.394*	*3*	*6*
Kendall's W	***0.264***	*p-value = 0.0215401*			***0.700***	*p-value = 0.0000075*		

The minimum (min.) column of Table 2.13 under the academician DM group, showed that the criteria C_2 (PMR), C_3 (DEF) and C_4 (DHM) were all ranked as the most important by at least one of the DMs and similarly, criteria C_1 (HPD), C_3 (DEF), C_5 (WBD) and C_6 (DER) each received the lowest rank from one of the ten DMs represented. Under the mean ranks column, criterion C_4 (DHM) was ranked the best overall with a rank of 1.60 while the least importance was assigned to criterion C_6 (DER) at 4.10. This result was consistent with the final criteria weight rank order from Table 2.9. Kendall’s coefficient of concordance, W was determined to be 0.264 and because the measure was less than 0.6 this indicated a low level of agreement (Kahraman et al., 2009) among the DMs in the academician group. The low consensus degree was attributed to the heterogeneity of the expert group that had diverging opinions.

The results from the fire brigade personnel DM group showed that criteria C_1 (HPD) and C_4 (DHM) were ranked with the highest level of importance by at least one of the DMs while the rest of the criteria ranked the least important. The overall mean ranking showed that criteria C_1 (HPD) and C_3 (DEF) were ranked as the most and least important, respectively with corresponding rank values of 1.44 and 5.06. There was a slight deviation from the rank order of the least important criterion determined to be C_3 (DEF) in comparison with that from the final weight ranking of C_6 (DER) criterion given in Table 2.9. The Kendall’s W of 0.700 was evaluated indicating a good level of agreement since the consensus level was more than 0.6 (Kahraman et al., 2009) among the fire brigade personnel DMs. The high consensus degree obtained was as a result of the homogeneity in the set of DMs within the fire brigade personnel that shared similar preferences.

2.5.2 Comparative analysis using AHP

The analytical hierarchy process (AHP) (Saaty, 1980) method, was used in this study for comparison and validation of the Best-Worst Method (BWM) results. For this analysis, the respondents comprising the two decision-maker (DM) groups of academicians and fire brigade personnel, were also asked to fill in a questionnaire designed based on the AHP method. The AHP model results were compared with BWM across the two DM groups and analysed by their respective pairwise comparisons, final aggregated weight coefficients of the criteria and their corresponding rankings, as well as the mean rankings from individual DM’s preference evaluations.

2.5.2.1 Aggregated criteria weight and ranking comparison

In the AHP model, the preferences (pairwise comparisons) of individual DMs from the academicians and fire brigade personnel groups were aggregated by taking the geometric mean to arrive at their corresponding final group weights of the criteria. Table 2.14 shows the summary of the obtained aggregated weight results from the AHP compared with the BWM results, for each DM group.

Table 2.14: Comparison of BWM with AHP weights.

Criteria	**Academicians DM Group**				**Fire brigade personnel DM Group**			
	BWM weights	*Rank*	***AHP weights***	*Rank*	***BWM weights***	*Rank*	***AHP weights***	*Rank*
C1 (HPD)	***0.1608***	*2*	***0.1584***	*2*	***0.3441***	*1*	***0.3644***	*1*
C2 (PMR)	***0.1439***	*3*	***0.1445***	*3*	***0.1261***	*3*	***0.1352***	*3*
C3 (DEF)	***0.1403***	*4*	***0.1012***	*5*	***0.0783***	*5*	***0.0678***	*5*
C4 (DHM)	***0.3504***	*1*	***0.3989***	*1*	***0.2775***	*2*	***0.2647***	*2*
C5 (WBD)	***0.1082***	*5*	***0.1033***	*4*	***0.1038***	*4*	***0.1115***	*4*
C6 (DER)	***0.0964***	*6*	***0.0938***	*6*	***0.0703***	*6*	***0.0564***	*6*
CR	*0.1195*		*0.0072*		*0.1016*		*0.0153*	

The consistency ratio (CR) calculated from the AHP showed an acceptable level of consistency in the pairwise comparisons of less than 0.1 for both the academicians (CR, 0.007) and fire brigade personnel (CR, 0.015) DM groups. Using the AHP method, the number of pairwise comparisons required for the calculation of the weight coefficients of the criteria, was 15, given by $n(n-1)/2$ pairwise comparisons, where n is equal to a total number of six criteria under consideration in this study. In contrast, the BWM required only 9 pairwise comparisons, $2n-3$. This demonstrated that the BWM provided a simpler and faster solution for the computation of the weights than the use of the AHP. Moreover, the BWM uses only integers which eased the calculations as opposed to both integers and fractional numbers used in AHP which made computations a tad difficult. Besides, the respondents from both DM groups found the BWM to be easier to understand than the AHP and could, therefore, more easily revise their preferences to improve the consistency.

From the AHP weights, the criteria were possible to be ranked in the following sequence for the academician DM group: $C_4 \succ C_1 \succ C_2 \succ C_5 \succ C_3 \succ C_6$ and for the fire brigade personnel DM group: $C_1 \succ C_4 \succ C_2 \succ C_5 \succ C_3 \succ C_6$. In comparison with the

BWM results, the AHP criteria rank order is closely similar except for criteria C_3 and C_5 which are interchangeably ranked 4th and 5th respectively in the BWM model. In the AHP, criteria DHM (C_4) and DER (C_6) were also perceived as the most and least influential, respectively whereas, for the fire brigade personnel DM group, HPD (C_1) was considered the most important criterion. The criteria rank order of the AHP for the fire brigade DM group was the same and therefore consistent with that from the BWM model, where DER (C_6) criterion was also viewed as the least important in both DM groups.

2.5.2.2 Comparison of mean rankings

The mean criteria rankings of the AHP model, based on the individual DM criteria preference rankings from both the academician and fire brigade personnel DM groups were computed and the obtained results were presented in Table 2.15.

Table 2.15: Mean rankings of AHP based on individual DM preference evaluations.

Criteria	***Academicians***						***Fire brigade personnel***					
	BWM Mean rank	*Min*	*Max*	***AHP Mean rank***	*Min*	*Max*	***BWM Mean rank***	*Min*	*Max*	***AHP Mean rank***	*Min*	*Max*
C_1 (HPD)	***3.60***	*2*	*6*	***3.30***	*1*	*6*	***1.44***	*1*	*2*	***1.3***	*1*	*2*
C_2 (PMR)	***3.60***	*1*	*5*	***3.40***	*1*	*5*	***3.67***	*2*	*6*	***3.6***	*2*	*5*
C_3 (DEF)	***4.05***	*1*	*6*	***4.10***	*1*	*6*	***5.06***	*3*	*6*	***5.0***	*4*	*6*
C_4 (DHM)	***1.60***	*1*	*5*	***1.60***	*1*	*4*	***1.78***	*1*	*4*	***1.9***	*1*	*3*
C_5 (WBD)	***4.05***	*3*	*6*	***4.20***	*2*	*6*	***4.17***	*3*	*6*	***3.8***	*2*	*5*
C_6 (DER)	***4.10***	*2*	*6*	***4.40***	*2*	*6*	***4.89***	*3*	*6*	***5.4***	*4*	*6*

In the AHP academician DM group, at least one of the DMs ranked the criteria C_1 (HPD), C_2 (PMR), C_3 (DEF) and C_4 (DHM) as the most important based on individual DM preference evaluations. Compared with the BWM result from Table 2.13, only three criteria: C_2 (PMR), C_3 (DEF) and C_4 (DHM) were ranked as the most important at least once by the DMs. Similar to the BWM model, criteria C_1 (HPD), C_3 (DEF), C_5 (WBD) and C_6 (DER) were assigned the lowest rank in the academician DM group. Consistent with the AHP criteria weight rank order (Table 2.14) and the mean criteria ranking from BWM (Table 2.13), criterion C_4 (DHM) was ranked the best overall with a mean rank of 1.60 whereas the lowest level of importance was attached to criterion C_6 (DER) at 4.4 for the academician DM group.

From the AHP model, at least one of the DMs in the fire brigade personnel DM group ranked criteria C_1 (HPD) and C_4 (DHM) with the highest importance level similar to the result from BWM whereas criteria C_3 (DEF) and C_6 (DER) were ranked as the least important. In contrast with the AHP model, the lowest importance ranking by at least one of the DMs in the BWM model included two extra criteria, C_2 (PMR) and C_5 (WBD). In the overall mean rankings of the AHP model, criteria C_1 (HPD) and C_6 (DER) were ranked as the most and least important, respectively with associated mean ranking values of 1.33 and 5.44. The mean rank order of the most important criterion was consistent though differed only in the least important criterion with that from the BWM result of mean rankings (Table 2.13) as well as final weight ranking (Table 2.9) for the fire brigade personnel DM group.

After the criteria identification and screening, the final weights from both the academician and fire brigade DM groups were evaluated through the proposed group decision-making (GDM) procedures discussed in the previous sub-sections, using the BWM. A degree of consensus was evaluated among the DM groups using *Kendall's W* from subsection 2.5.1.4. Additional statistical tests that included the *one-sample t-test*, *one-way ANOVA* and *Tukey's HSD test* showed significant differences in the criteria weight values clarifying the distinctions in the levels of importance and influence of criteria across the two DM groups. The BWM model results for each of the two DM groups were determined to be consistent and reliable as shown in the acceptable consistency ratios (CRs), comparison analyses by aggregated weights, their respective rankings, and validation of the model conducted using AHP.

2.5.3 GIS analysis

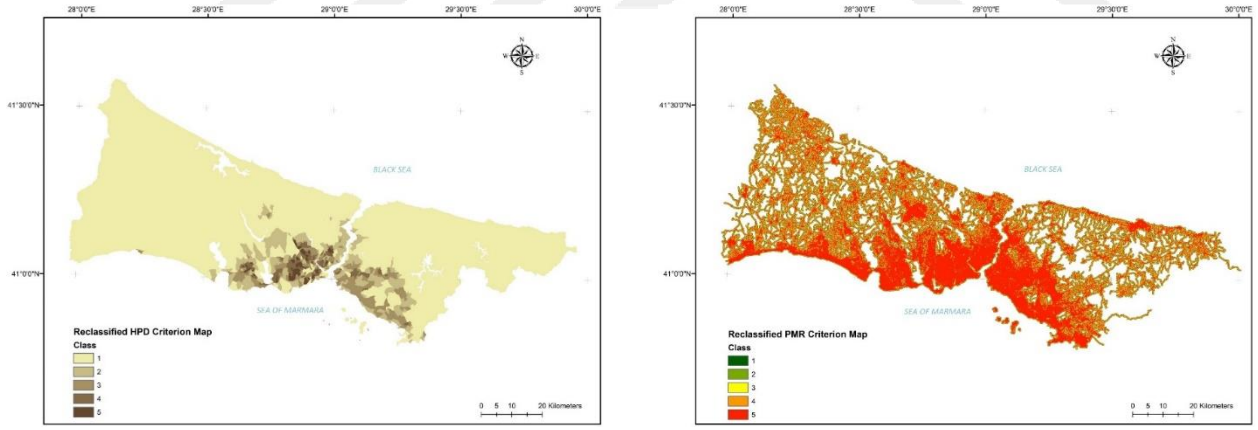
The calculated weights from the BWM model were subsequently applied onto the criteria for each of the two DM groups in the form of processed criteria map layers in GIS to spatially identify optimal areas, visualized via two resultant raster suitability maps for locating fire station facilities within a 5-minute response time for the case study region of Istanbul. ESRI ArcGIS 10.3 software was used to process and analyse each of the criterion map layers in vector data format before their conversion to raster data at a defined cell resolution of 50 x 50 m^2. The value ranges of the criteria were determined in terms of their corresponding thresholds of suitability for locating fire station facilities based on expert knowledge and input. A reclassification procedure using the natural breaks (Jenks) classification method was applied onto the criteria raster map layers using new class values ranging from 1 to 5, indicating a corresponding suitability value representation from very low to very high as shown in Table 2.16.

Table 2.16: Suitability map class value representation.

Suitability class values	**Criteria** (*measurement units per sub-district area of Istanbul province*)					
	C$_1$ (**HPD**)	C$_2$ (**PMR**)	C$_3$ (**DEF**)	C$_4$ (**DHM**)	C$_5$ (**WBD**)	**C$_6$** (**DER**)
	No. of people per hectare	*Metres*	*Service areas in minutes*	*Number of, per sub-district*	*The ratio in, total no. of buildings*	*PGA* values in g*
Class 1 - Very Low	0.0 - 44.8	240 - 300	1	0 - 4	0.0 - 10.3	1.6 - 2.4
Class 2 - Low	44.8 - 146.6	180 - 240	2	4 - 15	10.3 - 46.5	1.1 - 1.6
Class 3 - Medium	146.6 - 303.4	120 - 180	3	15 - 36	46.5 - 175.7	0.8 - 1.1
Class 4 - High	303.4 - 519.0	60 - 120	4	36 - 67	175.7 - 464.3	0.5 - 0.8
Class 5 - Very High	519.0 - 1333.2	0 - 60	5	67 - 153	464.3 - 1781.8	0.0 - 0.5

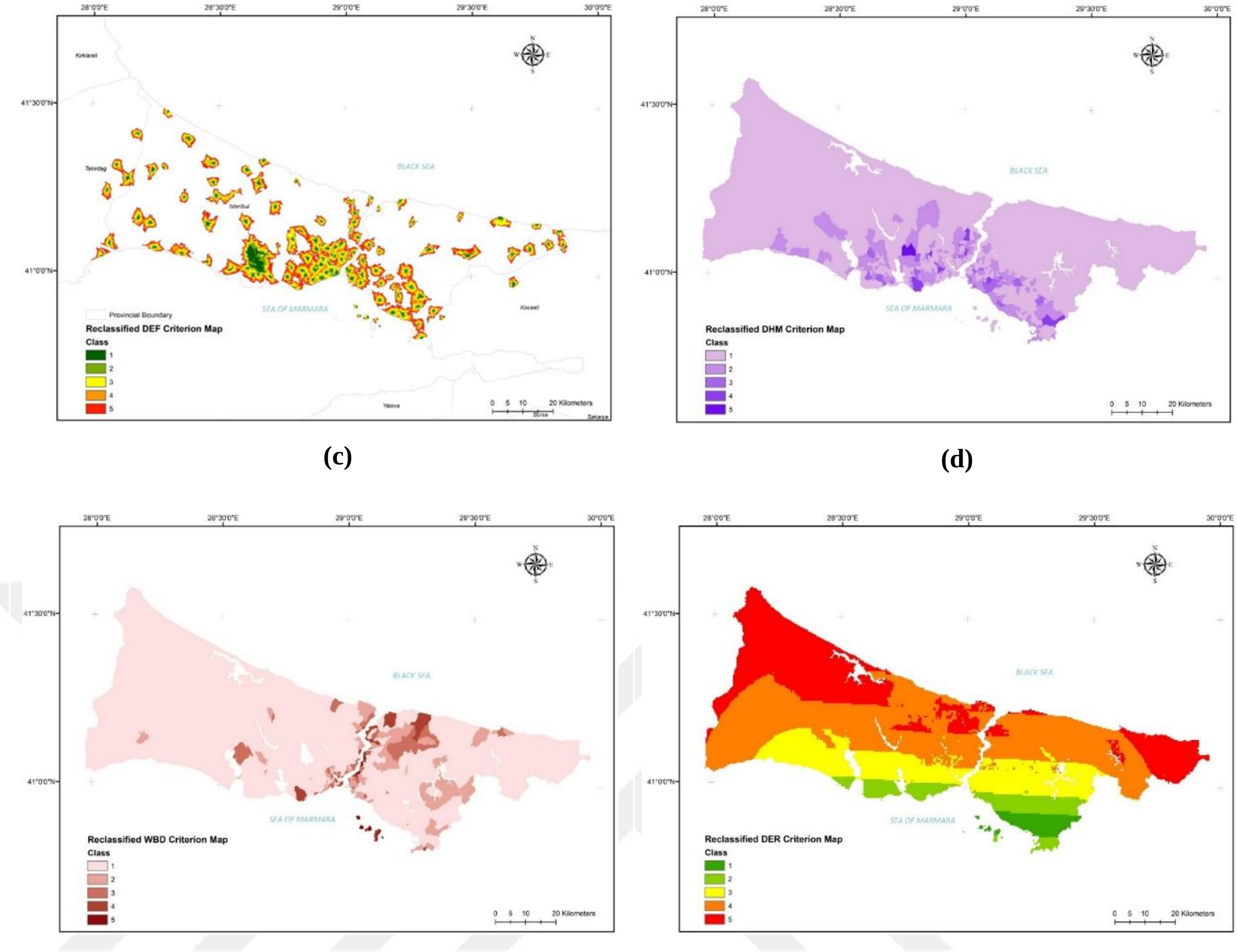
**PGA is the peak ground acceleration value of the Istanbul earthquake hazard map, in units of acceleration due to gravity (g)*

The six reclassified criteria raster map layers using the suitability index values ranging from 1 to 5 were presented in Figure 2.5.



(a) **(b)**

Figure 2.5: Reclassified raster criteria map layers; **(a)** HPD, **(b)** PMR, **(c)** DEF, **(d)** DHM, **(e)** WBD and **(f)** DER.



(c) (d)

(e) (f)

Figure 2.6 (continued): Reclassified raster criteria map layers; **(a)** HPD, **(b)** PMR, **(c)** DEF, **(d)** DHM, **(e)** WBD and **(f)** DER.

The BWM weights for each of the two DM groups were eventually multiplied by their respective reclassified criteria raster map layers using a *weighted sum – overlay* analysis and final reclassification operation in ArcGIS that resulted in the production of two separate composite raster suitability maps for new optimal fire station areas, each representing the academician (Figure 2.6) and fire brigade (Figure 2.7) DM groups, as illustrated.

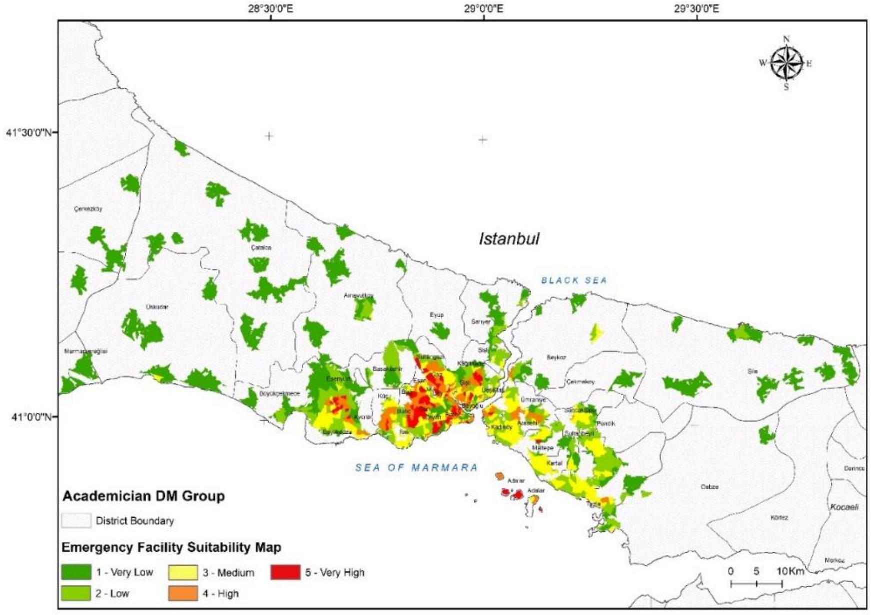


Figure 2.7: Academician DM group - suitability raster map for the new fire station and emergency facility areas of Istanbul.

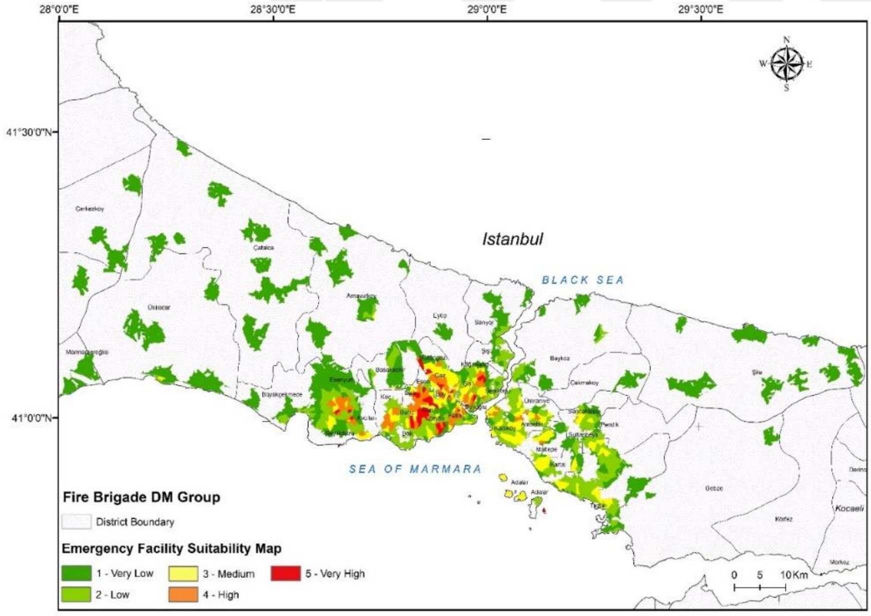


Figure 2.8: Fire brigade personnel DM group - suitability raster map for the new fire station and emergency facility areas of Istanbul.

2.5.3.1 Comparison of suitability maps

The raster suitability maps for locating new fire station facilities were generated as shown in Figures 2.6 and 2.7, based on the criteria weight inputs computed from the BWM preference evaluation procedure for both the academician and fire brigade personnel DM groups. The raster maps provided the necessary support in the group decision-making (GDM) process to spatially resolve the emergency facility location problem and visually present the model outputs to reflect the perceived levels of importance that each DM group had on the criteria under evaluation. A visual comparison of the two suitability maps indicated a similarity in the classified suitability areas depicting a high level of correlation and consistency in the BWM model result of the academician and fire brigade personnel DM group criteria weight evaluations. The noticeable variation between the two raster maps were distinguished by the presence of slightly more classified areas for the academician DM group than that for the fire brigade personnel DM group, represented by medium (class 3), high (class 4) and very high (class 5) suitability areas that were depicted in yellow, orange and red colours, respectively. The choice of red colour selected for the class representation for very high (class 5) suitability also intended to reflect the vulnerability corresponding to high population areas exposed to fire risk.

To thoroughly assess the spatial variability between the suitability maps, the two maps were compared statistically. A cell-by-cell comparison was applied to assess the similarity for each pair of pixels between the raster suitability maps and computed by dividing the number of equal pixels in both maps (361,456 pixels) by the total number of pixels (459,075 pixels). The spatial distribution of agreement as an overall measure of similarity was determined to be 0.787 or 78.7% (361,456 pixels/ 459,075 pixels) indicating a very high correlation between the maps. The similarity measure corresponding to 78.7% of the total number of pixels in similar class distributions of the two maps was represented by a total area coverage of 903.64 km^2.

A more accurate similarity measure called the *Kappa statistic* was used that accounted for bias in the model attributed to the overestimation of prevalent class categories by considering the total number of classes as randomly distributed over the maps. The similarity between the observed and predicted results is assessed by the *Kappa statistic*, *K* which is a function of two similarity statistical types: similarity in quantity, *Kappa Location* (or *KLoc*, that refers to the total number of pixels as a fraction of all pixels in a particular class over the entire map) and similarity of location, *Kappa Histo* (or *KHisto*, referring to the spatial distribution of two classes over the compared maps) (Hagen, 2002; Pontius, 2000). Therefore, for the map comparison analysis, Kappa statistic, K given by KHisto * KLoc, was calculated based on the *contingency table* (also referred to as *confusion matrix*) as depicted in Table 2.17.

Table 2.17: Contingency table.

Statistical measures	Suitability Map Classes				
	Class 1	***Class 2***	***Class 3***	***Class 4***	***Class 5***
Kappa	*0.849*	*0.527*	*0.499*	*0.568*	*0.666*
KLoc	*1*	*0.549*	*0.640*	*0.669*	*1*
KHisto	*0.849*	*0.961*	*0.780*	*0.849*	*0.666*

The contingency table, expressed in a cross-tabular matrix form consisting of the number of pixels and total map class areas detailed how the distribution of classes in the suitability map for the academician DM group related to that of the fire brigade DM group suitability map, and their corresponding total class area covered in km^2.

The overall *Kappa*, *KLocation*, and *KHisto* were determined to be 0.66 (66.0%), 0.768 (76.8%) and 0.859 (85.9%) respectively, for the two comparison maps. The Kappa statistics for each suitability map class are presented in Table 2.18.

Table 2.18: Kappa statistics for each suitability map class.

Academician DM Group Suitability Map Classes	Fire brigade personnel DM Group Suitability Map Classes					No. of Pixels	Total area (km^2)
	Class 1	***Class 2***	***Class 3***	***Class 4***	***Class 5***		
Class 1	*236,102*	*0*	*0*	*0*	*0*	*236,102*	*590.26*
Class 2	*34,404*	*64,371*	*0*	*0*	*0*	*98,775*	*246.94*
Class 3	*0*	*39,203*	*35,343*	*0*	*0*	*74,546*	*186.37*
Class 4	*0*	*1,315*	*14,060*	*16,669*	*0*	*32,044*	*80.11*
Class 5	*0*	*0*	*1,224*	*7,413*	*8,971*	*17,608*	*44.02*
						459,075	***1,147.69***

The Kappa statistical measures calculated indicated a high correlation and similarity between the academician and fire brigade DM group suitability maps, confirming the observations earlier inferred from the visual map interpretation.

2.6 Conclusions

This study presented a group decision-making (GDM) approach based on the integration of a novel Best-Worst Method (BWM) and GIS for planning suitable areas for the new urban fire station and emergency facilities in Istanbul. The suggested model incorporated the perspectives of two groups of decision-makers (DMs) comprising academic-affiliated professionals and fire brigade practitioners with related experience in emergency planning and disaster management activities. The study aimed to explore the different points of view of DMs in connection with the decision problem from an insider perspective for the case of fire brigade practitioners and an outsider viewpoint for the case of academic professionals.

From a survey of literature and expert input, criteria for suitability assessment of new fire station sites in Istanbul were comprehensibly determined from social, environmental, spatial, risk and safety considerations. Utilizing a new MCDM method called BWM, the relevant weights and preference rankings were derived based on pairwise comparisons of the best and worst criterion for each DM across the two DM groups. To check the reliability of the final weight results, a consistency ratio (CR) for each DM group was calculated and determined to be acceptable. From the individual decision matrices, the objective weights of the experts were derived using their respective consistency indices. The higher weights of the experts were assigned to those with higher consistency values. The results were also compared with the AHP method for validating the BWM model by considering the pairwise comparisons, computed weights, rankings from the weights and mean rankings. The BWM model proved to be a much simpler and faster approach for weight computation as it required fewer comparisons, 9 than the AHP which required 15. The final BWM weights, rankings from weights and mean rankings showed consistent and reliable results with the AHP.

From the results of the BWM weights, statistical tests that included the *one-sample t-test, one-way ANOVA* and *Tukey's HSD test* for each DM group, it can be inferred that the academician DM group strongly views the criterion, C_4 (DHM) as the most important for the fire station and emergency facility selection studies. This was apparent from the higher weight assignment and dominance that this criterion, C_4 (DHM) had over all the other criteria. From the fire brigade practitioners' perspective, criterion C_1 (HPD) was viewed as the most important. This was not an unusual phenomenon considering that the practitioners interact more with affected people in communities and view saving people's lives through rescue and emergency operations as their main objective and focus. Both DM groups considered criterion C_6 (DER) as the least important.

A degree of consensus was evaluated among respective DMs for both DM groups using *Kendall's coefficient of concordance*, *W* which indicated a low to a high level of agreement. It could be explained that a higher level of agreement was reached for the fire brigade personnel DM group because it was obvious that this group of DMs comprised like-minded individuals working in similar work environments/functionalities that shared the same perception, values and belief systems relating to fire station and emergency facility planning considerations. The academician DM group, on the other hand, incorporated experts of different training backgrounds, experiences, and specializations with more divergent views on the importance levels of criteria for emergency facility planning.

The planning decision outcome of establishing suitable sites for new urban fire station facilities could be visualized in the form of raster suitability maps via GIS depicting each DM group's influence on the overall result from the application of aggregated BWM weights on the criteria. The two raster suitability maps were compared visually and through the use of the *Kappa statistic* (calculated value of 0.66) to show high correlation and similarity. This indicated a high level of agreement between the two DM groups and demonstrated the utility and usability of the produced maps for requisite emergency facility planning and service management by relevant authorities and policy-makers.

The proposed group decision-making framework using a BWM-GIS hybrid model ensures that the fire station and emergency facilities are sufficiently planned for achieving sustainable development of urban environments. The quality of the overall planning decision process is therefore enhanced through explicitly promoting inclusiveness by stakeholder participation and improving the resilience of communities at risk by mitigating the social, environmental and economic impacts of fires.

3. A HYBRID APPROACH INTEGRATING ENTROPY-AHP AND GIS FOR SUITABILITY ASSESSMENT OF URBAN EMERGENCY FACILITIES[2]

3.1 Abstract

Globalization has become a major issue of focus as rapid urban populations and urbanization effects are on the rise. A critical need arises for effective urban planning for Istanbul in relation to the use of a hybrid approach integrating AHP-Entropy and GIS for emergency facility planning. In this paper, the combination of AHP and Entropy methods were used for evaluating criteria weights subjectively and objectively. These techniques were utilized with regard to the assessment of suitable areas for planning new urban emergency facilities for Istanbul province which experiences increasing urban fire-related emergencies. AHP and Entropy have been used to evaluate the weights of determined criteria from expert preference judgments and GIS for processing, analysis and visualization of the model result in the form of a suitability map for new urban emergency facilities. Validation of the model was performed on the criteria with the strongest influence on the decision outcome and spatially visualized using the Sensitivity Analysis (SA) method of One-At-a-Time (OAT). From the findings, it was estimated that 28.1%, accounting for a third of the project area is likely to be exposed to the risk of urban fires and therefore immediate planning of new urban emergency facilities is recommended for adequate fire service coverage and protection.

Keywords: Geographic information system (GIS); analytical hierarchy process (AHP); entropy; emergency facilities; multi-criteria decision making (MCDM); sensitivity analysis

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[2] This chapter is based on the article: Nyimbili, P. H., Erden, T., 2020: A hybrid approach integrating Entropy-AHP and GIS for suitability assessment of urban emergency facilities, ISPRS International Journal of Geo-Information, 9(7), 419. doi: https://doi.org/10.3390/ijgi9070419

3.2 Introduction

The phenomenon of technological development, globalization, population growth and its effects have given rise to urbanization. The growth and expansion of cities have been accentuated by the rise in population and migration to urban regions (Dociu & Dunarintu, 2012). This prevalence has also brought about the growing concern and potential risk of fires causing loss of lives and property damage, consequently, posing a threat to urban societies.

Istanbul is regarded as a regional economic, cultural and historic hub in the Euro-Asian region. It is the most urbanized province of Turkey inhabited by more than 15 million people, representing almost 20% of the country's population (TUIK, 2020). Concurrently, there has been a high and recurrent rise in the number of fire incidences experienced in Istanbul. More than 58,000 fire occurrences having an average response time exceeding five minutes have been reported by the Istanbul Metropolitan Municipality Department of Fire Brigade (IMM, 2016). Fire incidences mainly arise from careless actions or misuse of hazardous, flammable/explosive material and after strong earthquake eventualities (Girgin, 2011) which cause infrastructural damage with the most vulnerable facilities being large industrial and oil plants, electrical and gas lines (ISMEP, 2009). Against this background, this study aims to suggest a GIS-based Multi-Criteria Decision Analysis (MCDA) methodology for assessing the feasibility of planning additional urban fire and emergency facility locations by reducing the fire response time to within five minutes for a case study region of Istanbul. Thereby, mitigating fire impacts and risks lead to an improvement in fire safety and protection services as part of emergency preparedness and response planning action.

MCDA methods were developed to resolve complex problems that have many criteria to be considered, incorporating a broad range of opinions among stakeholders and conflicting goals in the process of making decisions. The common goal is to systematically select the most optimum planning decision outcome that transcends the shortcomings of the unstructured individual or group decision-makers, among many available alternatives based on varied criteria (Afshari et al., 2016; C. Lin et al., 2020). The selection of new urban fire facility sites represents a spatial, complex planning problem that requires a thorough and careful analysis of numerous criteria and the involvement of multi-disciplinary teams across different planning functions. Many MCDA methods exist and are more commonly used such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang & Yoon, 1981), Analytical Hierarchy Process (AHP) (Saaty, 1980), ELimination and Choice Expressing REality (ELECTRE) (Roy, 1968, 1990), CRiteria Importance Through Intercriteria Correlation (CRITIC) (Diakoulaki et al., 1995), Multi-Attribute Utility Theory (MAUT) (Steuer, 1986), Simple Multi-Attribute Rating Technique (SMART) (Edwards, 1971, 1977), Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) (Brans, 1982; Brans & Vincke, 1985). The key aspects of any MCDA problem require decision-makers' (DMs) or experts' judgements for appraising feasible alternatives based on multiple, conflicting and incompatible criteria (Malczewski & Rinner, 2015). Numerous spatial decisions often involve more than one DM as opposed to a single DM in a group decision-making (GDM) process. This is undertaken to enhance the quality of the decision-making endeavour as well as to minimize possible conflicts by building a higher degree of consensus. Elements of geographic decision alternatives involve the course of action to be taken and the location which can either be defined implicitly or explicitly, depending on the selected GIS data models (Malczewski, 1999, 2006). Site and facility selection, location-allocation and land-use suitability problems are representative of explicitly spatial alternatives such as (Erden & Coskun, 2010).

Processes for addressing spatial multi-criteria problems are premised on three fundamental concepts which form the foundation of GIS-MCDA approaches. These spatial decision support procedures include standardization, the weighting of criteria and decision rules. Standardization or value scaling procedures convert raw data of the criteria under evaluation to units that can be comparable. Criteria can be assigned values that indicate their level of importance relative to the other criteria under review and subsequently used by the relevant MCDA method in the evaluation of the decision alternatives (Zardari et al., 2015). The methods for criterion weight assessment can be categorized into global and local techniques. Local weighting methods account for the spatial heterogeneity of DM preferences whereas global methods assume that the DMs' preferences are spatially homogeneous and therefore a single weight is allocated to each criterion. Global weighting methods consist of rating, ranking, pairwise comparisons (e.g., AHP) and entropy techniques (Malczewski & Rinner, 2015). The criterion weighting process involving rating, ranking and pairwise comparison (Malczewski, 2006) methods are done subjectively, relying on the experts' judgements. The entropy-based technique, on the other hand, assigns weights objectively by mathematical determination of initial criterion value information (Hwang & Yoon, 1981) and therefore does not necessitate DMs to specify their preferences in relation to the evaluation criteria (Malczewski & Rinner, 2015).

Within this context, Entropy-based GIS-MCDA methods have been suggested to consider objective weighting approaches. These procedures evaluate criteria weights by use of mathematical models without the involvement of DM preferences which would bring subjectivity in the judgement information affecting the final decision outcome (Aalianvari et al., 2012). Very few Entropy-based criteria weighting methods have been utilized for GIS-MCDA applications (Malczewski & Rinner, 2015). Li et al. (2012) and Zheng et al. (2009) proposed the use of this criteria weighting method as TOPSIS and GIS-based Weighted Linear Combination (WLC) modules, respectively. Further, it has been suggested that GIS-MCDA methods should incorporate both subjective and objective criterion weighting techniques (Sahoo et al., 2016).

In the present study, a GIS-MCDA hybrid approach utilizing the AHP, combined with the Entropy technique has been recommended for assessing ideal locations of urban emergency facilities in Istanbul. GIS is proposed to be used as a spatial decision support tool for analysis and visualization of outputs in the form of raster suitability maps, therefore enhancing the quality of the planning decision. GIS analytical approaches have been utilized in many natural disasters and emergency-related research areas. A study by Lin et al. (2020) explored the use of a data mining technology applying an integrative self-organizing data (ISODATA) analysis and maximum likelihood (ISO-Maximum) clustering algorithm in a GIS environment to assess flash flood risk in Guangdong Province of China. The clustering algorithm was used to efficiently obtain flood risk classification results where deficiency of data existed leading to the production of the risk clustering map and final flash flood hazard, vulnerability and risk maps. García-Ayllón et al. (2019) used geostatistical analysis tools in a post-earthquake evaluation of seismic damage indicators for Lorca city in Spain. Bivariate GIS assessment was utilized to show a spatial statistical correlation of the distribution of the earthquake variables using geo-process and geostatistical tools in ESRI ArcGIS software. The geostatistical functions of Global Moran’s I, Anselin Local Moran’s I and Getis-Ord Gi were used to analyse the degree of spatial autocorrelation, the cluster and outliers and the segmentation of cold and hot spots, respectively. An optimized hot spot analysis (OHSA) using the Getis-Ord Gi statistic in GIS interface was implemented by Lu et al. (2019) for analyzing incremental spatial autocorrelation in Landslide surface detection and risk studies across the Volterra area of Italy. Maqsoom et al. (2020) applied the DRASTIC index function of the ArcGIS platform for modelling the groundwater susceptibility risk and vulnerability to contamination in Gilgit Baltistan City, Pakistan. In their study, a map removal sensitivity analysis using the raster math tool in GIS was also performed to analyze the model sensitivity.

In the literature, to the best of the authors’ knowledge, there has been no study conducted within the fields of emergency and fire facility planning that utilized the proposed model, worldwide. This, therefore, offers a unique research opportunity to be explored. In recent years, several studies related to the use of AHP and GIS for urban fire station facility selection were reviewed (Arabameri, 2014; Chaudhary et al., 2016; Dong et al., 2018; Erden & Coskun, 2010; Habibi et al., 2008; Lai et al., 2011; Tali et al., 2017; Uddin & Warnitchai, 2020; Wahab & Khayyat, 2014; W. Wang, 2019; Yagoub & Jalil, 2014). Many influencing factors can be considered for the location of new urban emergency facilities. For instance, Wang (2019) proposed the use of combined GIS, AHP and fuzzy evaluation methods for optimizing the locations of new fire stations in China by considering four selection factors such as social services, transit time, environmental geography and cost of fire station construction as well as operation. Chaudhary et al. (2016) assessed the population density, distance from roads, distance from rivers and land cover which included built-up areas to be ideal criteria for fire station suitability zone mapping using AHP and GIS in Kathmandu Metropolitan City of Nepal. Dong et al. (2018) attributed the complex layout of urban geography and increasing urban developments that included factories and warehouses as the main source of fire risks in Linyi city of China. The constraints of emergency facility planning layout incorporated drive time and road traffic conditions, the shortest path to the major fire risk and demand points, fire risk emergency rescue considering a response time of five minutes and capital costs. Population density and socio-economic criteria that included proximity from multi-story residential areas, health centres, commercial/shopping malls and public parks were considered by Wahab & Khayyat (2014) in their suitability analysis study integrating AHP and GIS approaches to select optimum sites for new fire departments in Erbil City, Iraq. Other researchers such as Lai et al. (2011) selected the population density, road distance to the nearest fire station and building loss criteria for layout planning of fire stations using GIS and AHP in Beijing, China. Habibi et al. (2008) considered the population density, accessibility, distance to high fire risk areas and plot sizes criteria for selection of fire stations utilizing the AHP, GIS and Index Overlay (IO) model in Tehran, Iran. Tali et al. (2017) proposed a location-allocation model for locating fire stations in the urban area of Mysore, India. They used the existing road network, location of existing fire stations, land use/land cover map for identifying available sites and fire incident data as the most essential criteria in the model analysis. The service area and location analysis were performed using the network analysis function in ArcGIS software.

In a recent study by Uddin & Warnitchai (2020) applied to Dhaka in Bangladesh, the main criteria of elements at risk, fire hazard, spatial and geological settings were evaluated for optimizing the location of new urban fire station facilities. These included assessed sub-criteria such as the density of population, residential and commercial buildings, critical facilities, fire hazard from an earthquake, the average distance from critical facilities, connectivity and accessibility via major roads, soil amplification factor and liquefaction susceptibility for earthquake vulnerability analysis. From the studies reviewed, the common factors considered to be essential for selecting ideal sites for fire stations in urban regions were identified and incorporated in our research. These included population density (HPD), proximity to arterial and main roads (PMR), distance to existing fire stations (DEF) and density of hazardous material facilities (DHM). Determination of ideal criteria is based on suitability to the prevailing local conditions of the study region, expert knowledge and availability of data. Accordingly, our proposed research procedure adopted additional selection factors such as the density of wooden buildings (WBD) and since Istanbul lies in a seismically active and fault zone, the distance to areas prone to earthquake risk (DER) criterion was also taken into account as similarly considered in the research by Uddin & Warnitchai (2020). The criteria identified and adopted for use in our study encompassed social/demographic, built environment, risk/safety aspects as well as the influence of spatial variability. Therefore, our proposed criteria incorporated in this research were comprehensive and critical for evaluating the best decision outcome. Further, the incorporation of the Entropy-based weighting method eliminates possible uncertainty of the expert judgements in the subjectively evaluated criteria weighting process of the AHP. This arises from several circumstances that include imprecise information, lack of expert knowledge and experience, limited capacity of the DM for accurately allocating precise weights to the criteria, also attributed to the intangible nature of the criteria (Kahneman et al., 1982; Weber, 1987).

The proposed hybrid AHP-Entropy model, using a combinative weighting approach considers both subjective and objective weighted procedures and is adopted to yield more accurate criteria weight results as recommended by some researchers (Alemi-Ardakani et al., 2016; Dehdasht et al., 2020; Z. Ding et al., 2018; Jahan et al., 2012). Furthermore, this study enhances the AHP-Entropy model by use of sensitivity analysis (SA) which examines the dependency of model output on changes of input criteria weights within a spatial domain. A generic SA approach, utilizing the One-At-a-Time (OAT) procedure is applied by changing one factor at a time while keeping others fixed, to observe criteria weight sensitivity which can subsequently be visualized relative to the model problem. The SA helps minimize uncertainty in the multi-criteria decision approach and tests the robustness of the proposed hybrid MCDA model, ensuring its stability for validation. The involvement of nineteen DMs that included both academic professionals and fire brigade practitioners enhanced the decision-making process ensuring more comprehensive and reliable model results.

The rest of the research paper is structured as follows. Subsection 3.3 describes the study area, data collection and research methodologies utilized such as AHP, Entropy, integrated AHP-Entropy and GIS analyses that include model validation using spatial sensitivity analysis (SA). The study results are presented in subsection 3.4, which illustrates the outputs of the GIS modelling procedures in the form of raster criteria map layers, final urban fire facility suitability raster map and simulations of SA outputs. The discussion and conclusions, of the key research results drawn from this study, are given in subsections 3.5 and 3.6, respectively.

3.3 Materials and Methods

3.3.1 Study area

The case study region of Istanbul province has the largest population in Turkey of about 15,519,267 as of 2019 (TUIK, 2020) and is the country's economic, cultural and historic centre. Its landmass straddles Europe and Asia between the Sea of Marmara and the Black Sea, separated by the Bosphorus strait. Istanbul province spans an estimated area of 5, 343.22 km2 and lies approximately between the latitudes 40° 44' 42" N to 41° 35´ 59" N and longitudes 27° 58´ 04" E to 29° 54´ 58" E (Figure 3.1).

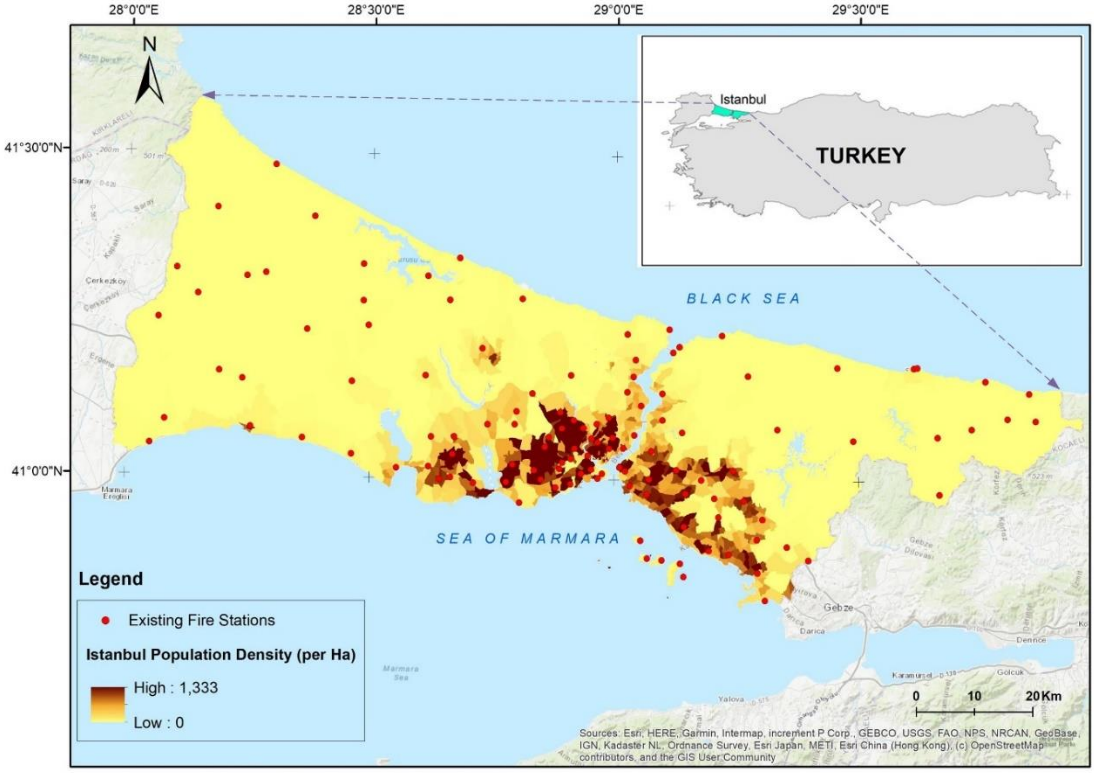


Figure 3.1: Istanbul province showing the existing fire stations and population density.

Istanbul is comprised of 39 districts, of which 25 districts are situated on the European side representing a population of 10,067,617 and 14 are on the Asian side having a third of the total population, of 5,451,650 people. A detailed map of the metropolitan area showing the population density relative to the districts of Istanbul and the spatial distribution of the existing emergency service stations is shown in Figure 3.2. As can be observed, a larger concentration of the existing emergency facilities is situated in the most densely populated regions correlating to higher population density values.

These areas have a high hazard zone rating with a large potential for fire risk as a result of urban developments and expansion, socio-economic and industrial/trading activities, tourist centres, clustered urban housing and multi-story residential areas, etc. The increasing demand for fire protection services takes into account the potential impact on communities such as damage to property and infrastructure, loss of lives, revenue and livelihoods.

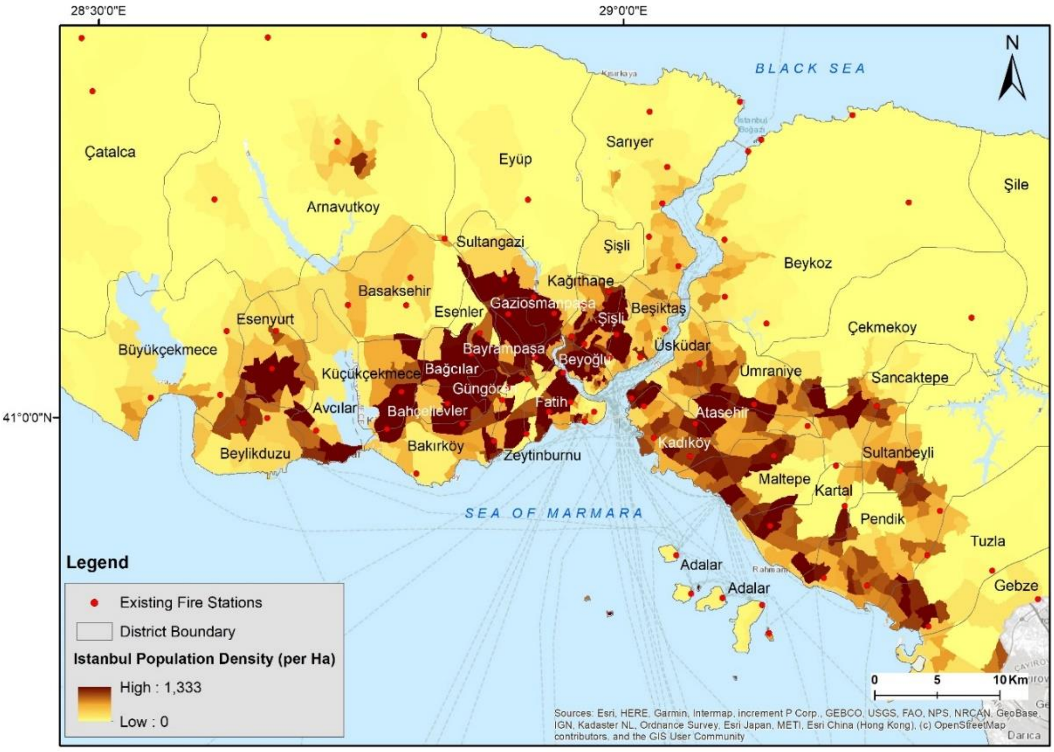


Figure 1.2: Detailed map showing the districts of the metropolitan area of Istanbul.

In recent years, the prevalence of urban fires and potential fire risk in Istanbul (IMM, 2016) exacerbated by rising urban populations and migration (Dociu & Dunarintu, 2012) has been a source of growing public safety concerns having profound negative impacts on social and economic aspects of the inhabitants.

3.3.2 Data and screening of criteria

Spatial planning of the distribution of urban emergency service systems that include fire, medical, police and ambulance services requires careful design and layout considerations. Fire stations also function as emergency medical communication and district/regional control centres in cases of major scale disasters and emergencies such as earthquakes, floods, landslides, etc. Therefore, planning locations of these facilities involves the combined effort of experts and decision-makers, administration, and emergency response personnel in consultation with other stakeholders such as local communities impacted by the decision outcome. The most influencing criteria for comprehensively planning new urban emergency facilities were selected in a thorough screening process based on recommendations from the literature and expert input (EnviroIssues, 2008; Erden & Coskun, 2010; Habibi et al., 2008; IMM, 2016). The population density is one of the main factors to be considered and represents a high potential for fire risk in especially areas with a very large concentration of people. These high population densities (HPD) zones include commercial, trading, social facilities and clustered urban settlements and therefore increase the demand for fire protection services with a greater potential for loss resulting from the impacts on communities. Emergency services should be located near or within these areas to provide adequate fire protection. The proximity to main roads (PMR) criterion was considered to facilitate easy access to the fire stations. Narrow roads such as streets are not easily accessible by fire engines and responding apparatus. Fire stations should, therefore, be located close to the main arterials and road networks but outside traffic-congested areas to achieve a better response time to emergency incidences (EnviroIssues, 2008). Planning and construction of new emergency facilities in areas already serviced by the existing facilities must be avoided. In this regard, the distance from existing fire stations (DEF) criterion is taken into account to ensure optimal service coverage without any overlaps. Drive time, topology and road traffic conditions defined by speed limits on the main transportation route network are considered for analysis of the emergency service coverage within a response time of 5 min. The density of hazardous materials (DHM) criteria was incorporated in the study in recognition of the demand for emergency services in or near land use areas having gas and oil stations, industrial and warehouse facilities containing hazardous materials such as compressed and liquid petroleum gases (LPG) (Habibi et al., 2008). These hazard-prone areas are often the sources of fires and explosions and therefore should take priority in planning new emergency facilities. Istanbul, being a historical, cultural and tourist centre still preserves the old building and housing architecture made of wood that easily catches fire and increases the spread of fire and related incidences. The wooden building density (WBD) criterion is determined as vital in planning new emergency facilities within these areas prevalent with a high density of wooden buildings. Environmentally critical areas susceptible to seismic risk are not preferred for siting new fire stations and consequently should be located as far away as possible (EnviroIssues, 2008). For this reason, the distance to earthquake risk (DER) criterion is considered in our research because Istanbul is vulnerable to occurrences of earthquakes which cause massive infrastructural damage. Post-earthquake hazards which induce post-ignition fires often result in more extensive damage than the initial earthquake. On that account, it is recommended that new emergency facilities should be built away from these liquefaction zones of high seismic risk as for example, in an earthquake event, damage to street and motorways would inhibit emergency vehicles and fire engines from reaching the emergency sites.

A summary description of the criteria and their influence on new urban fire station siting is given in Table 3.1.

Table 1.1: Criteria selection for new urban fire facilities.

Determined Criteria	**Description**	**Locational Influence on Planning New Fire Stations**
high population density (HPD)	areas with high population are at high fire risk and therefore prioritized for planning new fire stations	+
proximity to main roads (PMR)	fire stations must be situated in areas having easy accessibility to main transport routes to be able to reach fire incident areas faster	+
distance from existing fire stations (DEF)	new fire stations must be built away from service areas covered by already existing fire stations	-
density of hazardous materials (DHM)	areas with oil stations, facilities housing hazardous materials such as liquid petroleum gas (LPG) and compressed gases, etc. increase the spread and risk of fires, explosions; and should, therefore, be prioritized for planning new fire stations	+
wooden building density (WBD)	areas having wooden buildings increase the risk of fire spread and impact, hence are candidate locations for new fire stations	+
distance to earthquake risk (DER)	new fire station facilities should be built away from high earthquake risk areas (as Istanbul is prone to earthquake occurrences) to reduce the risk of infrastructural damage as a result of earthquakes	-

The collection and preparation of data were very vital components as the successful implementation of this research hinged on the reliability and accuracy of these procedures. Most of the data were collected from the Istanbul Metropolitan Municipality (IMM) and represent the most up-to-date records of main road network layers, existing fire station locations, locations of facilities that have hazardous materials that included oil stations, natural and processed gases/oils, compressed gases, liquid petroleum gas (LPG) and other chemical substances. The population density was obtained from the Turkish Statistical Institute (TUIK) (TUIK, 2020) and the earthquake hazard map for evaluating distances to areas of earthquake risk was acquired from the HAZTURK Project (Karaman et al., 2008). It is recommended that within concentrated urban environments, the minimum plot area for constructing fire and emergency medical service facilities approximately ranges from between 1,000 and 1,500 m^2 up to 3,000 m^2 for small and medium-sized stations to accommodate the full fire and emergency service programs (EnviroIssues, 2008; Habibi et al., 2008). In this research, we suggested processing and analyzing the data in the form of criteria map layers to a sub-district level using ESRI ArcGIS 10.3 software at a spatial cell size resolution of 50×50 m^2 accounting for a plot area within the stated site requirement guidelines.

3.3.3 Research methodology

The GIS-based AHP-Entropy methodology was initiated by defining the decision goal of assessing the suitability of locating new urban fire facilities in Istanbul. Within the context of this study, the research methodology was outlined as shown in Figure 3.3. In this regard, screening of the influencing factors was done based on a review of literature, expert knowledge and experience. Within a group decision–making (GDM) approach, a panel of decision-makers (DMs) were selected that had the requisite knowledge and experience in disaster and emergency planning and related works consisting of academic professionals, planners and fire brigade personnel. Using the *Delphi technique*, the DMs were interviewed from which their criteria preferences were acquired by the pairwise comparison method of the AHP to derive the subjective criteria weights.

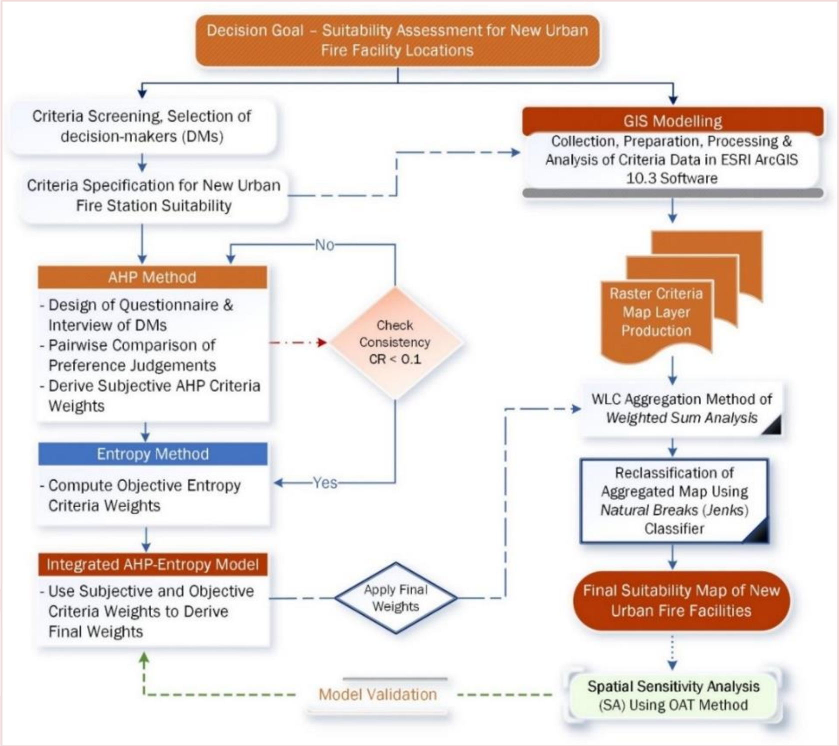


Figure 1.3: GIS-based AHP-Entropy model flow chart for new urban fire station suitability.

After checking for consistency in the DM judgements, the Entropy method was used to compute the objective criteria weights. The results from both the AHP and Entropy method were integrated to calculate the final criteria weights which were subsequently used as input in GIS via a Weighted Linear Combination (WLC) method of the weighted sum analysis function and reclassified for the final production of the raster suitability map of new urban fire facility sites. A spatial Sensitivity Analysis (SA) procedure was then performed for model validation.

3.3.3.1 AHP

The analytical hierarchy process (AHP) (Saaty, 1980) is a comprehensive multi-criteria decision analysis (MCDA) method that utilizes hierarchical structures to evaluate complex decision problems through a series of pairwise comparisons for weighting criteria. These pairwise comparisons are based on expert or decision-maker (DM) judgements that are used to synthesize priorities among criteria and alternatives to be evaluated. The decision-making process can be characterized in the main principles that include problem structuring, evaluation, computational analyses and synthesis of the priority model.

The approach for integrating GIS and AHP for the emergency facility decision problem in the present study follows the estimation of weights associated with criterion/attribute map layers which are subsequently combined with attribute map layers using a weighted linear combination (WLC) rule (J. Eastman et al., 1993). The key implementation steps are as outlined as follows:

Step 1: Decomposing complex unstructured problems into decision goals, criteria and alternatives.

Step 2: Developing the AHP hierarchy model to be used in the urban emergency facility selection suitability map.

Step 3: Design and construction of a judgement matrix using the *pairwise comparison* method representing experts' subjective preferences of criteria and alternatives. The outcome of the comparisons will be in the form of a positive pairwise comparison matrix $A = a_{ij}$, and reciprocal elements for all $a_{ji} = 1/a_{ij}$ as shown in equation (3.1):

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{3.1}$$

$$(i, j = 1, 2, \ldots, n)$$

Step 4: Assigning ranking values of relative importance to the subjective judgements based on a 9-point ratio scale proposed by Saaty (1980) and calculation of the respective weights of each criterion.

Step 5: Checking the consistency of the pairwise comparison assessments using a Consistency Ratio (CR). Consistency ensures coherence in the DMs' judgements in specifying their respective criteria preferences. If the CR < 0.1, the level of consistency is acceptable and comparison judgements are reliable.

Step 6: Synthesis of ratings (criteria) and alternatives to compute the overall priority variables for each decision alternative using a weighted sum of criteria weights.

3.3.3.2 Shannon entropy weight method (EWM)

Entropy is a concept based on information theory first introduced by Shannon (1948) and is widely used across engineering, economics, physics, finance, spectral analysis, information and physical sciences, language modelling and social disciplines. It is a measure of the uncertainty or degree of disorder in a system or information contained in the original data (attribute values of alternatives) formulated using probability theory. In solving most MCDA problems, the determination of criteria weights is essential to indicate the level of importance of each criterion relative to other criteria affecting decision alternatives and outcomes. Entropy weights can determine the amount of useful information provided by the index, based on differences between the attribute values without relying on subjective information from experts or DMs. Compared with subjective-based weighting methods, the key advantage of the entropy method is that it eliminates human interference in the weighting process, thereby objectively determining the criteria weights (Ding et al., 2017; Taheriyoun et al., 2010). These weights evaluated by the entropy method are called objective weights which imply that the higher the entropy, the smaller the value difference among evaluated objects resulting in a smaller relative weight, and vice versa. This indicates lower information content as some information may be lost or unreadable (Munier et al., 2019; Zou et al., 2006).

In recent years, some examples of the Entropy Weight Method (EWM) applied in GIS-based MCDA include waste landfill site selection (Ding et al., 2018), landslide susceptibility mapping (Jaafari et al., 2014; Wang et al., 2016; Youssef et al., 2015), flood risk assessments (Lin et al., 2020; Xu et al., 2018) and migration modelling (Rashid, 2019).

The objective weights can be calculated using the Shannon entropy method by the following procedures (Alinezhad & Khalili, 2019; Hwang & Yoon, 1981; Malczewski & Rinner, 2015):

Step 1: Formation of a decision matrix, **R** which shows the performance of *m* feasible alternatives with respect to *n* evaluation attributes (criteria).

$$R = X = (X_{ij})_{mn} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{3.2}$$

$$(i = 1, 2, \dots, m;\ j = 1, 2, \dots, n)$$

Step 2: Normalization of each criterion of the decision matrix to have comparable and dimensionless performance measures (indices).

Denoting p_{ij} as the standardized value of the non-negative index, X_{ij}, which is the performance measure of the *j*th attribute in the *i*th alternative, calculated by:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, \tag{3.3}$$

$$(i = 1, 2, \dots, m;\ j = 1, 2, \dots, n)$$

Step 3: Computation of the entropy value (E_j) for each criterion by the equation:

$$E_j = -k \sum_{i=1}^{m} p_{ij} \ln p_{ij}, \tag{3.4}$$

$$(i = 1, 2, \dots, m;\ j = 1,2, \dots, n)$$

where $k = 1/\ln(m)$ is a constant that ensures $0 \leq E_j \leq 1$. The larger the value of E_j, the greater the degree of differentiation of index *i* is, and the more information that can be derived. Therefore, a higher weight should be assigned to the index.

Step 4: After normalizing $(1 - E_j)$, determination of the entropy weights (w_j), of the *j*th attribute (each criterion), is given by:

$$w_j = \frac{1 - E_j}{\sum_{j=1}^{n} (1 - E_j)}, \tag{3.5}$$

$$j = 1, 2, \dots, n$$

where $0 \leq w_j \leq 1$ and $\sum_{j=1}^{n} w_j = 1$, following the entropy properties.

The value, $(1 - E_j)$, is known as the *degree of diversification*, D_j of the *j*th index. It describes the divergence degree of the inherent information of each criterion. The larger the value of D_j, the larger the variation in the *j*th index.

The entropy weight specifies the importance of the criterion in the decision-making process where the smaller the entropy value, indicates a larger entropy-based weight having more information that can be derived from the particular criterion (Wu et al., 2011).

3.3.3.3 Integrated AHP-entropy

Although derived entropy weights are effective and depict useful information, they rely heavily on the objective data that ignore the wealth of the knowledge and experience of the experts in decision-making which may not be in tandem with reality and comprehensibility of the problem situation. Considering the entropy weights only, irrespective of the expert's opinion would be insufficient and may not always accurately reflect the importance of the index in practice, resulting in biased decision-making (Cui et al., 2018; Wang et al., 2009; Weijs et al., 2010; Zardari et al., 2015). It is, therefore, necessary to combine the subjectivity of the AHP and the objectivity of the Entropy Weight Method (EWM) to ensure that weights are comprehensively determined for increased reliability and effectiveness. Integrating the two approaches aims to leverage the knowledge and experience of expert judgements and objective variability of the evaluation data.

An overall combined weight value is calculated from the AHP and Entropy weighting procedure using the general form of the Shannon Entropy weight, w_j^* given by the following equation:

$$w_j^* = \frac{S_j\, w_j}{\sum_{j=1}^{n} S_j\, w_j}, \tag{3.6}$$

$$j = 1, 2, \ldots, n$$

where, S_j is the subjective weight calculated from the AHP, and w_j is the objective weight derived from the Entropy method.

3.3.3.4 GIS analyses

A Geographic Information System (GIS) is a computer system designed with an array of tools and functionality to capture, store, manipulate, manage, analyse and visualize spatial data. Additionally, when combined with MCDA analytical methods, a GIS provides powerful capabilities to handle the limitations of GIS when dealing with multiple complex criteria and objectives, essentially evolving into a decision support system (DSS) (Erden, 2012; Jankowski, 1995; Malczewski, 2006; Nyimbili & Erden, 2018; Rashid, 2019). The integration of GIS and MCDA, hence known as GIS-MCDA and its applications have been a subject of growing research interest for researchers (Erden & Karaman, 2012; Karaman & Erden, 2014; Malczewski & Rinner, 2015; Nyimbili et al., 2018; Rashid, 2019).

In our study, the objective is to suggest areas suitable for locating urban emergency facilities within Istanbul and this goal is operationalized by selecting six influencing criteria/attributes. These criteria are identified as factors which increase or decrease the suitability of discrete alternatives or as constraints to limit alternatives (Eastman et al., 1995; Eastman, 2009). Representation of the feasible alternatives is in the form of a raster suitability map, consisting of a large number of raster cells in our selected study region.

After the criteria are selected and derived, the following main processes and analyses are implemented in a GIS, using ESRI ArcGIS 10.3 software:

1. *Standardization and extraction of data*: Most of the input data representing each criterion map layer were initially in vector format. After a series of processing and data management operations that included *spatial join*, *field calculator*, a process of rasterization was performed to convert the polygon-based data to raster data. The criteria map layers were processed and resampled to a selected cell resolution of 50 x 50 m^2 based on plot area recommendations stated in subsection 3.3.2 and other procedures as a prerequisite for further GIS modelling and analyses.
2. *Buffer analysis*: A multiple-ring buffer analysis was performed on the main road map layer to generate incremental buffer distance maps having a value range from 0 to 300 m, at 60m intervals. The buffer distance classifications used for the road network was as adopted by Erden & Coskun (2010) and from similar work by Chaudhary et al. (2016). This analysis determined the suitability index for locating new emergency facilities which should be positioned close to the main road network for easy access to the fire brigades.
3. *Network analysis*: *A network analysis* tool, was used to find service areas of the existing fire station facilities accessible on the main road network. This analysis showed the efficiencies and gaps of the current fire station coverage for defined travel time (emergency response time of 5 min) using the main roads at impedance values ranging from 1 to 5 min. The service areas were

evaluated using the attribute information at intersections of each road line segment layer that included the three road type classifications (local, main and highways), respective speed limit (in km/hr) and road segment lengths (in km). The travel time for each road segment was then evaluated in the attribute table of the main road layer data using the attribute information of the three road types and their corresponding speed limits – local (30km/hr), main (60km/hr) and highways (90km/hr). A topology of the road layer was created using a new network dataset generated from the road layer. This network dataset simulated the real road network of Istanbul.

The criteria were analysed by using actual travel distances, vehicle speeds, time delays caused by roadway conditions such as congestion, connectivity of road network and taking one-way or unusable roadways into account. The network dataset was subsequently used as input for the new service area analysis in the Network Analyst function. Service area polygons using the ring overlap type were generated using the current 121 fire station facilities at travel time impedance value settings (away from the facility locations) ranging from 1 to 5 min. These service areas modelled the fire station coverage scenario at an emergency response travel time of 5 min.

4. *Overlay analysis*: Using a compensatory decision rule method of weighted linear combination (WLC) (Carver, 1991; Nyerges & Jankowski, 2009), all the criteria map layers are aggregated into a single raster suitability map of urban fire station locations. Utilizing the *weighted sum* overlay tool, the final suitability map, S is generated by multiplying each criterion by its respective AHP-Entropy weight assignment followed by the summation of the results:

$$S = \sum w_i x_i \tag{3.7}$$

given w_i as the weight of criterion i, where $w_i \epsilon [0,1]$ and x_i is the standardized score of criterion i, $x_i \epsilon [0,1,2,3,4,5,6]$.

5. *Sensitivity Analysis*: In any decision-making process, and particularly for Multi-Criteria Decision-Making (MCDM) methodology, it is necessary to undertake a sensitivity analysis (SA) due to uncertainties in the input data,

processing, selection of criteria and respective thresholds as well as influencing exogenous factors which the decision-maker (DM) cannot control e.g., government policy, weather (Y. Chen et al., 2010; Munier et al., 2019). Therefore, SA is performed after problem-solving, to ascertain if a solution is retained when there are variations in this uncertain data, hence significantly contributing to accurate decision-making (Alinezhad & Amini, 2011; Munier et al., 2019). SA examines the correlation between the inputs and outputs of a modelling application (Y. Chen et al., 2010). As defined by Saltelli et al. (2000), it is "*the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation, and how the model depends upon the information fed into it*". SA is paramount for validating and calibrating numerical models and checking the *robustness* of the final decision solution against known, decremental or incremental input parameter changes in values (Y. Chen et al., 2010; Munier et al., 2019; Ticehurst et al., 2003; Zoras et al., 2007). In this respect, SA is mostly used to determine how variations in criteria weight alter the ranking because criteria weights frequently contribute to uncertainty and contention (Y. Chen et al., 2010; Munier et al., 2019). This is likely because the scale and nature of the criteria are unknown or because the DMs have no understanding of their criteria preferences, or because, notably, in group decision-making (GDM) there is often a possibility of acquiring more than one set of results because the series of weights are derived as opposed to only a set of weights (Y. Chen et al., 2010). A solution is therefore considered stable when the ranking is retained for different alterations in the criteria weights (Munier et al., 2019).

Spatial SA approaches have been utilized in several GIS-based MCDA studies to enable geographic visualization and analysis of weight sensitivity as recommended by several researchers (Al-Mashreki et al., 2011; Y. Chen et al., 2010, 2013, 2009; Feick et al., 2010; Feizizadeh et al., 2014; Hanssen et al., 2018; Şalap-Ayça & Jankowski, 2016; Yu & Wen, 2016). In this paper, the SA method of One-At-a-Time (OAT) (Daniel, 1958, 1973) is used to estimate criteria weight sensitivity by changing one input factor at a time whilst keeping all other factors fixed to analyse the resultant effects on model outputs, visually in a GIS.

If the weight of the *i*th attribute (criterion) is changed from $w_i°$ to w_i then the weight of the other criteria, w_j would change as given by given by Memariani et al. (2009):

$$w_j = \left(\frac{1 - w_i}{1 - w_i°}\right) * w_j° \tag{3.8}$$

where w_j is the new weight value of the other attribute (criterion) to be changed; $w_i°$ and $w_j°$ are the initial weight values of the criteria before being subjected to SA.

The different stages involved in the research methodology were briefly described. After defining the decision goal of assessing the suitability for planning new emergency facility locations in Istanbul, the data and criteria screening, decision-maker (DM) formulation and interview procedures were initiated as elaborated in subsections 3.3.2 and 3.3.3. The DMs' preferences of the six selected criteria were used to evaluate the subjective weights via the pairwise comparison approach in the AHP method (subsection 3.3.3.1). Using the Entropy method, described in subsection 3.3.3.2, the objective weights were subsequently derived. To ensure that the weights of the criteria were comprehensively determined, the AHP and Entropy methods were integrated to compute an overall combined weight value in a process given in subsection 3.3.3.3. The overall weight value was then implemented in GIS for modelling and analysis under subsection 3.3.3.4 after the preparation, pre-processing and analysis of criteria data in the form of raster criteria map layers. The main procedures in the GIS analyses included standardization and data extraction, buffer, network and overlay analysis. By a weighted linear combination (WLC) method, the weights from the combined AHP-Entropy process were applied onto the six aggregated criteria map layers using the *weighted sum overlay* analysis to generate the final suitability map for planning new urban emergency facilities. In the spatial sensitivity analysis (SA) process outlined at the end of subsection 3.3.3.4, the final decision solution and AHP-Entropy model were validated and checked for robustness.

The next subsection presents the research results of the implementation of the research methodology from the DM evaluation of criteria weights using AHP, Entropy and integrated AHP-Entropy techniques. The GIS modelling, after processing, analysis and reclassification of each of the six aggregated raster criteria map layers resulted in the production of a final urban fire facility suitability map. Map simulations of the spatial sensitivity analysis (SA) are presented for the criteria with the strongest influence to test the model validity and range of sensitivity by using the *One-At-Time* (OAT) method.

3.4 Results

3.4.1 Evaluation of criteria weights

Nineteen decision-makers (DMs) consisting of academic professionals/experts and fire brigade practitioners with over 10 years of experience in emergency planning, were invited to fill in a questionnaire using the Delphi technique, designed to capture their criteria preferences and judgements. The DMs' preference judgements reflected which criteria they perceived to be the most important in selecting suitable locations for urban fire station facilities. The results of the level of importance among the six criteria were analysed and evaluated as weight coefficients using the AHP, Entropy and combined AHP-Entropy methods.

3.4.1.1 Subjective weights from the AHP

Using the AHP method, the pairwise comparison matrix for all the nineteen DMs was aggregated by *geometric mean*, to provide the group judgements as shown in Table 3.2.

Table 1.2: Preference matrix for DM's group judgements.

Criteria	HPD	PMR	DEF	DHM	WBD	DER
HPD	1	1.98	3.15	0.64	2.15	3.27
PMR	0.5	1	1.86	0.34	1.55	2.09
DEF	0.32	0.54	1	0.30	0.68	1.23
DHM	1.56	2.91	3.28	1	2.99	3.86
WBD	0.47	0.65	1.47	0.33	1	1.49
DER	0.31	0.48	0.81	0.26	0.67	1

The values of the E_{max} (6.037), CI (0.00739) and CR (0.00596), from the group judgment computations, were used to evaluate the final AHP weights ($\boldsymbol{W}$) and corresponding rankings of the six criteria as given in Table 3.3.

Table 1.3: AHP weights and rankings.

Criteria	W (%)	Rank
HPD	*24.8*	*2*
PMR	*14.4*	*3*
DEF	*8.5*	*5*
DHM	*33.7*	*1*
WBD	*11.1*	*4*
DER	*7.5*	*6*

To check the reliability of the evaluations, the consistency ratio (CR) was calculated to be 0.00596 which was less than 0.1 (indicating reliable and consistent judgements).

3.4.1.2 Objective weights from entropy

The collected responses from the DMs were also analysed to compute the objective weights using the Shannon Entropy Weight Method (EWM) following the steps outlined in subsection 3.3.3.2. The entropy ($\boldsymbol{E}_j$), degree of diversification ($\boldsymbol{D}_j$) and objective criteria weights ($\boldsymbol{W}_j$) for the assessment of suitable locations for urban fire station facilities are presented in Table 3.4.

Table 1.4: Entropy, degree of diversification, entropy weights and rankings.

Criteria	E_j	D_j	W_j (%)	Rank
HPD	*0.8933*	*0.1067*	*20.1*	*2*
PMR	*0.8702*	*0.1298*	*24.4*	*1*
DEF	*0.9294*	*0.0706*	*13.3*	*5*
DHM	*0.9259*	*0.0741*	*13.9*	*4*
WBD	*0.9159*	*0.0841*	*15.8*	*3*
DER	*0.9340*	*0.0660*	*12.4*	*6*

3.4.1.3 Subjective-objective weights from the AHP-entropy model

In this study, both advantages of the AHP and entropy methods were considered and it was therefore proposed to integrate the AHP and entropy for weighting the criteria for the decision problem (Feng & Chen, 1992). The combined AHP-Entropy weight

$(\boldsymbol{W}_j^*)$ was calculated using equation (3.6) from subsection 3.3.3.3 and the results are as shown in Table 3.5.

Table 1.5: AHP, Entropy and Integrated AHP-Entropy weights of criteria and the final ranking.

Criteria	***AHP (%)***	***Entropy (%)***	W_j^* **(%)**	**Final Rank**
HPD	*24.8*	*20.1*	***29.3***	***1***
PMR	*14.4*	*24.4*	***20.7***	***3***
DEF	*8.5*	*13.3*	***6.6***	***5***
DHM	*33.7*	*13.9*	***27.6***	***2***
WBD	*11.1*	*15.8*	***10.3***	***4***
DER	*7.5*	*12.4*	***5.5***	***6***

More realistic weights were computed using this approach and used for subsequent GIS modelling and analysis to generate a final suitability map for the assessment of suitable locations for urban fire station facilities.

3.4.2 GIS modelling

3.4.2.1 Processing, analysis and criteria map layer production

Based on the six determinant factors identified for suitably locating urban fire station facilities in Istanbul, these were used as input in a GIS for processing and analysis to produce raster criteria map layers. All the six criteria in the form of criteria map layers were processed and analysed to raster map resolution of cell size, 50 x 50 m^2. The raster cell value ranges for each criterion map ranging from the lowest to the highest suitability were as shown in Table 3.6.

Table 1.6: Suitability class value ranges for each criterion from the lowest to the highest.

Criteria	***Suitability class value ranges***	
	Lowest suitability	***Highest suitability***
HPD (no. of people per hectare)	*0*	*1,333.2*
PMR (metres)	*300*	*0*
DEF (service areas in minutes)	*1*	*5*
DHM (number of, per sub-district)	*0*	*153*
WBD (ratio in, total no. of buildings)	*0*	*1,781.8*
DER (PGA[1] values in g)	*2.39*	*0.26*

[1] PGA = peak ground acceleration value of the Istanbul earthquake hazard map, in units of acceleration due to gravity (g).

Each of the criterion map layers depicted by the suitability class value ranges shown in Table 3.6, and whose processing procedures are briefly described were as illustrated in Figure 3.4. The determination of which areas were suitable was dependent on the desired reclassification scheme (the *natural breaks* classifier) result of the range of data values for the final suitability raster map to be generated in subsection 3.4.2.1.

1. *High population density* (HPD): The HPD criterion map layer was initially processed from population data per sub-district area of Istanbul and calculated in hectares (ha) (Figure 3.4 (a)). Generally, our definition of a high density of population is determined by the data value ranges of our specified reclassification.

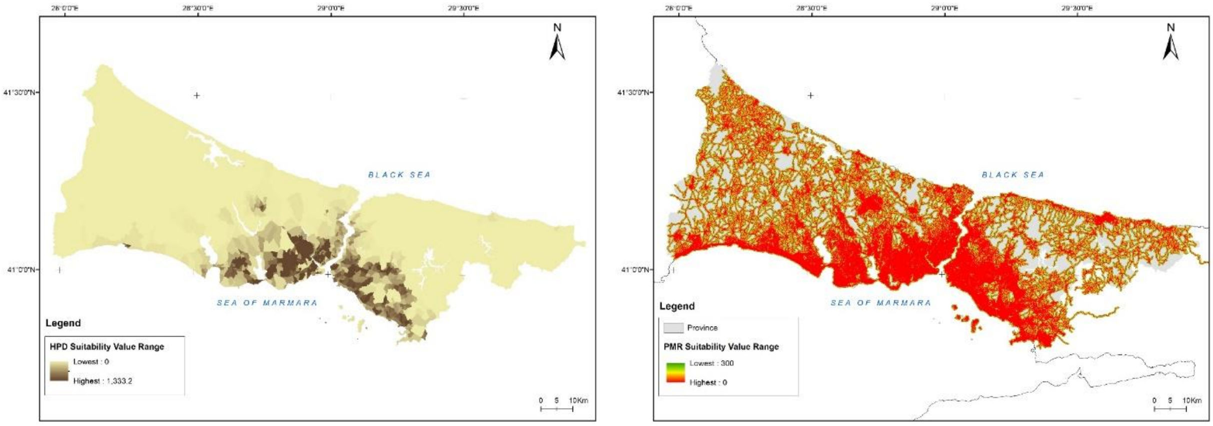
2. *Proximity to the main road* (PMR): The PMR criterion map layer was processed from a multiple ring buffer analysis which was defined from the main roads of Istanbul over a value range of up to 300m in incremental distances of 60m (Figure 3.4 (b)). The main road data was specified by attribute information for the three road segment types namely local, main and highways with corresponding average speed limits (based on traffic flow and road width data) of 30, 60 and 90 km/h. The buffer distance map generated at varying Euclidean distances characterized the level of accessibility of the fire engines from the emergency station to emergency sites to achieve a better response time. Areas at distances beyond 300m from the main roads were considered to be less suitable while those close to the road were ideal for locating fire station facilities. The inter-connections of the road network, as well as the width (for easier passage), provided alternative access points to a fire station site.

3. *Distance from the existing fire stations* (DEF): Using the *network analysis* function as described in subsection 3.3.3.4, the DEF criterion map layer was processed in a service area determination of 121 existing fire stations and topology of road layers at travel impedances ranging from 1 to 5 min (Figure 3.4 (c)).

4. *Density of hazardous material facilities* (DHM): For the DHM criterion layer, processing was done based on the number of latest records of facilities' locations with hazardous materials and other flammable chemical substances

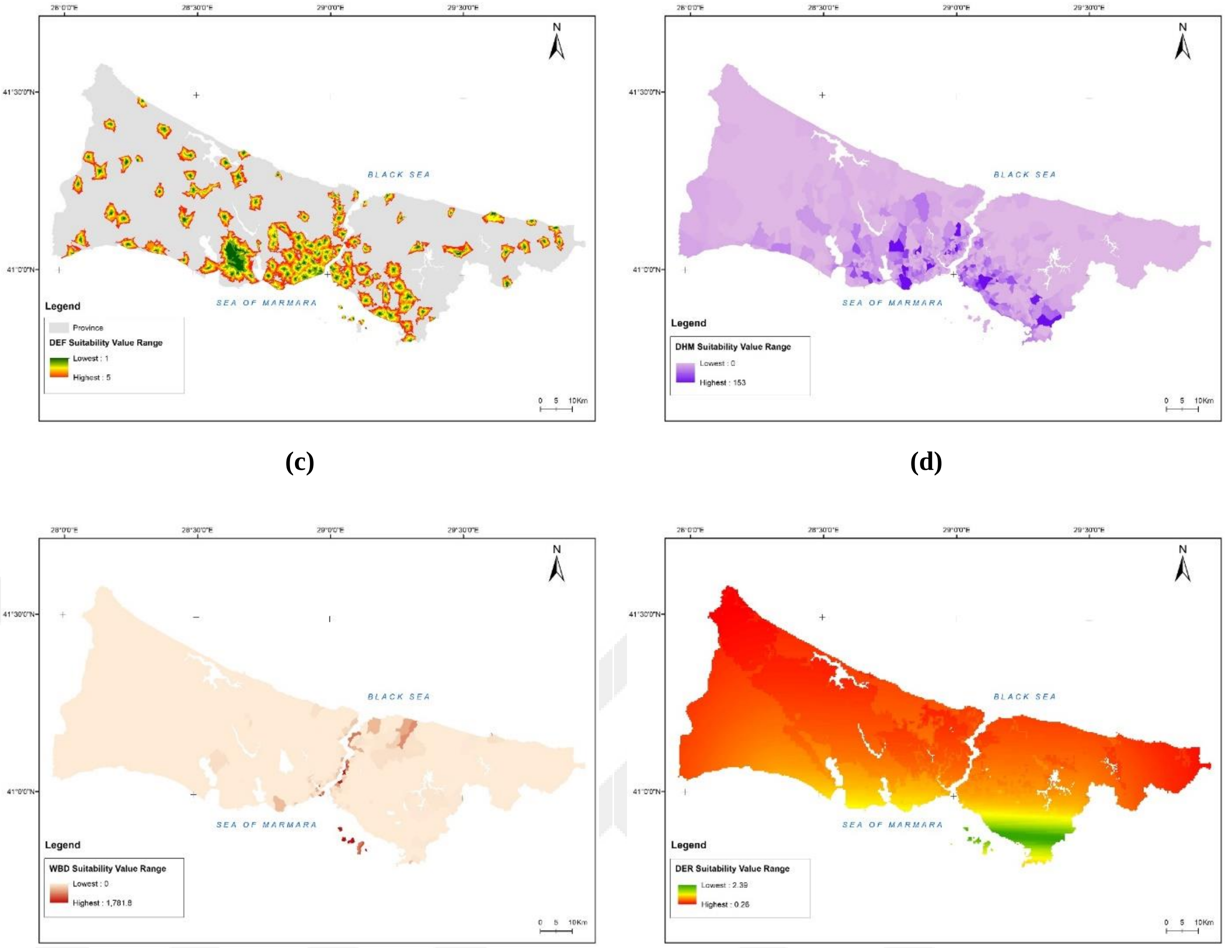
that included liquid petroleum gas (LPG), oil stations and compressed gases/oils; determined per sub-district area of Istanbul (Figure 3.4 (d)).

5. *Wooden building density* (WBD): The WBD criterion map layer, was processed by computing the ratio of the number of wooden buildings to the total number of wooden buildings in each sub-district. The density of the wooden buildings is the representative ratio values per sub-district of Istanbul (Figure 3.4 (e)).
6. *Distance from earthquake risk* (DER): The DER criterion map layer was derived from the earthquake hazard map of Istanbul indicated by peak ground acceleration (PGA) values in units of gravity, which showed areas exposed to earthquake risk (Figure 3.4 (f)). For Istanbul, areas of higher seismic risk are located closer to the southern part because of the nearness to the fault line which runs along the Sea of Marmara. These areas represent the highest PGA values indicating the highest amount of earthquake risk as shown in darker green colour. For this reason, it is not preferred to locate fire station facilities in these zones which are considered to be of low suitability. The further away from these regions, the lesser the exposure to earthquake risk and in turn, the higher the suitability, whose interval value scale is dependent on the chosen reclassification result of the data values.



(a) **(b)**

Figure 1.4: The processed: **(a)** HPD, **(b)** PMR, **(c)** DEF, **(d)** DHM, **(e)** WBD and **(f)** DER criterion map layers related to the suitable locations for urban fire station facilities.



(c) **(d)**

(e) **(f)**

Figure 1.5 (continued): The processed: **(a)** HPD, **(b)** PMR, **(c)** DEF, **(d)** DHM, **(e)** WBD and **(f)** DER criterion map layers related to the suitable locations for urban fire station facilities.

3.4.2.2 Urban fire facility suitability assessment

The thematic raster data layers representing the six criteria, from Figure 3.4, were aggregated in ESRI ArcGIS 10.3 using a method of Weighted Linear Combination (WLC) via equation (3.8). The final weights from the integrated AHP-Entropy model were applied to each of the criterion maps using the *weighted sum* (overlay analysis) and then reclassified using the *natural breaks* (*jenks*) classification into five categories ranging from 1 to 5. The class value of 5 (in red colour) depicts the most suitable areas whereas class value 1 (in bluish colour) represented the least suitable areas for locating new urban fire station facilities as displayed in the final composite suitability map for Istanbul in Figure 3.5.

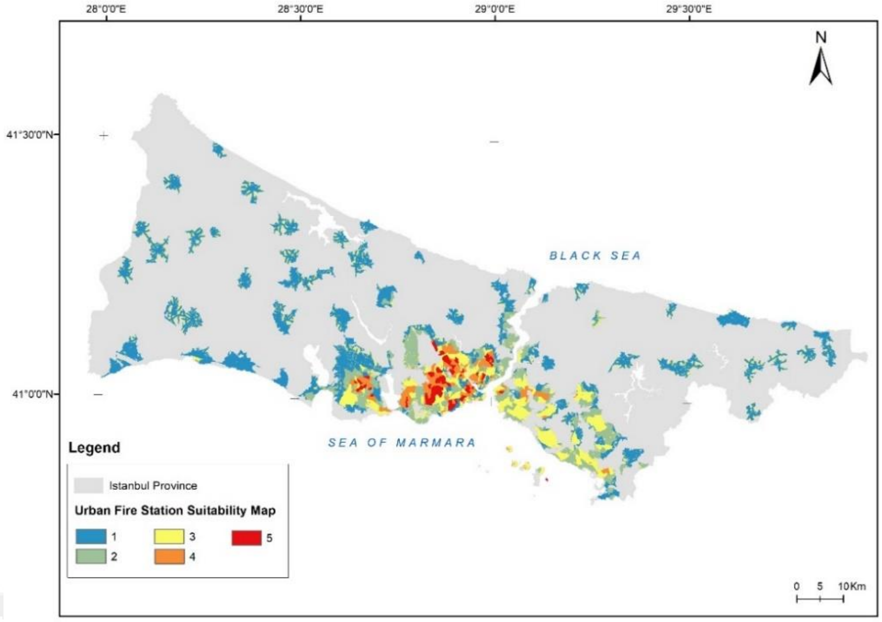


Figure 1.6: Final Urban Fire Station Suitability Map of Istanbul Province.

A quantitative assessment of the land area covered by each of the resulting suitability classes is given in Table 3.7.

Table 1.7: Land area coverage of suitability.

Suitability map class	***Area in km²***	***% Suitability***
Class 1 (lowest)	*490.143*	*42.7*
Class 2 (low)	*334.865*	*29.2*
Class 3 (moderate)	*206.648*	*18.0*
Class 4 (high)	*77.725*	*6.8*
Class 5 (very high)	*38.308*	*3.3*

The results of the land area coverage in the suitability analysis account for 322.68 km^2 from the representative class values labelled 3 to 5 as *moderate*, *high* and *very high*, mostly covering the metropolitan areas of Istanbul.

3.4.2.3 Spatial simulation of sensitivity analysis results

The spatial dimension of the sensitivity analysis (SA) of the integrated AHP-Entropy model results was evaluated in terms of the criteria weight using the One-At-a-Time (OAT) method given by equation (3.8). This study considered varying the criteria weights having the strongest influence, identification of the sensitivity of the respective criteria to known weight changes relative to the stability of the rankings and visualizing the spatial changes of the evaluation results.

From the final AHP-Entropy model results, the HPD and DHM criteria had the strongest influence on the urban fire facility location decision problem, yielding weight values of 29.3% and 27.6% respectively. Therefore, the sensitivity analysis was performed by adjusting the weight values of the HPD and DHM criteria to five new incremental weight bands of 20% ranging from 0% to 80%.

The resulting distribution of the adjusted weights and rankings for the rest of the criteria were tabulated in Tables 3.8 and 3.9.

Table 1.8: Sensitivity analysis of the HPD criterion (the value shaded in grey) adjusted to new weight values ranging from 0% to 80%.

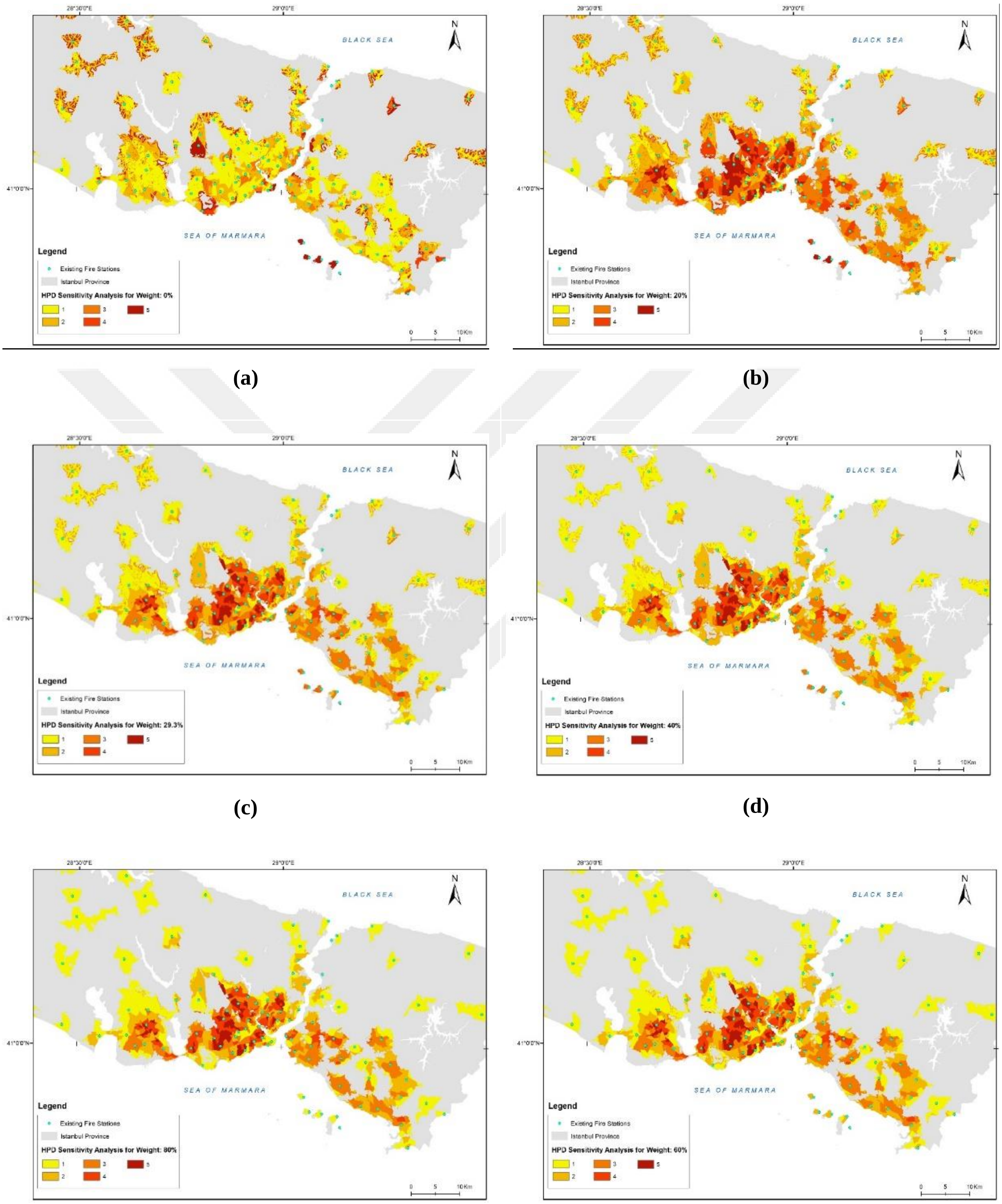
Criteria	***Initial***		***0%***		***20%***		***40%***		***60%***		***80%***	
	Weight (W)	***Rank (R)***	***W***	***R***	***W***	***R***	***W***	***R***	***W***	***R***	***W***	***R***
HPD	***0.293***	*1*	***0.000***	*6*	***0.200***	*3*	***0.400***	*1*	***0.600***	*1*	***0.800***	*1*
PMR	*0.207*	*3*	*0.293*	*2*	*0.235*	*2*	*0.176*	*3*	*0.117*	*3*	*0.059*	*3*
DEF	*0.066*	*5*	*0.094*	*4*	*0.075*	*5*	*0.056*	*5*	*0.038*	*5*	*0.019*	*5*
DHM	*0.276*	*2*	*0.390*	*1*	*0.312*	*1*	*0.234*	*2*	*0.156*	*2*	*0.078*	*2*
WBD	*0.103*	*4*	*0.146*	*3*	*0.117*	*4*	*0.088*	*4*	*0.058*	*4*	*0.029*	*4*
DER	*0.055*	*6*	*0.077*	*5*	*0.062*	*6*	*0.046*	*6*	*0.031*	*6*	*0.015*	*6*
Total	*1.000*		*1.000*		*1.000*		*1.000*		*1.000*		*1.000*	

Table 1.9: Sensitivity analysis of the DHM criterion (the value shaded in grey) adjusted to new weight values ranging from 0% to 80%.

Criteria	***Initial***		***0%***		***20%***		***40%***		***60%***		***80%***	
	Weight (W)	***Rank (R)***	***W***	***R***	***W***	***R***	***W***	***R***	***W***	***R***	***W***	***R***
HPD	*0.293*	*1*	*0.404*	*1*	*0.323*	*1*	*0.243*	*2*	*0.162*	*2*	*0.081*	*2*
PMR	*0.207*	*3*	*0.286*	*2*	*0.229*	*2*	*0.172*	*3*	*0.114*	*3*	*0.057*	*3*
DEF	*0.066*	*5*	*0.092*	*4*	*0.073*	*5*	*0.055*	*5*	*0.037*	*5*	*0.018*	*5*
DHM	***0.276***	*2*	***0.000***	*6*	***0.200***	*3*	***0.400***	*1*	***0.600***	*1*	***0.800***	*1*
WBD	*0.103*	*4*	*0.143*	*3*	*0.114*	*4*	*0.086*	*4*	*0.057*	*4*	*0.029*	*4*
DER	*0.055*	*6*	*0.075*	*5*	*0.060*	*6*	*0.045*	*6*	*0.030*	*6*	*0.015*	*6*
Total	*1.000*		*1.000*		*1.000*		*1.000*		*1.000*		*1.000*	

Assessment of the SA results of the HPD and DHM criteria were simulated using ESRI ArcGIS software in the form of re-processed composite suitability maps that incorporated the new distribution of the criteria weight values by utilizing the weighted sum analysis function. By use of the reclassify function in the *Spatial Analyst* tool of ArcGIS, each cell of the aggregated maps was reclassified into five suitability class values using the *natural breaks (jenks)* classifier. The simulated SA outputs were geographically visualized at cut-off weight values of 0%, 20%, 40%, 60% and 80%

for each of the HPD and DHM criteria as presented in Figures 3.6 and 3.7, covering the metropolitan region of Istanbul for better visual appreciation.



(a)

(b)

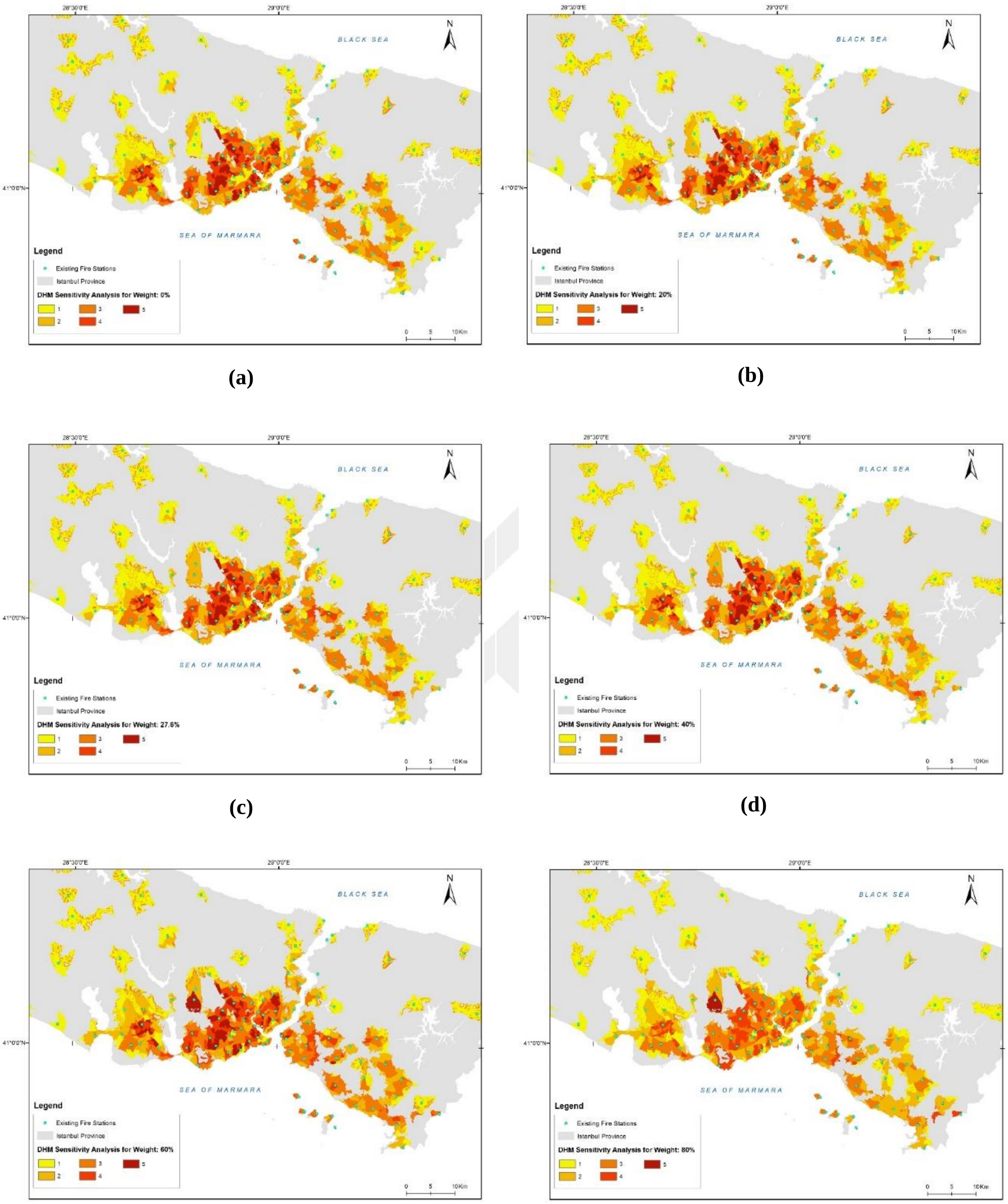
(c)

(d)

(e)

(f)

Figure 1.7: The simulated SA outputs were geographically visualized at cut-off weight values of: **(a)** 0%, **(b)** 20%, **(c)** 29.3%, **(d)** 40%, **(e)** 60% and **(f)** 80% for the HPD criterion.



(a) (b)

(c) (d)

(e) (f)

Figure 1.8: The simulated SA outputs were geographically visualized at cut-off weight values of: **(a)** 0%, **(b)** 20%, **(c)** 27.6%, **(d)** 40%, **(e)** 60% and **(f)** 80% for the DHM criterion.

The model output sensitivity was tested by visually assessing the spatial variability in the generated maps at the defined input weights.

3.5 Discussion

For achieving a more intuitive, realistic and comprehensive model result, drawing from the advantages of both weighting techniques as applied in several studies (Al-Aomar, 2010; J. Singh et al., 2019; G. Wu et al., 2017; Zangenehmadar & Moselhi, 2015; Zeng et al., 2019), integration of the AHP and Entropy techniques, were used in this study. Based on a similar study by Erden & Coskun (2010) that used the AHP, this work broadens the contribution to the research by combining the use of AHP and Entropy in both subjectively and objectively evaluating the weights of the criteria deemed relevant for recommending sites for new urban emergency facilities. Furthermore, the inclusion of fire brigade practitioners in our study, which had not been previously considered, increases the reliability of this research result, reflecting valuable insights into the practitioners' point of view in decision-making as part of a collaborative process. Additionally, the use of the spatial sensitivity analysis (SA) based on the *One-At-a-Time* (OAT) method in the current research examines the criteria weight sensitivity to variations thereby increasing the comparability and robustness of the model results which are visualized spatially.

The computed criteria weight and ranking results from the AHP-Entropy method (Table 3.5) show that the high population density (HPD) and the density of hazardous materials (DHM) factors, with the weights of 29.3% and 27.6%, respectively have the strongest influences on the urban fire facility location problem. On the other hand, the distance to earthquake risk (DER) and the distance to existing fire stations (DEF), with corresponding weights of 5.5% and 6.6%, were perceived by the DMs to have the least and the weakest influence on the decision-making outcome. In contrast with the previous work by Erden & Coskun (2010), the criteria deemed to have the highest influence were DHM and HPD with a weight of 40% and 16%, respectively. Our research coincides with the previous work in terms of the two criteria perceived to have the highest influence on the decision outcome. However, the differences in the weight evaluation results could be largely attributed to the divergent views and perceptions of the DM groups. Only a group of academicians and academic-related professionals were used in the criteria preference and weight evaluations by the AHP method in the previous study (Erden & Coskun, 2010) while our work comprised a heterogeneous mix of DMs that included fire brigade personnel/practitioners and frontline staff. In the previous research, the criteria perceived to have the least influence were DER and DEF, corresponding with our research findings. Additionally, the variations in the weight coefficients are a result of the differences in methodologies used to obtain the final result, where our current work integrates with the Entropy approach. This offers an improvement in overcoming the limitations of the AHP by introducing objectivity to avoid human interference in the indicator weight evaluations whilst at the same time, leveraging expert knowledge and practical experience to increase the reliability and effectiveness of the decision outcome.

The representative criteria were modelled in GIS via a multi-criteria analysis in the form of processed criterion map layers and visualized (Figure 3.4). Using the derived AHP-Entropy weights, a Weighted Linear Combination (WLC) approach of a weighted sum analysis function, was applied to aggregate each of the criterion map layers and subsequently reclassified into five class values to produce a final suitability map for new urban fire facilities of Istanbul as shown in Figure 3.5. A visual interpretation of the results indicates areas of high potential urban fire risk that are of immediate priority for the construction of new urban fire and emergency facilities. Class values ranging from 3 to 5 depicted in yellow, orange and red colours, corresponding to moderate, high and very high suitability can be prioritized accordingly (also dependant on site-acquisition access and ground siting conditions). These areas of potentially high urban fire risk represent almost a third of the area under consideration, accounting for about 28.1% as evaluated in Table 3.7. It can be inferred that most of the areas most suitable for planning new fire station facilities are located on the European side of Istanbul which also conforms to the areas that have a very high population density and with a high density of hazardous material facilities as a result of high industrial and trading activities. These findings are congruent with the results in the previous work (Erden & Coskun, 2010) that recommended new sites in the metropolitan region of Istanbul. Notable among these suitable zones for new emergency facilities are included in the district areas of Esenyurt, Avcılar, Beylikdüzü, Bahçelievler, Güngören, Küçükçekmece, Bayrampaşa, Esenler, Fatih, Beyoğlu, Şişli, Kaığthane, Beşiktaş, Sarıyer, Gaziosmapaşa, Sultangazi, Bakırköy, Bağcılar, Sultangazi, Bahçelievler, and Zeytinburnu. Similarly, on the Asian side, especially with expansive urban infrastructural and industrial activity, district areas to be prioritized for the provision of sufficient fire protection services consist of Üsküdar, Kadikoy, Ümraniye, Ataşehir, Maltepe, Sancaktepe, Kartal, Tuzla, Pendik and Adalar.

The high suitability index on the map coincides with areas of potentially high urban fire risk convergent with the results obtained in (Erden & Coskun, 2010) which are largely consistent with the dominance of the HPD and DHM criteria represented with the highest weight coefficients. From the DM perspective, these criteria are the most significant in planning fire emergency infrastructure. In this context, the dominance of the HPD and DHM factors and their influence on the spatial domain was examined using simulations of the sensitivity analysis (SA) based on the One-At-a-Time (OAT) technique whose results were given in Tables 3.8 and 3.9. The spatial changes were analysed and visualized as aggregated urban fire suitability maps for each of the HPD and DHM criteria at their respective assigned weight values of 0%, 20%, 40%, 60% and 80% as illustrated in Figures 3.6 and 3.7. The corresponding distribution of the rest of the criteria weights was re-calculated as tabulated in Tables 3.8 and 3.9. For the HPD criterion, decremental and incremental changes to the initial (original) weight value by about 10% and 10-15%, respectively do not yield significantly observable changes on the resulting suitability maps. This implies that at weights within the variation band of between 20% to about 40-45%, the model is not subjective to changes while it is sensitive to changes in weights outside this band. Therefore, it can be said that the model weight sensitivity of the HPD criterion is within the range of 20% to about 40%-45%. The stability of the rank preference order when the HPD criterion weight is increased beyond the new weight value of 40% also correlates to the model sensitivity (Table 3.8). Decreasing and increasing the initial DHM criterion weight value by about 20%, does not result in significant visual changes on the suitability map indicating that the model is sensitive to weight variations within the band of between about 10% and 40-45%. To this effect, the preference order of the criteria rankings when the weight of the DHM criterion is increased from the new weight value of 40%, are consistent and in conformity to the sensitivity of the model (Table 3.9). The SA results also indicate that the other criteria have a notable spatial influence on the suitability assessment decision outcome since the HPD and DHM criteria are only dominant within the specified model sensitivity ranges of weights.

The research outcome provides a base map that is useful for assessing the long-term impact of current and future demands of fire and emergency services. However, there is a need to match the provision of better fire protection services in parallel with the demands of the complex urban dynamic system. From this perspective, some limitations exist in some aspects of this research. Key among these is data availability. Additional variables should be considered such as land use and cover for assessing the availability of open spaces for new site developments, and the acquisition of historical records of fire incident data for urban fire risk estimation as recommended by Uddin & Warnitchai (2020). Validation of our research results would be conducted by cross-checking areas of urban fire risk with actual fire incident data for risk and spread modelling. Future research is directed towards the inclusion of these selection factors in addition to the use of building inspection records for predicting fire risk and improving the capacity of fire emergency facility planning. In collaboration with the Istanbul Metropolitan Municipality (IMM) fire department and policymakers, a data-driven approach will be developed to assist in optimizing fire and emergency service facility planning using machine learning, geo-coding, and geo-information visualization techniques. Other variables related to the size and type of the fire brigade facilities such as firefighting equipment, number of staff and vehicle capacity should be considered in optimizing our facility planning efforts in view of budget constraints and cost-saving strategies. In this case, it may not be necessary to construct a new fire station in areas where the options to expand existing infrastructure and improve fire fighting capacity would be established as cost-effective alternatives for adequately meeting the increasing demands for fire protection services.

A comprehensive assessment of fire risk to include regions outside urban areas is suggested to account for impacts of forest fires in the fire station and emergency facility planning not accounted for in our current scope of the study.

3.6 Conclusions

This study establishes a framework utilizing a GIS-based unified AHP-Entropy model for assessing the suitability of locating new urban emergency facilities within a five-minute travel distance within Istanbul, Turkey to be used by planners and decision-makers (DMs) engaged in emergency management services. Nineteen DMs and experts that included fire brigade personnel were incorporated through a group decision-making (GDM) process via the AHP method. By the pairwise comparison approach of the AHP technique, the DMs’ preferences of the relative importance of the six determinant criteria were captured through the evaluation of questionnaires administered using the Delphi technique. Based on these assessments, the subjective weights of the criteria were derived. However, due to human interference in the weights of the criteria and other uncertainties which have a negative influence on the decision outcome, the Shannon Entropy Weight Method (EWM) was used to enhance the objectivity of the evaluations. To achieve a more comprehensive and reliable result, the weights from the AHP and Entropy methods were integrated and subsequently used as input in GIS via Weighted Linear Combination (WLC) approach to produce a reclassified final suitability map of new urban emergency facility locations. From the suitability indices, 39.3 km^2 (3.3%), 77.7 km^2 (6.8%) and 206.6 km^2 (18.0%) of the coverage area were classified as having very high, high and moderate suitability, respectively. This result confirms the visual map interpretation and assessment that indicates that almost a third of the study region, about 28.1%, is at risk of urban fires and should be prioritized for urgent planning and construction of new urban fire stations to provide sufficient fire protection services.

The accuracy and robustness of our proposed AHP-Entropy model were validated by performing a sensitivity analysis (SA) using the One-At-a-Time (OAT) method whose results for the criteria with the strongest influence, HPD and DHM, were geographically visualized. The model sensitivity for the HPD criterion was evaluated to be between variations in weight values of 20% to 40-45% while that for the DHM criterion was determined to be between 10% and 40-45%. This outcome correlated with the stability of the criteria rankings, showing the consistency, robustness and reliability of the model.

Our proposed method combining GIS and AHP-Entropy can be replicated globally in wider application areas of group decision-making related to emergency planning and aversion to risk and other disasters as it is easy to use, reliable and effective. The research findings will be shared with the planning authorities of Istanbul for coordination and collaboration in line with regulatory and planning strategies for the provision of adequate fire protection and emergency services. Future research, in this regard, is directed towards the acquisition of fire incidence and other relevant data for real-time modelling of urban fire risk, applying machine learning and artificial intelligence techniques.

4. GIS-BASED FUZZY MULTI-CRITERIA APPROACH FOR OPTIMAL SITE SELECTION OF FIRE STATIONS IN ISTANBUL, TURKEY[3]

4.1 Abstract

Fire stations play a central role in protection and response activities as part of emergency management services in cases of fire incidences. With the rising urban populations and city expansions, the demand for more fire services resultantly increases. It then becomes critical to effectively plan the location of emergency facilities to adequately service the population and ensure the protection of lives and infrastructure. This study, therefore proposes the use of the fuzzy extension of the Multi-Criteria Decision-Making (MCDM) method of Analytical Hierarchical Process (AHP), hence called fuzzy AHP, integrated with Geographic Information Systems (GIS) approach to optimally site new fire stations for the case of Istanbul region. This proposed fuzzy approach simulates the subjective expert judgements for the preferences of the six criteria assessed for fire station suitability mapping and thereby accounted for the uncertainty of crisp comparison values via triangular fuzzy numbers (TFNs). The criteria weights evaluated from this procedure were used in a weighted overlay analysis of the reclassified criteria map layers in ArcGIS to generate a fire station suitability map. These resultant fuzzy AHP criteria weights were validated using another MCDM technique, called Best-Worst Method (BWM) and found to be comparable and consistent. The criteria that had the strongest influence on the selection of sites for fire stations were identified to be: the density of hazardous material facilities (DHM), a high population density (HPD) and proximity to main roads (PMR) with associated weights of 33.3%, 24.4% and 15.2%, respectively. Based on a thorough assessment within the areas represented by class values ranging from 3 to 5 on the suitability map, a total of 34 new fire station sites were selected complementing the existing 121 fire stations. Further, a prioritization analysis from

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[3] This chapter is based on the article: Nyimbili, P. H., Erden, T., 2020: GIS-based fuzzy multi-criteria approach for optimal site selection of fire stations in Istanbul, Turkey, Socio-Economic Planning Sciences, 71, 100860. doi: https://doi.org/10.1016/j.seps.2020.100860

low, medium to high, was performed to plan the phases for the construction of new fire stations in view of competing budgetary needs and resource constraints. The methodology to achieve this was proposed and modelled for enhancing the decision-making process in urban fire station site selection studies.

Keywords: Geographic information system (GIS); Multi-criteria decision-making (MCDM); Fuzzy analytical hierarchical process (FAHP); Site selection; Fire station

4.2 Introduction

Istanbul province is the most urbanized with regard to not only infrastructure and industry but in population as well in excess of 15 million representing around 18.8% of Turkey’s population (TUIK, 2018). However, as a result of this, it also experiences an increasing number of fire-related events. According to the 2016 annual report (2016) of the Istanbul Metropolitan Municipality Department of Fire Brigade, 58, 666 fire incidents occurred with an average response time of more than five minutes. This study, therefore, becomes vital to improve fire response action by planning new emergency fire centres, thereby, lessening the fire response time to within five minutes. Emergency planning has been stimulated by recent improvements in geo-technological areas in which an increasing amount of spatial data is required for complex decision-making by emergency managers and planners involving large numbers of stakeholders across inter-disciplinary teams and multiple criteria (Erden, 2012; Penjani Hopkins Nyimbili & Erden, 2018). For such kind of problems, GIS-based MCDA approaches can be utilized to enhance the quality of decision-making by the integration of geographical data and value judgements (Jacek Malczewski, 2006). Different types of MCDA methods such as the widely popular, Analytical Hierarchical Process (AHP) (Saaty, 1980), can be used for revealing and integrating the preferences of decision-makers in connection with resolving GIS-based planning and site selection optimization problems. In this framework, the study aims to develop a methodology for fire station selection using GIS modelling and integrated with fuzzy AHP, by establishing the weights of the influencing parameters for optimally locating new urban fire stations in Istanbul study region.

The research is focused on the GIS-based application of the fuzzy AHP method for Istanbul, with reference to the earlier work done by Erden & Coskun (2010) that utilized the conventional AHP technique covering the city centre of Istanbul, Turkey. Six criteria for the selection of fire stations were identified and selected based on a thorough literature review and international practices as part of the problem structuring phase. The fuzzy AHP procedure was then used to calculate criteria weights via fuzzy pairwise comparisons based on triangular fuzzy numbers (TFNs) of linguistic variables. These preference evaluations were more representative in computing the criteria weights as they were obtained from administered questionnaires of nineteen professionals that incorporated both academicians and fire brigade practitioners associated with emergency planning services. The fuzzy AHP weights were checked using another MCDM technique known as Best-Worst Method (BWM) (Rezaei, 2015) to validate the study results and proposed methodology. These fuzzy weights, once verified, were eventually used as input into a GIS where the criteria were processed and analysed in form of criteria map layers, and then integrated by the use of weighted overlay analysis to produce a fire station suitability raster map. A three-level prioritization analysis from low to high was performed to plan the construction of the new fire stations in a phased approach based on cost implications. These urban fire station facilities would address the increasing demands of fire protection services by minimizing the response time to less than 5 minutes (acceptable by international standards).

The paper examines the background of the study from a state-of-the-art research contribution analysis in subsection 4.3, followed by a description of the study region and data used in the research in subsection 4.4. In subsection 4.5, the study framework and fuzzy AHP methodology are introduced and proposed and implemented in subsection 4.6. The results of the study are presented, interpreted and discussed in subsection 4.7. Finally, the conclusions and research directions are expressed in subsection 4.8.

4.3 Background and Research Contribution

Extensive research on related problems of risk management and site selection has been undertaken using multi-criteria decision-making (MCDM) methods, which can be grouped into multi-attribute decision-making (MADM) and multi-objective decision-making (MODM) techniques. Within the class of MODM, researchers have widely applied techniques involving combinations of mathematical programming such as goal programming (GP), genetic algorithms (GA), simulated annealing (SA) and other variants for solving location/allocation optimization problems (Aktaş et al., 2013; Badri et al., 1998; Bolouri et al., 2018; Çatay, 2011; Chevalier et al., 2012; Gholami-Zanjani et al., 2018; Görmez et al., 2011; G.-H. Tzeng et al., 1999; L. Yang et al., 2007; Yao et al., 2019).

Our study focuses on the usage of MADM techniques due to the nature of the facility selection discrete decision problem which requires the participation of several decision-makers (DMs), allowing consideration of multiple complex and conflicting criteria of varying dimensions/measurement units. MADM methods are widely popular, easy to understand and therefore easily implemented by DMs utilizing less complex computational model procedures compared to MODM approaches. Moreover, the flexibility of MADM enables their integration with other techniques such as fuzzy logic and geographic information systems (GIS). Combined approaches of GIS and MADM methods of the analytical hierarchical process (AHP) are available in several literature. Examples of risk management related studies are explored in (Erden & Karaman, 2012; Eskandari, 2017; Karaman & Erden, 2014; Q. Liu et al., 2019; Nyimbili et al., 2018; Palchaudhuri & Biswas, 2016). Site selection works include landfill site selection (Kontos et al., 2005; Sekulović & Jakovljević, 2016; Wang et al., 2009), determination of the most suitable location for an industrial site (Rikalovic et al., 2014), site selection study for wind turbine farms (Van Haaren & Fthenakis, 2011), site selection of aquifer recharge with reclaimed water in urban areas (Pedrero et al., 2011), and location of a suitable site for a local park (Zucca et al., 2008).

However, not as many studies are prevalent within the domain of fire station site selection using these combined approaches, thus presenting a research opportunity. A state-of-the-art literature search for fire station selection works related to the use of AHP and GIS has been examined (Arabameri, 2014; Chaudhary et al., 2016; Erden & Coskun, 2010; Lai et al., 2011; Reveshti & Heidari, 2007; Wahab & Khayyat, 2014; W. Wang, 2019; Yagoub & Jalil, 2014). From these studies, the only variations in the methodology exist in the selection of criteria deemed most important for selecting new fire stations, perhaps arising from differences in opinions of which factors the researchers viewed to be essential. Nevertheless, there are common factors that have been examined in almost all the studies reviewed such as population density, the distance to main roads, and existing fire stations. Our study procedure proposed is a clear improvement on current methods, as it holistically explores the most essential contributing criteria in new urban fire station selection problems based on best practice experience and international norms to include elements such as density of hazardous material facilities, the density of wooden buildings and areas of risk subjected to earthquakes (especially for Istanbul region which falls in a highly earthquake-prone region). Moreover, to the best of the authors' knowledge, from the available literature, there has been no fire station selection study carried out in Istanbul that combined the use of AHP and GIS methods, apart from the work previously done by Erden & Coskun (2010). Let alone, that which utilizes fuzzy AHP approaches. Further, our present study suggests a widely representative model result in evaluating the criteria weights by using judgements of nineteen experts comprising of both academic-related professionals and fire brigade personnel. Another MCDM method, known as the Best-Worst Method (BWM) (Rezaei, 2015) is proposed to be utilized to check the reliability of these fuzzy AHP criteria weights to achieve the least possible criteria weight differences in value when both MCDM methods are compared. Thus, validating the model result and thereby enhancing the significance of this research. This study, also suggests new urban fire station locations via a three-level prioritization analysis (low, medium and high) for implementation in phases given budget limitations. From the studies analysed, it can be inferred that there exist some research gaps and potential in the usage of integrated fuzzy AHP and GIS in research application domains of fire station selection problems in general and particularly as applied to the case study region of Istanbul.

In the AHP technique (Saaty, 1980), the decision problem is initially broken down into a hierarchy of easily comprehendible sub-problems that can be evaluated subjectively into numerical values. The ranking of each alternative on a numerical scale is performed to select the most optimal as the best solution (Bhushan & Rai, 2007). This process is accomplished by comparison of the elements to one another, two at a time, by pairwise comparison in the built hierarchy structure. Despite the conventional AHP method (Saaty, 1980) being a powerful tool in MCDA for solving problems and its strengths, the AHP has been criticised by some researchers for its weaknesses of uncertainties and inadequacy in dealing with imprecision or vagueness of linguistic assessment (Erden & Coskun, 2010; Saaty, 1990; Saaty, 2008). Yang & Chen (2004) expressed that the AHP does not take account of the inherent uncertainty in human perception related to the mapping of decision-makers (DMs) judgement to a crisp number (scale of 1-9) resultantly having a significant effect on the AHP outcome. Concerns about the certainty of the comparison ratios used in the AHP were raised by Buckley (1985) where DMs can express feelings of uncertainty while comparing/ranking varying criteria or alternatives. Not regarding this fuzziness or vagueness of human behaviour in the process of decision-making may contribute to imprecise judgments and erroneous decisions (Bouyssou et al., 2000; Tsaur et al., 2002). The choices of the DM in the classical AHP method (Saaty, 1980) which uses a crisp scale of 1 – 9, are assessed with natural language labels (e.g. low, medium, high, etc.) depicted by a crisp number in the given scale and registered in comparison matrices. Owing to the inherent uncertainty in human perception, as previously asserted, these human desires cannot be accurately represented by crisp numbers (Ahmed & Kilic, 2019). Therefore, to overcome these problems of uncertainty, and to accurately transform human preferences into ratio scales, modifications and extensions to Saaty's AHP were made by incorporating fuzzy set theory (Zadeh, 1965) where the weighting scale consists of fuzzy numbers.

In fuzzy AHP (FAHP), the scale based on fuzzy numbers instead of crisp numbers is used to record pairwise comparisons from which weights are established to rank and compare the relative importance between the alternatives or criteria. In this way, DMs generally feel more confident in expressing their judgement by providing fuzzy numbers as opposed to crisp numbers. Common sense linguistic expressions, in the form of fuzzy numbers, can be modelled (Ayağ, 2014). Resultantly, fuzzy AHP and its variations have been widely and successfully applied to deal with fuzzy decision-making problems (Buckley, 1985; Chang, 1996; Du et al., 2016; Xu, 2000). The computation of fuzzy AHP weights from fuzzy pairwise comparison matrices (FPCM) can be performed using several popular methods that have been developed. A fuzzy logarithmic least squares method was suggested by Van Laarhoven & Pedrycz (1983) to obtain triangular fuzzy weights. Buckley (1985) derived the fuzzy weights of criteria by the geometric mean method. Chang (1996) developed an approach for triangular fuzzy numbers called the extent analysis method, which derives crisp weights from an FPCM. The Lambda-Max method, which is the direct fuzzification of the λ_{max} method was proposed by Csutora & Buckley (2001); and Mikhailov (2003) developed a fuzzy preference programming (FPP) method. In our study, the Buckley (1985) method of the geometric mean was used due to its simplicity in extension to the fuzzy case and guarantee of a unique solution to the reciprocal comparison matrix (Beskese et al., 2015; Büyüközkan et al., 2004; Kordi & Brandt, 2012). In recent years, there has been an increasing number of studies on the application of fuzzy AHP and GIS for resolving site selection problems that have been analysed. These include landfill site selection (Beskese et al., 2015; N. Chang et al., 2008; Charnpratheep et al., 1997; Torabi-Kaveh et al., 2016); hospital site selection (Vahidnia et al., 2009); selection of solar power plant location (Kengpol et al., 2013); and solid waste disposal site selection (Abdulhasan et al., 2019).

The main purpose and innovation of the research are to propose a GIS-based fuzzy AHP model within a group decision-making (GDM) framework for optimizing the planning of new urban emergency fire stations in Istanbul, Turkey. There has been no research conducted in Turkey that has explored the suitability of new urban fire station sites using the proposed MCDM method of fuzzy AHP. In this study, the application of the fuzzy AHP model to a real case study environment was necessitated by consideration of its advantages over conventional MCDM techniques and the usefulness of developing a GDM approach. Fuzzy AHP is applied to better model the inherent uncertainty in human perception expressed in the opinions of decision-makers (DMs') through crisp numbers as used in the AHP approach from the prior study, which may otherwise lead to imprecise judgements and incorrect decisions. Additionally, the reliability of the fuzzy AHP result, in our present work is assessed using another MCDM method, known as the Best-Worst Method (BWM) (Rezaei, 2015). The GDM process allowed the participation of nineteen DMs consisting of academician-affiliated professionals and fire brigade practitioners to yield a more representative model result.

4.4 Study Region and Data

Turkey's metropolitan province of Istanbul is the most populous and urbanized, spanning an approximate total area of 5, 343.02 km^2 with a population of about 15,067,724 as of 2018 (Malczewski, 2006). In the last decade, Istanbul has had an annual average growth rate of about 16.4% and as a result of this increasing population as well as city infrastructure expansion activities, there has been a continual rise in fire occurrences (IMM, 2016). Since the year 1900, there have been over 2,391 recorded deaths caused by fires representing about 35.4% of all disasters within the associated classification of the technological sub-group of disasters affecting Turkey (EM-DAT, 2019). Against this background, the optimal selection of suitable locations of fire stations to lessen the fire response time to 5 min or less is very crucial in the mitigation of fire impacts and improving the fire response action.

Our study region covers the whole of Istanbul province, which consists of approximately 960 sub-districts as shown in Figure 4.1.

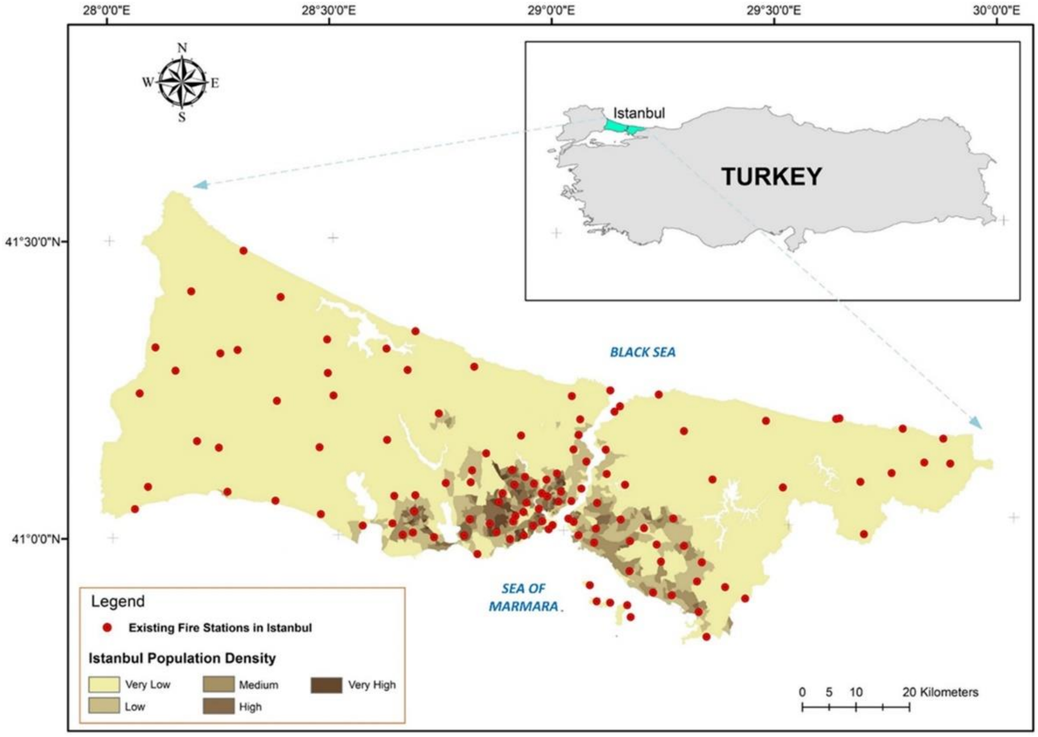


Figure 4.1: Study region showing existing fire stations and population density.

Building on the earlier work by Erden & Coskun (2010) that applied integrated AHP and GIS, our research extends the AHP method to the use of fuzzy AHP (FAHP) and GIS. This study covers the whole extent of Istanbul province and is not only focused on a selected city centre area of Istanbul province as from research undertaken earlier. This research covered the full extent of the Istanbul region and thereby incorporated a more up-to-date and much wider coverage area of all the six criteria data layers representative for suitably recommending new fire stations. These comprised of: a total of 121 current fire stations' locations extracted from the latest Istanbul Fire

Department database and were used to determine the distance from existing fire stations; population density information representing the updated population of Istanbul according to its sub-districts as at 2017; the most recent and expanded main road network data; wooden building density representative of all wooden buildings within the whole Istanbul region because of old architecture and buildings made of wood that increases the spread and impact of fire; and computation of the distance from areas exposed to earthquake risk based on the earthquake hazard map evaluated for the whole Istanbul. The criterion for the density of hazardous material facilities consisted of extensive records of oil stations, chemical substances, liquefied petroleum gas (LPG) and compressed gases, natural and processed gases/oils not included in the earlier study. Furthermore, the preference judgements were extended to nineteen DMs that included fire brigade personnel, not previously examined in the preceding work.

4.5 Fuzzy-AHP Methodology and Study Framework

4.5.1 The AHP

Besides being adaptable, the AHP method (Saaty, 1980) is structured for analysing complex decision-making problems through a hierarchical framework and ranking process of selecting the best alternatives among many having multiple and conflicting criteria. This evaluation is performed systematically via pairwise comparison procedures of individual judgements and decision criteria on a qualitative scale.

The following are the general procedures of the AHP (Lee et al., 2008; Vahidnia et al., 2009): (i) definition of problems and statement of goals, outcomes, criteria and alternatives; (ii) hierarchical break down of complex problem into specific criteria and alternatives; (iii) pairwise comparison evaluation among alternatives/criteria and generation of pairwise comparison matrices; (iv) estimation of relative weights; (v) computation of the consistency ratio (CR) to indicate acceptable level of consistency in priorities of the decision-makers (If CR < 0.1, then judgments are acceptable and weights can be used); (vi) aggregation of the relative weights of the decision elements to ascertain the best overall alternative rating.

The pairwise comparison scale for AHP criterion evaluation as described by Saaty (1980) expresses the linguistic judgments by numerically scaled levels of importance, where; equal importance = 1, moderate importance = 3, strong importance = 5, very strong importance = 7 and extreme importance = 9. Similar alternatives are distinguished by the even numbers 2, 4, 6 and 8. The reciprocals of these numbers express the inverse relationship (Vahidnia et al., 2009).

4.5.2 Fuzzy AHP

Zadeh (Zadeh, 1965) first proposed the fuzzy set theory for modelling fuzziness or vagueness of human expressions. The theory generalises classical (crisp) set theory where individuals are grouped into classes that do not have sharp or crisp boundaries. Vagueness arises from linguistic imprecision in our natural language and depends on how we communicate. This vagueness or fuzziness can be represented by possibility distributions which are fuzzy membership functions. The membership function $\mu_A(z)$ of a fuzzy set A is assigned a real number in the interval [0, 1] for each element $x \epsilon X$ and $\mu_A(x)$ defines the degree of membership $x \epsilon A$ (Hansen, 2005; Singh et al., 2019). Therefore, fuzzy AHP utilizes fuzzy value number ranges to model the imprecision or uncertainty of decision-makers (DMs) (Lee et al., 2008). DMs are allowed to freely select value ranges that reflect the style of human thinking which gives them confidence in their interval judgements as opposed to expressing their judgements in numerical value (crisp) form (Erensal et al., 2006). In fuzzy AHP, triangular fuzzy numbers (TFNs) are used to express the weights of the nine-point judgement scales for representing the relative importance among hierarchical criteria. A TFN is a special type of number whose membership function is characterised by three real numbers (ℓ, m, u) (Karimi et al., 2011) as shown in Figure 4.2.

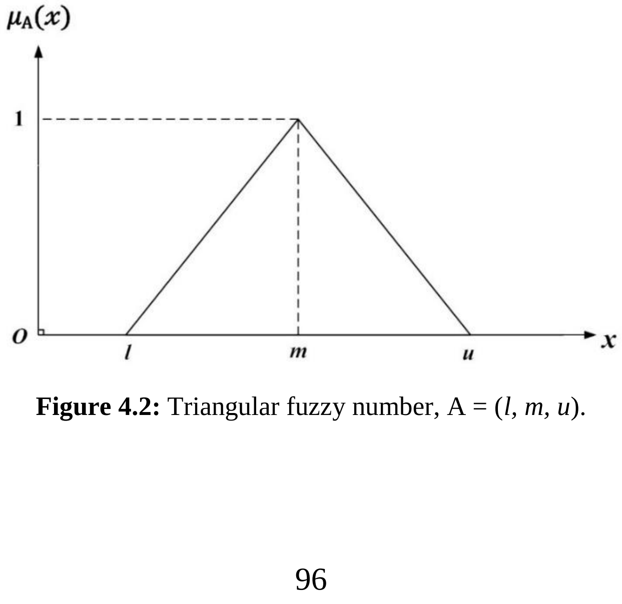


Figure 4.2: Triangular fuzzy number, A = (*l*, *m*, *u*).

The parameters ℓ, m and u are the lower, mean and upper bounds of the TFN. Where parameters ℓ and u limit the field of the possible evaluation and m gives the maximal degree of membership function $\mu(x)$, described by equation (4.1). The membership function u describes the degree to which any given element x contained in domain X belongs to the fuzzy number A (Karimi et al., 2011; Vahidnia et al., 2009).

$$\mu_A(x) = \begin{cases} (x - \ell)/(m - \ell), & \ell \leq x \leq m \\ (u - x)/(u - m), & m \leq x \leq u \\ 0 & otherwise \end{cases} \tag{4.1}$$

These TFNs are used in the pairwise comparison matrices to obtain a *fuzzy pairwise comparison matrix (*FPCM) (Chan et al., 2012; Singh et al., 2019). Several fuzzy AHP methods that use the TFNs for the pairwise comparison scales have been suggested (Erensal et al., 2006). Our study proposed the use of the *geometric mean method* by Buckley (Buckley, 1985) mainly because of its computational easiness and guarantee of a unique solution.

4.5.2.1 Geometric mean method

The geometric mean method developed by Buckley (Buckley, 1985) was used in this study and considered the triangular fuzzy membership function for deriving fuzzy weights of criteria. Triangular Fuzzy Numbers (TFNs) are used to express the expert judgements, generating the triangular fuzzy comparison matrix as shown in equation (4.2).

$$\tilde{A} = (\tilde{a}_{ij})_{nxn} = \begin{bmatrix} (1\,,1\,,1) & (l_{12}, m_{12}, u_{12}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (1\,,1, 1) & \cdots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & \cdots & (1\,,1\,,1) \end{bmatrix} \tag{4.2}$$

where, $\tilde{a}_{ij}$ = (l_{ij}, m_{ij}, u_{ij}) and $\tilde{a}_{ij}^{-1}$ = $(1/u_{ji}, 1/m_{ji}, 1/l_{ji})$

for $i, j = 1, \ldots, n$ and $i \neq j$

Fuzzy set operators of *multiplication*, *addition* and *subtraction,* used in the fuzzy pairwise comparison approach computation for fuzzy sets $\tilde{a}_i$ and $\tilde{a}_j$ are illustrated from equations (4.3), (4.4) and (4.5) as follows:

$$\begin{aligned}\tilde{a}_i \otimes \tilde{a}_j &= (\tilde{a}_{i1}, \tilde{a}_{i2}, \tilde{a}_{i3}) \otimes (\tilde{a}_{j1}, \tilde{a}_{j2}, \tilde{a}_{j3}) \\ &= [(\tilde{a}_{i1} * \tilde{a}_{j1}), (\tilde{a}_{i2} * \tilde{a}_{j2}), (\tilde{a}_{i3} * \tilde{a}_{j3})]\end{aligned} \tag{4.3}$$

$$\begin{aligned}\tilde{a}_i \oplus \tilde{a}_j &= (\tilde{a}_{i1}, \tilde{a}_{i2}, \tilde{a}_{i3}) \oplus (\tilde{a}_{j1}, \tilde{a}_{j2}, \tilde{a}_{j3}) \\ &= [(\tilde{a}_{i1} + \tilde{a}_{j1}), (\tilde{a}_{i2} + \tilde{a}_{j2}), (\tilde{a}_{i3} + \tilde{a}_{j3})]\end{aligned} \tag{4.4}$$

$$\begin{aligned}\tilde{a}_i \ominus \tilde{a}_j &= (\tilde{a}_{i1}, \tilde{a}_{i2}, \tilde{a}_{i3}) \ominus (\tilde{a}_{j1}, \tilde{a}_{j2}, \tilde{a}_{j3}) \\ &= [(\tilde{a}_{i1} - \tilde{a}_{j1}), (\tilde{a}_{i2} - \tilde{a}_{j2}), (\tilde{a}_{i3} - \tilde{a}_{j3})]\end{aligned} \tag{4.5}$$

Positive triangular fuzzy matrices are then constructed. The positive triangular fuzzy numbers transformed from linguistic variables representing the scores of pairwise comparisons are as tabulated in Table 4.1 (Lee et al., 2008).

Table 4.1: Pairwise comparison scale for AHP (Saaty, 1980) of linguistic variables using their equivalent fuzzy numbers.

Linguistic variables	**Positive triangular fuzzy number (*l, m, u*)**	**Positive reciprocal fuzzy number (*l, m, u*)$^{-1}$**
Equal (E)	(1, 1, 1)	(1, 1, 1)
Moderate (M)	(2, 3, 4)	(1/4, 1/3, 1/2)
Strong (S)	(4, 5, 6)	(1/6, 1/5, 1/4)
Very strong (VS)	(6, 7, 8)	(1/8, 1/7, 1/6)
Extremely strong (ES)	(9, 9, 9)	(1/9, 1/9, 1/9)
Intermediate values (IV)	(1, 2, 3), (3, 4, 5), (5, 6, 7), (7, 8, 9)	(1/3, 1/2, 1), (1/5, 1/4, 1/3), (1/7, 1/6, 1/5), (1/9, 1/8, 1/7)

The corresponding triangular membership function can be illustrated in Figure 4.3.

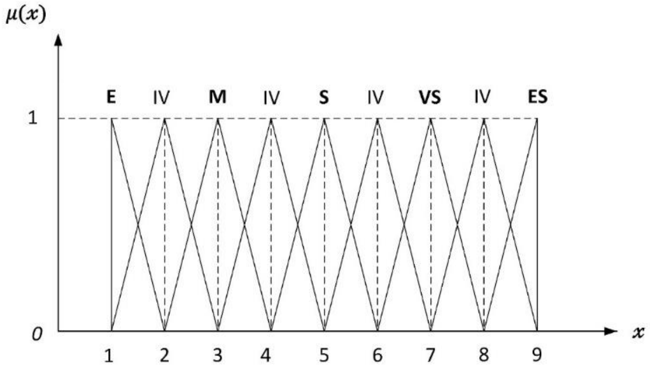


Figure 4.3: Triangular membership function of linguistic variables.

Using the *geometric mean method*, the final fuzzy weights of each criterion can be computed as follows:

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus . . . \oplus \tilde{r}_n)^{-1} \tag{4.6}$$

where $\tilde{r}_i$ is the *fuzzy geometric mean value* given by,

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes . . . \otimes \tilde{a}_{in})^{1/n} \tag{4.7}$$

De-fuzzification of the *fuzzy weights*, $\widetilde{w}_i$ to obtain crisp numerical values using the *centre of area* (COA) method is calculated by:

$$w_i = \left(\frac{l+m+u}{3}\right) \tag{4.8}$$

Finally, *normalization* of the weights, w_i is then performed.

4.5.3 Proposed GIS-based fuzzy AHP model for fire station site selection

In most real-world applications, site selection is a complex and multistage process involving multiple sites and evaluation of criteria. Fuzzy Analytical Hierarchy Process (FAHP) solution approach is well suited to the decision problem of site selection.

The solution process of the FAHP decision model is initiated with the establishment of the criteria for site selection which are organized in a hierarchy from a general goal to multiple attributes in progressive levels. The weights of the site selection criteria are calculated using qualitative factors via fuzzy pairwise comparisons to assess their relative importance in relation to the various opinions of the decision-makers (DMs). These final criteria weights are then used in the final analysis results to suggest the optimal sites for constructing fire station facilities (Yang & Lee, 1997). The main objective of GIS is to provide support for making spatial decisions. In the context of the decision-making process, the GIS capabilities can be analysed for supporting spatial decisions such as site selection.

The main aim of the study was to propose a model to support DMs in selecting optimal sites for fire stations applied for a case study region of Istanbul. The FAHP procedures are conceptualized in Figure 4.4.

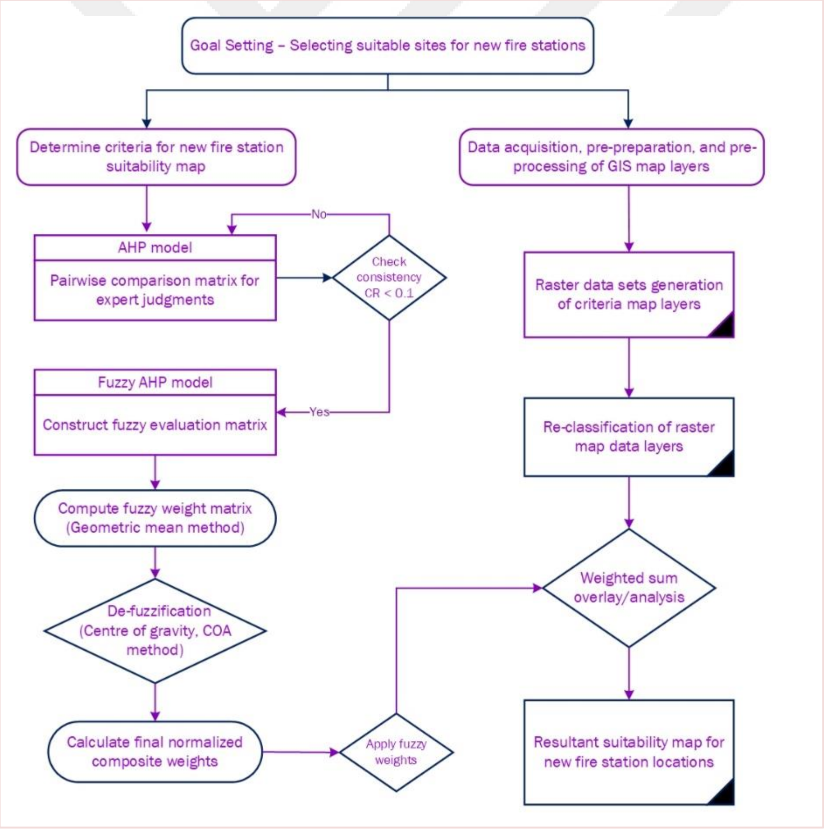


Figure 4.4: Fuzzy AHP conceptual flow chart.

The conceptual flow chart in Figure 4.4 illustrates the proposed FAHP methodology applied in this study. From inception, the setting of the goal was clearly defined as the site selection for new urban fire stations and emergency facilities. From this well-defined objective, the criteria for suitably locating sites for new fire stations were assessed. The hierarchical structure of the site selection problem and criteria is represented in Figure 4.5.

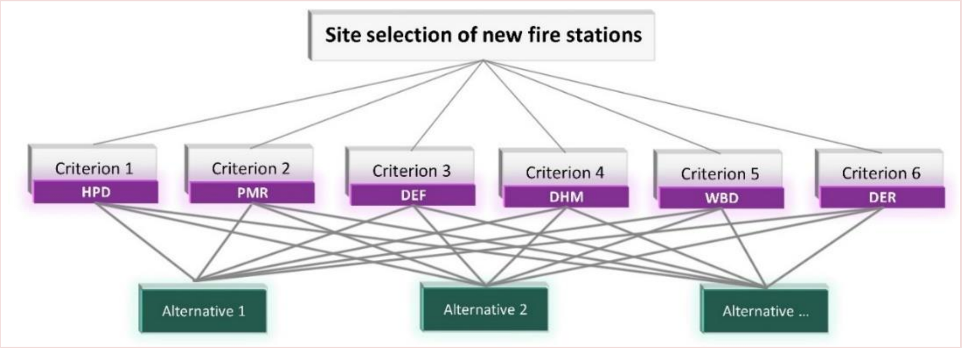


Figure 4.5: Hierarchical structure of site selection problem.

The site screening stage consisted of data acquisition and transfer to ESRI ArcGIS software environment for preparation, pre-processing and analysis. The criteria in the form of input map layers were then converted to raster data sets for re-classification analyses. The consistency of the decision-making process was first examined in the site evaluation stage using conventional AHP. The relevant criteria were evaluated using pairwise comparison matrices by a group of nineteen (19) fire brigade personnel and academic-related professional DMs to compute the consistency ratio (CR) of the aggregated decision matrix. After verification of the consistency of the decision-making process by ensuring $CR < 0.1$, the experts performed the re-evaluation of each criterion by using linguistic variables given in Table 4.1 and their transformed triangular fuzzy number (TFN) equivalents. New fuzzy pairwise comparison matrices (FPCM) were constructed using the FAHP model as depicted in Table 4.2, from which a fuzzy weight matrix was computed by the *geometric mean* method (Buckley, 1985) by equations (4.6) and (4.7) in the previous subsection. The de-fuzzification process by the *centre-of-area* (*COA*) approach, expressed by equation (4.8), was performed to transform the total fuzzy weights into real numbers. The final weights were then obtained by normalization of the de-fuzzified weights. These normalised weights were thereafter applied to each of the criterion map layers in ArcGIS by multiplying with the corresponding weight using a weighted overlay function. Finally, the resultant suitability raster map for locating potential sites for new fire stations was generated.

4.6 Implementation of Proposed FAHP Methodology

4.6.1 Preparation and selection of criteria map layers

In achieving the research objective, requirements of the important factors were contemplated. Six criteria were selected based on a project report regarding critical risk areas and locations of fire stations in Istanbul (IMM, 1989) and as recommended by Gay & Siegel (1987) as well as Johnston (1999) that the criteria should include densities of population, in-between distances of fire stations and special hazards. This fulfils the need to achieve a comprehensive planning approach that takes into account the entire operation of a fire department in the provision of the most cost-effective fire protection system. These six criteria identified and selected were: high population density (HPD), proximity to main roads (PMR), distance from existing fire stations (DEF), density of hazardous material facilities (DHM), wooden building density (WBD) and distance from the areas subjected to earthquake risk (DER) (Erden & Coskun, 2010). Succeeding the identification of the criteria, the criteria weights were calculated using fuzzy AHP technique. The weighted overlay method in GIS was then applied to acquire a resultant raster suitability map showing the most feasible locations for new fire stations.

4.6.2 Preparation of data and analysis

The input data format for each of the six criterion map layer was vector-based polygon data. The criteria map layers used in the study assessment were all processed to a cell size resolution of 50 x 50 m^2 which was assessed to be good for visual analysis and comparison. One of the key sources of these data sets was from the Istanbul Metropolitan Municipality (Fire Department database) such as the updated locations of the existing 121 fire stations for establishing the distance from the existing fire station (DEF). From the HAZTURK project (Karaman et al., 2008), the Istanbul earthquake hazard map in raster data format was acquired and resampled to a cell resolution size of 50 x 50 m^2 for computing the distance from areas exposed to earthquake risk (DER). The updated population data for Istanbul by sub-district as of the year 2017 was collected from the Turkish Statistical Institute (TUIK, 2018). This population data was thus used to compute the population density for evaluating areas with high population density (HPD) by dividing the number of people by the respective sub-district area in hectares (ha). Based on the JICA and IMM (2002) project, the data for the preparation of the input map layers for the wooden building density (WBD), proximity to the main roads (PMR) and density of hazardous material facilities (DHM) were obtained. The most updated main road network data was characterized by attribute information such as distance, mean travel speeds (kilometres per hour), road type, the speed limit along each segment (based on traffic information). This road layer data and fire station locations were used to run a network analysis for service area determination i.e. to calculate the coverage of service areas within a fire response time of 5 minutes. The wooden building density (WBD) was calculated as a ratio of the number of wooden buildings to the total number of buildings in each sub-district of Istanbul. The density of hazardous material facilities (DHM) was evaluated for the whole of Istanbul by calculating the number of facilities which contain the most recent records of oil stations included other chemical substances, liquefied petroleum gas (LPG) and compressed gases, natural and processed gases/oils per sub-district area.

The HPD criterion map layer was processed and had a range of values from 0 to 1,333 representative of the number of people per sub-district area in hectares (ha).

The PMR criterion had a value range from 0 to 300 metres that specify the distance from the main road segment layer evaluated by multiple ring buffer analysis of incremental distance values in metres of 60m, 120m, 180m, 240m and 300m (Habibi et al., 2008).

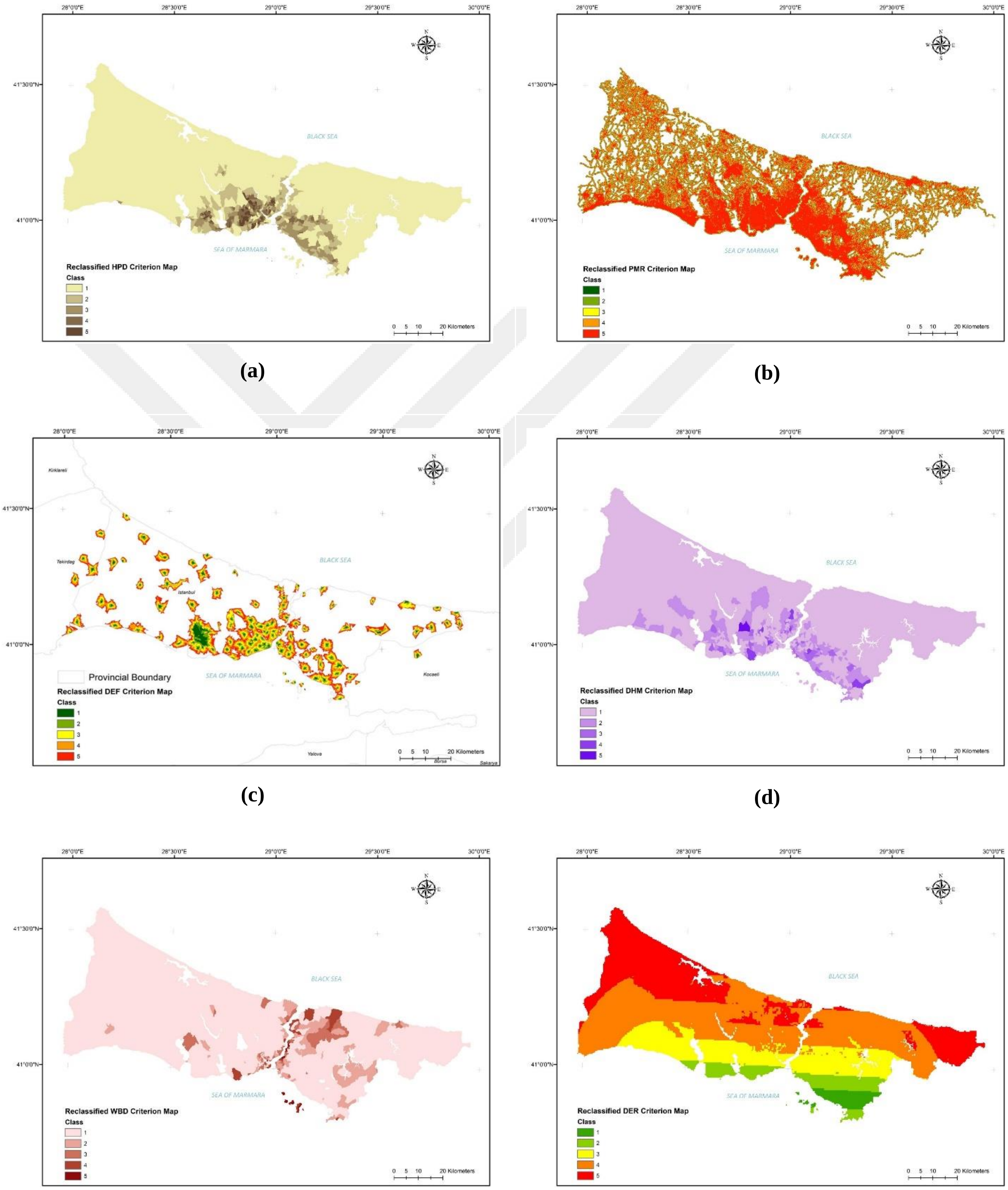
The DEF criterion map layer had a range of values from 1 to 5 representing the coverage of service areas from each of the existing 121 fire stations in minutes (regarding the response time to fire incidence of five minutes). The service area analysis was evaluated by use of the 121 fire stations location and main road layers. Network analysis was performed to estimate the coverage of service areas by utilizing the attribute information at intersections of each of the main road line segments such as distance in kilometres, speed in kilometres per hour and type of road. By utilizing the three road types and their respective speed limits – local (30km/h), main (60km/h) and highways (90km/h), road segment lengths (in km), the time of travel per road segment was computed in the attribute table of the main road layer data. A created topology road layer and a new network dataset, as input in network analysis for new service areas determination, were evaluated from the existing 121 fire stations using the travel time impedance value ranging from 1 to 5 minutes. The service areas for fire stations within a 5-minute coverage distance were indicated by the generated service area polygons. The WBD criterion map layer represented the ratio of the number of wooden buildings to that of the total number of all buildings per sub-district and had values ranging from 0 to 1,782. The DER criterion map layer generated from the Istanbul earthquake hazard map represented the peak ground acceleration values in units of gravity (g).

Succeeding all these processing and analyses of the criteria map layers in a GIS environment, which were in polygon data format, each was converted to raster data format specified to a map resolution of 50 x 50 m^2. Based on the established value ranges of the criteria, each of the map layers was reclassified with new class values of representation ranging from 1 to 5 by use of the natural breaks (Jenks) data classification method as also used by Chaudhary et al. (2016) in their study. The *natural breaks* (*Jenks*) classification method gave a better visual classification result and is ideal for distinguishing classes present in our criterion data resulting from unevenly distributed map data values on the histogram. The class value of 5 indicated the most suitable areas of highest priority while the class value of 1 represented the least ideal areas for locating new fire stations. The range of values of the criteria, the fuzzy membership functions and their associated class values were depicted in Table 4.2.

Table 4.2: Value ranges of criteria reclassified with their associated new class values, adapted from Erden & Coskun (2010).

Criteria	**Fuzzy membership functions**	**New class values**				
		1	2	3	4	5
HPD (people per hectare)	*Large*	0.0-44.8	44.8-146.6	146.6-303.4	303.4-519.0	519.0-1333.2
PMR (metre)	*Decreasing linear*	240-300	180-240	120-180	60-120	0-60
DEF (service areas in minutes)	*Increasing linear*	1	2	3	4	5
DHM (number in per sub-district)	*Large*	0-4	4-15	15-36	36-67	67-153
WBD (ratio in total no. of buildings)	*Large*	0.0-10.3	10.3-46.5	46.5-175.7	175.7-464.3	464.3-1781.8
DER (PGA values in g)	*Small*	1.6–2.4	1.1-1.6	0.8-1.1	0.5-0.8	0.0-0.5

Each of the reclassified criterion map layers represented by value ranges from 1 to 5 were as shown in Figure 4.6.



(a) (b)

(c) (d)

(e) (f)

Figure 4.6: Reclassified raster criteria maps: **(a**) HPD, **(b)** PMR, **(c)** DEF, **(d)** DHM, **(e)** WBD and **(f)** DER.

Following the processing, data conversion and reclassification of the criteria map layers, the fuzzy AHP decision model was constructed to determine the weights of the criteria for application in GIS. Interviews of 19 professional experts and fire service personnel engaged in emergency management and planning fields were conducted to reflect their views on the importance of each respective criterion over another based on their own experiences. The profile of the experts included fire service department personnel, industrial engineers, planners, geomatics engineers and emergency management professionals.

A questionnaire was prepared for generating a fuzzy pairwise comparison matrix using the standard linguistic variables of Table 4.1 and their equivalent triangular fuzzy numbers (TFNs) defined in the aggregated judgements of all the experts (Table 4.3).

Table 4.3: Fuzzy pairwise comparison matrix for aggregated expert preferences with respect to criteria.

Criteria	HPD	PMR	DEF	DHM	WBD	DER
HPD	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)
PMR	(1/3, 1/2, 1)	(1, 1, 1)	(1, 2, 3)	(1/4, 1/3, 1/2)	(1, 2, 3)	(1, 2, 3)
DEF	(1/4, 1/3, 1/2)	(1/3, 1/2, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)
DHM	(1, 2, 3)	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(2, 3, 4)	(3, 4, 5)
WBD	(1/3, 1/2, 1)	(1, 1, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)
DER	(1/4, 1/3, 1/2)	(1/3, 1/2, 1)	(1, 1, 1)	(1/5, 1/4, 1/3)	(1, 1, 1)	(1, 1, 1)
	$\boldsymbol{\lambda}_{max}$ = 6.037		CI = 0.007		CR = 0.006 $<$ 0.1 (*acceptable*)	

Verification of the consistency in the decision-making process was performed by calculating the consistency ratio (CR) which was calculated to be less than 0.1, indicative of consistent judgements.

The total fuzzy weights were evaluated from the fuzzy pairwise comparison matrix and transformed into ordinary crisp numbers by the *centre of area* de-fuzzification method before being normalized (refer to subsections 4.5.2.1 and 4.5.3). The normalized weights for each of the six criteria from the fuzzy AHP process were presented in Table 4.4.

Table 4.4: Fuzzy geometric mean value $(\tilde{r}_i)$, fuzzy weights $(\tilde{w}_i)$, de-fuzzified (crisp) and normalised weights (w_i) for criteria.

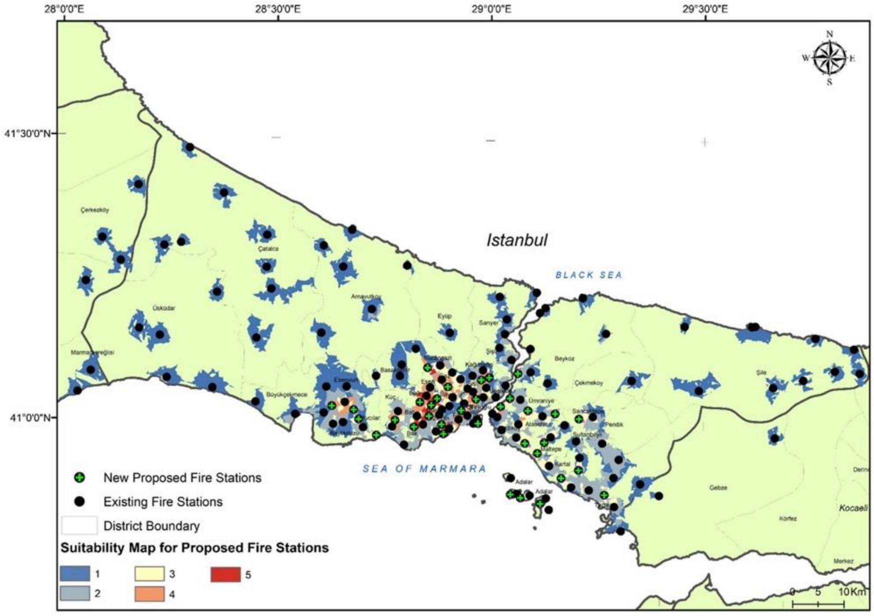
Criteria	Fuzzy geometric mean value $(\tilde{r}_i)$	Fuzzy weights $(\tilde{w}_i)$	De-fuzzified weights (w_i)	Normalized weights (w_i)
HPD	(1.26, 1.82, 2.29)	(0.13, 0.25, 0.43)	0.27	0.244
PMR	(0.66, 1.05, 1.54)	(0.07, 0.14, 0.29)	0.17	0.152
DEF	(0.52, 0.62, 0.79)	(0.06, 0.09, 0.15)	0.10	0.087
DHM	(1.70, 2.45, 3.14)	(0.18, 0.34, 0.59)	0.37	0.333
WBD	(0.66, 0.74, 0.89)	(0.07, 0.10, 0.17)	0.11	0.102
DER	(0.51, 0.59, 0.74)	(0.05, 0.08, 0.14)	0.09	0.082

To check the validity of the final fuzzy AHP weights, another MCDM technique, known as the best-worst method (BWM) by Rezaei (2015) was applied. BWM is one of the most recently developed MCDM methods that use two vectors of comparison to evaluate the weights of criteria. In essence, the best (e.g. most desirable, most important) and the worst (e.g. least desirable, least important) criteria are identified by the decision-maker. Thereafter, pairwise comparisons are carried out, where the best criterion is compared to the other criteria and the other criteria to the worst criterion. A *min-max* problem is constructed and solved to calculate the six different optimal criteria weights. A consistency ratio (CR) that checks the reliability of the comparisons is also assessed by the BWM technique. A CR ≤ 0.25 indicates a very high level of consistency. A summary of the comparative analysis of the criteria weights obtained by the two (2) methods is shown in Table 4.5.

Table 4.5: Comparison analysis between fuzzy AHP and BWM (Rezaei, 2015) criteria weights.

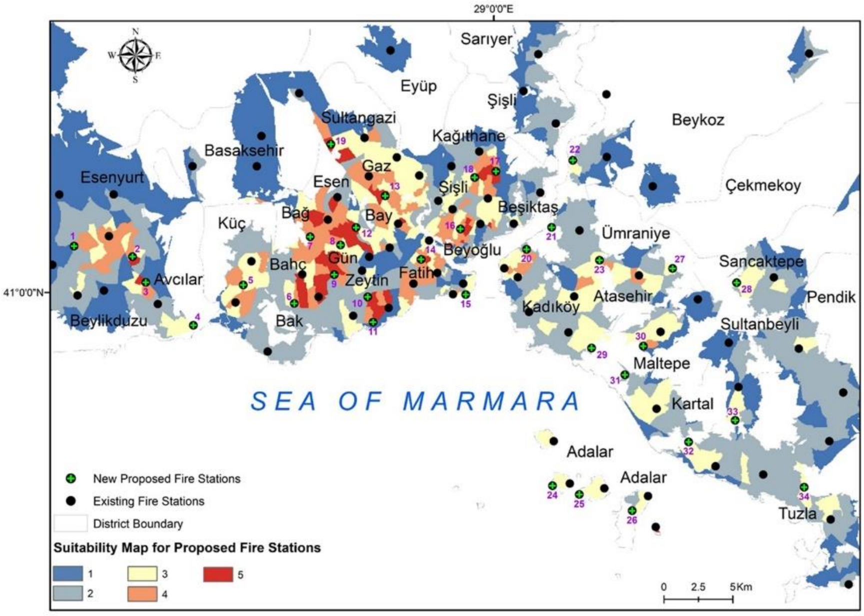
			Criteria						*Consistency Ratio (CR)*
			HPD	PMR	DEF	DHM	WBD	DER	
Fuzzy AHP	Weights		**0.244**	**0.152**	**0.087**	**0.333**	**0.102**	**0.082**	***0.00596***
		Minimum	*0.074*	*0.063*	*0.070*	*0.090*	*0.074*	*0.077*	*(CR ≤ **0.1** - Acceptable)*
		Maximum	*0.376*	*0.385*	*0.284*	*0.347*	*0.331*	*0.298*	
BWM	Weights		**0.251**	**0.145**	**0.111**	**0.309**	**0.103**	**0.081**	***0.10455***
		Minimum	*0.035*	*0.071*	*0.037*	*0.111*	*0.036*	*0.035*	*(CR ≤ **0.25** - Very High Consistency Level)*
		Maximum	*0.476*	*0.378*	*0.427*	*0.521*	*0.167*	*0.159*	
Fuzzy AHP vs BWM Weights		*Absolute Difference*	*0.007*	*0.007*	*0.024*	*0.024*	*0.001*	*0.001*	
		Absolute Average Difference	***0.011***						

Within the ArcGIS environment, these final normalised weights of each criterion were multiplied by their corresponding reclassified raster map criteria layers in a weighted overlay analysis to produce a composite raster suitability map for locating new fire stations (Figure 4.7 (a)) and a zoomed-in suitability map showing the proposed new fire station locations, more distinctively (Figure 4.7 (b)).



(a)

Figure 4.7: (a) Suitability map for new fire station locations of Istanbul.



(b)

Figure 4.8 (continued): (b) Zoomed-in suitability map showing proposed new fire station locations.

4.7 Results and Discussion

From the fuzzy AHP procedure, the normalized weights for all the six criteria were computed as shown in Table 4.4. The reliability and consistency of the weights evaluated from the fuzzy AHP approach were assessed using another MCDM procedure, known as the Best-Worst Method (BWM) (Rezaei, 2015). The optimal weights from the BWM technique were compared with those calculated from the fuzzy AHP method and analysed, as presented in Table 4.5. The analysis results indicate that the fuzzy AHP criteria weight values were comparable and consistent with those from the BWM showing marginal differences (with an average absolute difference in weight values of only 0.011). For the fuzzy AHP, a very low consistency ratio (CR) for the weight calculation of 0.006 (less than 0.1) indicated the consistency and robustness of the preferences. For the BWM, the CR of about 0.106 (less than 0.25) showed a very high level of reliability and consistency in the comparisons. In comparison with the previous study outcome by Erden & Coskun (2010), the CR of the AHP result in this study was lower than that previously obtained of 0.007 indicating more reliable and consistent preference judgements. This improved model result could be largely attributed to the inclusion of the frontline decision-makers from the fire service departments in the AHP procedure. Ensuing the validation of the fuzzy AHP results with BWM, the weights of fuzzy AHP were subsequently used in ESRI ArcGIS 10.3 for multi-criteria site analysis. The weighted overlay method was applied onto the reclassified criteria maps in GIS using these weights to produce a composite raster suitability map for siting new fire stations (Figure 4.7). The suitability map was reclassified into five (5) class values using the same data classifier method of *natural breaks* (*Jenks*), as used to generate the criterion map layers. The class value ranges from 1 to 5 show the variations of the need from the lowest to the highest for new fire stations, where the value of 1 represented the areas not required for any new fire station to be built while the value of 5 represented the areas most needed for constructing new fire stations.

Based on the interpretation of and analysis of the suitability map, 34 new fire stations were proposed to be constructed for the whole of the Istanbul region (Figure 4.7). An elaborate evaluation of these proposed new sites regarded the highest weights established from the expert judgements (Table 4.4) as having more influence on deciding where to locate the fire stations. These factors and their associated weights included the density of hazardous material (DHM) - 33.3%, high population density (HPD) – 24.4% and proximity to main roads (PMR) – 15.2%. In contrast to the earlier findings by Erden & Coskun (2010), the largest criteria weights obtained were DHM – 39.9%, HPD – 15.8% and PMR – 14.5%. Though showing similar ranking order of highest criteria weight coefficients, there were significant differences in the level of influence observed for the DHM and HPD criteria of 6.6% and 8.6%, respectively which impacted the final decision result. Other site selection considerations included the distance from existing fire stations within a service coverage area of 5-min response time representing an average radial distance ranging 1.5 – 2 km; housing expansion and infrastructure developments taking place in service areas of sub-districts indicating rising populations, especially on the Asian side of Istanbul; the temporal aspect of population distribution that is dynamic and shifts drastically between night and day as people migrate from residences to places of work and commerce (e.g. industrial centres). This assessment was also applied to the cases of tourist and trading centres which attract a high volume of people during the day (day-time population) such as areas surrounding Sultan Ahmet in Fatih district. The census population data used in the study represented the residential (night-time) population (as most census population datasets) and therefore did not reflect these trends. Another factor accounted for was the increasing volume of the migrant population in areas such as Çağlayan and Çeliktepe areas of Şişli district.

The 34 proposed new fire stations were categorized into three levels of construction priority because of cost constraints, planning and other special considerations as summarized in Tables 4.6 **(a)**, **(b)** and **(c)**.

The proposed new fire stations were given arbitrary object ID numbers for identification and descriptive purposes as shown in Table 4.6 and visualized in Figure 4.7. On the European side of Istanbul, in high priority areas (priority 1) of classes 4 and 5, new fire stations numbered 3, 9 and 12 were selected. These locations in Avcilar, Bahçelievler and Esenler district areas, respectively, have a very high density of population and presence of facilities with hazardous materials. Stations 5 and 8 were required in Küçükçekmece and Güngören district areas, respectively, because of the very high density of population and of wooden buildings density, especially within the bordering areas. In Fatih and Beyoğlu districts, three (3) fire stations 14, 15 and 16 were proposed mainly as a result of these areas having very high population density, a high volume of migrant populations, a high number of wooden buildings, tourist and trading centres. Most notable among these service areas is Sultan Ahmet, a famous tourist area attracting thousands of tourists during the day. Şişli and Sultangazi districts have very high population densities, industrial and trading centres, and a large number of migrant populations thus requiring stations 17, 18 and 19 for adequate fire protection services. The presence of very high populations, a large number of wooden buildings and facilities which have hazardous materials in Bakirköy, Bağcilar and Zeytinburnu districts reinforce the need for proposing fire stations 6, 7, 10 and 11.

On the Asian side of Istanbul, housing expansions and infrastructural developments occurring indicate rising populations and commercial activity that in turn give rise to an increase in fire incidences. As a result, high population densities, and a large number of hazardous material facilities are prevalent in these areas, hence, planning for new stations 20, 21, 23, 28, and 29 becomes crucial.

Table 4.6: (a) Proposed new fire station locations based on construction priority 1: high.

Priority 1: Areas in class 4 or 5 (of high priority for fire station siting) and other special considerations			
Object IDs	Sub-district/ service areas	District	Dominant factors and considerations for the proposed location
3	Mustafa Kemalpaşa	AVCILAR	Very high population density, presence of hazardous material facilities
5	Sultan Murat	KÜÇÜKÇEKMECE	Very high population density, high number of wooden buildings in the bordering district area (Bakirköy)
6/7	Fevzi Çakmak, Çobançeşme/ Kirazlı	BAKIRKÖY/ BAĞCILAR	Fairly high population density, surrounding areas with a high number of wooden buildings and hazardous material facilities
8	Çınar, Merkez	GÜNGÖREN	Very high population density, presence of wooden buildings
9	Haznedar, Mareşal Çakmak, Akıncılar, Soğanlı	BAHÇELİEVLER	Very high population density, presence of hazardous material facilities
10, 11	Çırpıcı, Nuripaşa, Osmaniye	ZEYTİNBURNU	Very high population density, fairly large number of wooden buildings in surrounding areas and presence of hazardous material facilities
12	Fevzi Çakmak	ESENLER	Very high population density, presence of hazardous material facilities
14, 15	Hırka-i Serif, Sultan Ahmet	FATİH	Very high population density and a high volume of migrant populations, a fairly high number of wooden buildings, tourist and trading centres
16	Hacıamet	BEYOĞLU	High population density, fairly large number of wooden buildings, trading centres
17, 18	Çeliktepe, Çağlayan	ŞİŞLİ	Very high population density, industrial and trading centres, a large volume of migrant populations
19	Sultançiftliği	SULTANGAZİ	Very high population density, a large volume of migrant populations
20, 21	İçadiye, Kuzguncuk, Beylerbeyi, Çengelköy	ÜSKÜDAR	High population density, very high wooden building density, infrastructure developments
23	Atatürk	ÜMRANİYE	High population density, presence of hazardous material facilities
28	İnönü	SANCAKTEPE	High population density, presence of hazardous material facilities
29	19 Mayıs, Kozyatağı	MALTEPE	High population density, fairly high number of hazardous facilities

Table 4.7: (b) Proposed new fire station locations based on construction priority 2: medium.

Priority 2: Areas in class 3 (of medium priority for fire station siting) and other special considerations

Object ID	Sub-district/ service areas	District	Dominant factors and considerations for the proposed location
1	Atatürk, Gökevler, Hürriyet, Barboros Hayrettin Paşa	BÜYÜKÇEKMECE	High population density, servicing nearby areas that have a high number of hazardous material facilities and industries
2	İnönü, Yunus Emre	ESENYURT	High population density
4	Gümüşpala	AVCILAR	High population density
13	Merkez	GAZİOSMANPAŞA	High population density, presence of hazardous material facilities
22	Anadolu Hisarı	BEYKOZ	Very high wooden building density, housing developments, hazardous material facilities
24, 25, 26	Burgazada, Heybeliada, Nizam, Madem	ADALAR	The very high number of wooden buildings, tourist areas/centres with a high volume of day-time population
30	Fındıklı	MALTEPE	Very high population density, presence of hazardous material facilities

Table 4.8: (c) Proposed new fire station locations based on construction priority 3: low.

Priority 3: Areas in class 3 (of low priority for fire station siting) and other special considerations

Object ID	Sub-district/ service areas	District	Dominant factors and considerations for the proposed location
27	Adem Yavuz	ÜMRANİYE	Fairly high population density
31	Küçükyalı Merkez	MALTEPE	Fairly high population density, presence of some hazardous material facilities
32, 33	Atalar, Gümüşpınar	KARTAL	Fairly high population density, presence of some hazardous material facilities
34	Çamçeşme, Esenler	TUZLA	Fairly high population density

For the medium priority sites for fire stations in class 3 areas, stations 1, 2, 4, 13 and 22 were suggested to better serve areas of Büyükçekmece, Esenyurt, Avcilar, Gaziosmanpaşa and Beykoz districts largely due to the high population densities and a high number of industries and facilities that contain hazardous materials. Special attention was given to Adalar district area which is composed of three groups of islands where each has only one existing fire station. Due to the very high number volume of tourists as well as trading activities that take place on these islands mostly during the day (day-population) and a large number of wooden buildings prevalent, this situation poses a great risk of spread in cases of fire incidence without the ability to adequately cope with emergency fire protection services. For this reason, new fire stations 24, 25 and 26 were proposed to be constructed or perhaps a more immediate cost-effective option of increasing fire protection equipment and capacities such as the number of vehicles, personnel and fire hydrants. Station 30 in Maltepe district with an area of very high population density and presence of hazardous material facilities was recommended.

The least priority of fire station sites in terms of phases of construction (priority 3) was planned on the Asian side of Istanbul in Ümraniye, Maltepe, Kartal and Tuzla districts to meet the growing population demand resulting from infrastructure expansion and industrial development activity. These were stations numbered 27, 31, 32, 33 and 34.

It is evident as the model results reveal, that the areas prone to high fire risk are situated within the main built-up (industrialised) and densely populated metropolitan city regions of Istanbul. This underscores the critical need for planning new fire stations to meet the growing demand for fire protection services as part of preparedness and mitigation activities against fire risk. Planning authorities are therefore urged to incorporate in their city infrastructure expansion and development projects, the construction of new fire stations in these high-risk zones for adequate protection of lives and property/infrastructure.

One of the limitations of this study is that there could be some level of uncertainty and inaccuracy as a result of the subjectivity related to categorizing continuous data into clear threshold class values of criteria suitability estimations which currently, in research domains, rely on expert input. This could present a future research opportunity. Another limitation exists in the assumption that the criteria are independent. A variation in any one of the criteria may have a causal effect on another and overall model. These inter-relationships among criteria and identification of the cause and effect factors could be further explored by the use of the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method (Gabus & Fontela, 1973, 1976).

4.8 Conclusions and Future Research

The integrated approach of fuzzy AHP and GIS was used in this research to provide a model for optimally locating new fire stations for the case study region of Istanbul. The developed model can be used by decision-makers actively involved in domains of planning and emergency management services to increase the reliability of the outputs by incorporating fuzzy set theory to lessen the uncertainties inherent in expert judgments. By this proposed methodology, the weights of the six criteria for fire station suitability were evaluated using fuzzy pairwise comparison matrices of surveyed responses of nineteen experts incorporating fire brigade practitioners as well as academic professionals. The participation of both fire brigade personnel and academic-related professionals with related knowledge and experience in the decision-making process ensured that an inclusive and holistic planning decision outcome/model was realistically achieved. To validate the fuzzy AHP results, another MCDM method of Best-Worst Method (BWM) was used in which the evaluated criteria weights were compared and determined to be closely correlated. This demonstrated the high level of consistency and reliability of the fuzzy AHP model and final suitability map for the selection of new fire stations, which will prove useful to be used as a basis for informing planning decisions for related site selection studies.

The research result further provided useful insight into the most important criteria in fire station site selection which were the density of hazardous material facilities (DHM) with a weight of 33.3%, followed by high population density (HPD) with a weight of 24.4% and proximity to main roads (PMR) having a weight factor of 15.2%. Based on a thorough assessment and analysis, the importance levels of these criteria were viewed as having a greater influence on deciding where to locate the fire stations resulting in a total of 34 new fire stations being proposed besides the existing 121 fire stations. Noteworthy factors taken into account included; the service coverage distance from existing fire stations within a 5-minute response time, continued infrastructure and settlement expansions resulting in increasing populations and commercial activities in service areas, day-time population not represented in the census population data used in the study within the service areas attracting high volumes of people in tourist and trading hotspots, and increasing migrant populations prevalent in industrial and commercial areas.

A three-level prioritization analysis from low to high was performed in a phased planning approach accounting for the substantial costs associated with the construction of the proposed 34 new urban fire station facilities. Within the areas represented by class values ranging from 3 to 5 on the suitability map, 20 new fire stations were categorized to be highly prioritized (priority 1) for urgent construction, 9 fire stations were of medium priority (priority 2) while 5 stations were of low priority (priority 3).

In this paper, it has been demonstrated that the proposed fuzzy AHP and GIS framework can be used to enhance the quality of decision-making through visual interpretation of model results for site selection and emergency services planning. Istanbul is continually expanding in size, population and economically, and therefore requires robust emergency preparedness measures and adequate coverage from potential threats from fires through a sufficient number of well-planned fire stations.

Future research is oriented toward comparing the results of the proposed model with other MCDM methods such as OWA, SAW, TOPSIS, ELECTRE and their modifications and fuzzy extensions in fire station site selection studies.

5. MODEL RESULTS VALIDATION OF THE APPLIED MCDA TECHNIQUES USING THE DEMATEL METHOD

5.1 Introduction and Background

Fire risk and emergency planning within the spatial scale of the urban environment is an interconnected and complex decision-making procedure involving multiple criteria as well as stakeholder participation of transdisciplinary nature (Erden, 2012; Nyimbili & Erden, 2018). In the context of urban emergency planning and fire risk mitigation, the present research suggests the implementation of the MCDM technique based on the Decision-Making Trial and Evaluation Laboratory (DEMATEL) to evaluate the inter-dependencies of the criteria necessary for the optimal planning of new urban fire emergency facilities in Istanbul, Turkey.

The DEMATEL method was developed by the Geneva Research Centre of the Battelle Memorial Institute (Gabus & Fontela, 1973, 1976) to solve complex global issues involving structural relationships in complex systems (Wu, 2008). The DEMATEL method was utilized in this research to analyse the inter-relations among the assessment criteria for the urban emergency facility site selection process, thereby building the causal relationship diagram and digraph. The fundamental research question to be addressed in this paper is how the criteria for the selection of new urban fire stations are interrelated and their relative significance in the planning process. Prevailing studies have reaffirmed the benefits of the application of the DEMATEL technique. For instance, Lin & Wu (2008) suggested that DEMATEL is the most appropriate approach in causal analyses for supporting decision-makers in separating the examined criteria of a system into cause and effect groups, therefore assisting in determining criteria of highest influence. The DEMATEL approach, according to Lin et al. (2011), can be used to resolve causal relationship concerns for essential skills for a successful design service within the semiconductor industry of Integrated Circuit (IC). Li et al. (2014) explored the use of the DEMATEL technique in emergency management to uncover crucial success variables. Azizi et al. (2014) evaluated suitable site conditions for setting up a wind power plant in Iran using a DEMATEL combined model in a GIS environment. Further, Chen (2016) used DEMATEL to improve the quality assessment for the airline industry in Taiwan in the long run, to build a long-term competitive advantage. The interrelationships and impacts among the evaluation criteria were examined in order to give airlines a guideline for the assessment and improvement of service quality. For successful disaster preparation, Trivedi (2018) suggested using DEMATEL to analyze complicated interrelationships between drivers of shelter location selection. By examining the interdependence between the major risk variables of Sponge City Public-Private Partnership (PPP) in the setting of China, Zhang et al. (2019) used the DEMATEL approach to analyze them. DEMATEL was used by Altuntas & Gok (2021) to help governments make efficient quarantine measures in the wake of the COVID-19 pandemic, which has a direct impact on the hospitality business. The major essential hospitality sector criterion assessed in their study was inter-regional travel flow between areas in Turkey for local tourism. DEMATEL was used to examine direct and indirect inter-relationships among Turkey's regions, as well as travel information, to provide practical solutions for assisting policymakers in making effective quarantine decisions during the pandemic while minimizing the impact on the tourism and hospitality industries.

The DEMATEL approach was used in this study to plan the locations of the new fire emergency facilities in Istanbul, which were previously determined from prior works. (Nyimbili & Erden, 2021; Nyimbili & Erden, 2020a, 2020b, 2020c). These criteria under evaluation are *high population density* (HPD), *proximity to main roads* (PMR), *distance from existing fire stations* (DEF), the *density of hazardous materials* (DHM), *wooden building density* (WBD) and *distance to earthquake risk* (DER). However, the MCDM methods coupled with geographic information systems (GIS), such as AHP, Fuzzy AHP, Entropy-AHP and BWM utilized from previous studies are unable to determine the dependence, feedback and inter-relationships among the criteria involved. Therefore, the current paper presents a unique research opportunity as it, on the first occasion, explores the use of the DEMATEL technique to overcome these limitations. In DEMATEL, an assumption is made that all criteria are *mutually dependent* and *influence other* criteria. On this account, the significance of this study is that it establishes the importance and causal relationships among the criteria which are modelled visually in form of a digraph and thereby determines the most influential criteria to be considered for the urban emergency facility site selection process. The research outcome will contribute substantially towards policy formulation for effective and comprehensive planning of urban emergency facilities and fire risk mitigation strategies for Istanbul, Turkey.

The following is how the rest of the research is structured: subsection 5.2 outlines the research method and the construction of the DEMATEL model. A brief description of the criteria affecting the planning of the new urban emergency facilities is also expressed. The implementation of the DEMATEL model is elaborated in subsection 5.3 while the results of the findings and model validation from previous studies are discussed in subsection 5.4.

5.2 Research Methodology

The selection of new urban emergency facility and fire station sites in Istanbul is a complex problem involving multiple criteria as well as a thorough procedure of evaluating many alternatives to arrive at an optimal solution.

In this research, within the structuring and construction stage of the research methodology, the decision goal is well defined and the MCDA method of DEMATEL (Gabus & Fontela 1973, 1976) was selected as the most suited to resolve the complexity related to the multiple evaluations of inter-related criteria.

Based on a comprehensive literature search and previous studies (Erden & Coskun 2010; Nyimbili & Erden 2020a, c, 2021), the relevant criteria for the development of new metropolitan emergency departments were determined to create a structural model. Thereafter, using the group decision-making (GDM) approach, a committee of experts was selected from which an aggregate of their assessments using a 5-point comparison scale of the DEMATEL method was captured. This information acquired reflected the decision makers’ preference judgements of the criteria influences and inter-relationships.

The criteria interactions and inter-relations were then evaluated using the DEMATEL method during the assessment stage to construct a causal diagram and a digraph. Visualization of the criteria’s complex causal interrelation into a visible structural representation is made possible using the constructed causal diagrams that provide useful insight, thereby enabling effective problem solving and decision-making by identifying and distinguishing the cause and effect criteria under evaluation (Tzeng & Huang, 2011).

Finally, during the analysis of the inter-relations stage, the criteria's significance and causal linkages, inter-dependence, direction as well as level of interaction were investigated. Consequently, validation of the DEMATEL model result was conducted by comparing results from previous studies to generate further insights. Figure 5.1 provides the overall framework applied in this research.

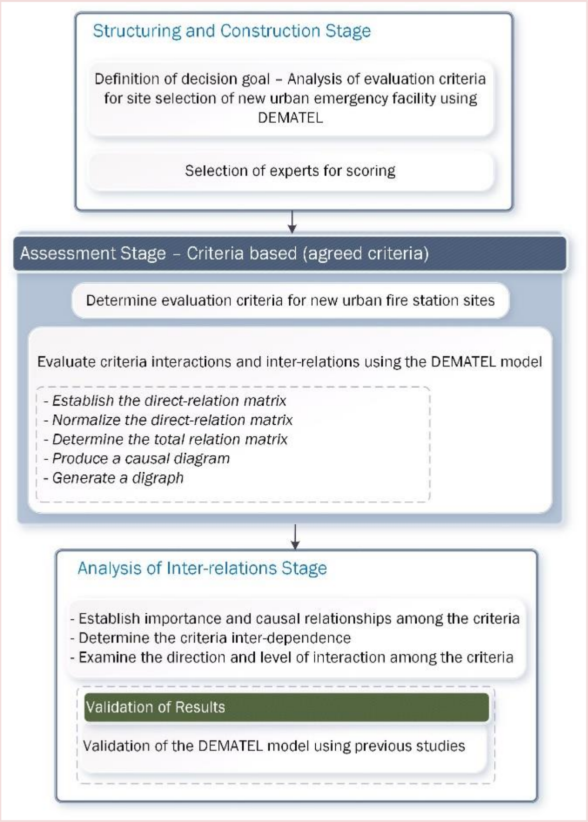


Figure 5.1: Proposed DEMATEL framework

5.2.1 The DEMATEL method

The technique of DEMATEL (Gabus & Fontela 1973, 1976) was developed to resolve intricate problems connected with multiple inter-related criteria using a structural modelling approach.

The DEMATEL method comprehensively constructs and analyses a structural model using directed graphs or *digraphs* visually, to segregate multiple criteria into the cause and effect groups that enable the capture of causal relationships between criteria. The generated *influence map* supports the analysis of inter-twined cluster problems to visualize the directed criteria relationships and also to specify the level of interactivity between criteria (Tzeng & Huang, 2011).

By using DEMATEL in this study, quantitative extraction of the inter-relationship between evaluation criteria for selecting new urban emergency facility sites is taken into account. In this regard, both direct and indirect influences among multiple criteria are considered (Dey et al., 2012; Tzeng & Huang, 2011). Over the years, the DEMATEL method has been widely used to handle a variety of complex practical decision-making challenges, such as in aviation safety assessments (Liou et al., 2007), supplier selection (Dey et al., 2012), urban rail transit projects (Yuan et al., 2015), landfill site selection (Kharat et al., 2016), adaptive reuse of culturally significant industrial structures (Vardopoulos, 2019) and recovery solutions for eco-tourism centres amid the Covid-19 outbreak (Hosseini et al., 2021). The DEMATEL model construction procedure is broken down into the following stages:

Stage 1: *Calculate the average initial direct-relation matrix [$\boldsymbol{A}$] using scores*

The DEMATEL method's comparison scale must be built in order to measure the relationship between criteria *i* and *j*, according to the four (4) influential levels varying from 0 (no impact) to 4 (very high influence) as shown in Table 5.1.

Table 5.1: Comparison scale of the DEMATEL method.

Numerical		Definition
0	⟹	No influence
1	⟹	Low influence
2	⟹	Medium influence
3	⟹	High influence
4	⟹	Very high influence

Using the comparison scale, a panel of representative experts is asked to determine their view of the direct effect that each element *i* exerts on each other element *j*, as shown by a_{ij}. The influence of a particular criterion over itself is 0, and therefore all the diagonal elements will be 0. Following the collection of these sets of direct matrices from the experts, an average matrix **A** is created, with each element representing the mean of the corresponding elements in the experts' direct matrices (in the case of group decision-making (GDM)).

The *k*th expert assigns an integer rating x_{ij}^{k} that represents the degree of influence that criterion *i* has on criterion *j*.

Equation (5.1) calculates the *n x n* matrix **A** by taking the average of the individual expert's scores,

Matrix **A** (*mean initial direct-relation matrix*) = $[a_{ij}]$

$$a_{ij} = \frac{1}{H} \sum_{k=1}^{H} x_{ij}^{k} \tag{5.1}$$

where,

H = total number of experts

k = number of respondents surveyed

Stage 2: *Normalizing the direct-relation (or direct-influence) matrix*

The normalized direct-influence (or direct-relation) matrix **D** is computed using equations (5.2) and (5.3) based on the direct-relation matrix **A**.

Let,

$$S = \max\left(\max_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}, \quad \max_{1 \le j \le n} \sum_{i=1}^{n} a_{ij}\right), \tag{5.2}$$

then,

$$\mathbf{D} \text{ (the direct-influence matrix)} = \frac{\mathbf{A}}{S} \tag{5.3}$$

The direct impact that criterion *i* has on the other criteria are represented by the sum of each row j of matrix $\mathbf{A}$; $\max(\max_{1\le i\le n}\sum_{j=1}^{n}a_{ij},\ \max_{1\le j\le n}\sum_{i=1}^{n}a_{ij})$ depicts the direct impact on others.

Stage 3: *Calculate the total relation matrix (*$\mathbf{T}$*)*

The total-relation matrix implies total-influence matrix. The total-relation matrix **T** is computed using equation (5.4) after producing the normalized direct-relation matrix **D**.

$$\mathbf{T} = \mathbf{D}\,(I - \mathbf{D})^{-1} \tag{5.4}$$

where, I = identity matrix.

Stage 4: Producing a causal diagram

In the total-influence matrix **T**, the sum of rows and columns are represented individually as vectors **D** and **R**, respectively. "*Prominence*," the horizontal axis vector $(\boldsymbol{D}+\boldsymbol{R})$, is created by adding **D** to **R**, which denotes the criterion's importance. Similarly, the vertical axis $(\boldsymbol{D}-\boldsymbol{R})$ termed "*Relation*," is created by subtracting **R** from **D**, and can be used to separate criteria into *causal* and *effect groups*. From the foregoing statements, if $(\boldsymbol{D}-\boldsymbol{R})$ is positive, the criterion belongs to the *causal group*, and if $(\boldsymbol{D}-\boldsymbol{R})$ is negative, the criterion belongs to the *effect group*. As a result, the *causal diagram* may be obtained by mapping the $(\boldsymbol{D}+\boldsymbol{R},\ \boldsymbol{D}-\boldsymbol{R})$ dataset.

Then,

$$\boldsymbol{T} = [t_{ij}]_{nxn} \qquad i,j = 1,2,\dots,n \tag{5.5}$$

$$\boldsymbol{D} = [D_i]_{nx1} = (\textstyle\sum_{j=1}^{n} t_{ij})_{nx1} \tag{5.6}$$

$$\boldsymbol{R} = [R_j]'_{nx1} = (\sum_{i=1}^{n} t_{ij})'_{1xn} \tag{5.7}$$

where transposition is indicated by the *superscript apostrophe*.

If D_i is the sum of the *i*th row of matrix ***T***, then D_i is the sum of all of the other criteria's direct and indirect impacts of criterion *i*. Furthermore, if R_j is the sum of the *j*th column of matrix ***T***, then R_j is the sum of all of the other elements' direct and indirect impacts on j.

Additionally, note that when $j = i$ (i.e. the sum of the row and column aggregates); $(D_i + R_i)$, yields an index of the intensity of the given and received influences. That is, illustrates how much criterion *i* impacts or is impacted by criterion *j*. Also, if $(D_i + R_i)$ is positive, criterion *i* influences other criteria, whereas if it is negative, criterion *i* is influenced by the other criteria. (Liou et al., 2007; Yang et al., 2008; Chen, 2016). In other words, $(D_i + R_i)$ represents the significance of criterion *i* whereas $(D_i - R_i)$ denotes the net impact of criterion *i* (Altuntas & Gok, 2021).

Stage 5: Confirm the threshold value (α), *obtain inner dependence matrix and generate a digraph showing causal relations*

To filter the minor effects given in matrix ***T***, it is required to select a threshold value, α, which is derived based on calculating the mean elements in matrix ***T*** or the representative experts' judgments (Yang et al., 2008; Chen, 2016; Altuntas & Gok, 2021). This final stage is necessary to identify the relationship structure of the most important variables. Each criterion t_{ij} offers information about how criterion factor *i* influences j, according to the matrix **T**. A threshold value for each criterion's influence intensity is required to reduce the complexity of the Impact Relation Map (IRM). If an element's influence level in matrix ***T*** exceeds the threshold value, α, that element is included in the final IRM (Liou et al., 2007; Yang et al., 2008). In an *inner dependence matrix*, only the criteria whose impact in matrix ***T*** is larger than the threshold value will be displayed (Lin et al., 2011).

5.2.2 Criteria affecting the planning of new urban emergency facilities

Existing studies analyze six criteria when deciding where to build new emergency centres in cities. These criteria were screened after a comprehensive evaluation process from previous studies as suggested by Erden & Coskun (2010) and Nyimbili & Erden (2020b, a, c, 2021). The developed criteria encompass social, built, accessibility and risk and safety dimensions as shown in Table 5.2. Brief operational definitions of the criteria most influential for selecting new urban facility sites are also described.

Table 5.2: Factors affecting the planning of new urban emergency facilities.

Dimensions	**Criteria**	**Description**
Social	HPD	*Densely populated areas are at risk of fires.*
Built	WBD	*Old wooden building structures within built-up areas pose a huge risk of the spread of fire.*
Accessibility	DEF	*Fire stations and emergency facilities should be located away from the already serviced areas.*
	PMR	*Accessibility of emergency facilities to the main road and transportation routes is essential in enabling faster response to fire incidences.*
Risk and Safety	DHM	*Hazardous materials in industrial facilities and warehouses that include LPG, pressured gases, oil stations, etc increase the risk of fires and explosions.*
	DER	*Planning of emergency facilities away from areas prone to earthquakes prevents infrastructural and structural damage in the event of a disaster.*

After screening and determination of these criteria, a committee of experts through a consultative procedure provided their linguistic assessments of the direct relations among criteria for optimal planning of new urban emergency facility locations using the DEMATEL technique as clarified in the following segment.

5.3 Implementation of the DEMATEL approach

In the implementation of the DEMATEL model, a committee of experts with emergency facility and disaster planning experience was consulted to assess the association between paired criteria that influence the optimal planning of urban emergency facilities in Istanbul. The experts provided their judgement of the interaction between each of the pair of criteria. By doing so, the linguistic assessments of direct relations among criteria were obtained.

As the result of this evaluation, the DEMATEL method's comparison scale (Table 5.1) was used to produce an *average direct-relation matrix*, ***A***, which was obtained as the preliminary data of the analysis. The direct-relation matrix, ***A*** computed for the panel of experts was as shown in Table 5.3.

Table 5.3: Average direct-relation matrix for the experts.

Criteria	**C$_1$** (HPD)	**C$_2$** (PMR)	**C$_3$** (DEF)	**C$_4$** (DHM)	**C$_5$** (WBD)	**C$_6$** (DER)
C$_1$ (HPD)	*0*	*2*	*3*	*2*	*3*	*0*
C$_2$ (PMR)	*2*	*0*	*2.5*	*1.5*	*0*	*0*
C$_3$ (DEF)	*2*	*2*	*0*	*1*	*1.5*	*0*
C$_4$ (DHM)	*2*	*2*	*1.5*	*0*	*1*	*1*
C$_5$ (WBD)	*1*	*2*	*2.5*	*1*	*0*	*0.5*
C$_6$ (DER)	*1*	*1*	*1*	*1*	*1*	*0*

Normalization of the direct-relation matrix was performed by equations (5.2) and (5.3) to generate the *normalized direct-relation matrix*, ***D***. Table 5.4 summarizes the findings.

Table 5.4: Normalization of the direct-relation matrix.

Criteria	**C$_1$** (HPD)	**C$_2$** (PMR)	**C$_3$** (DEF)	**C$_4$** (DHM)	**C$_5$** (WBD)	**C$_6$** (DER)
C$_1$ (HPD)	*0*	*0.2*	*0.3*	*0.2*	*0.3*	*0*
C$_2$ (PMR)	*0.2*	*0*	*0.25*	*0.15*	*0*	*0*
C$_3$ (DEF)	*0.2*	*0.2*	*0*	*0.1*	*0.15*	*0*
C$_4$ (DHM)	*0.2*	*0.2*	*0.15*	*0*	*0.1*	*0.1*
C$_5$ (WBD)	*0.1*	*0.2*	*0.25*	*0.1*	*0*	*0.05*
C$_6$ (DER)	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0*

The total influence matrix, ***T*** is then calculated by equation (5.4) as presented in Table 5.5.

Table 5.5: The total influence matrix.

Criteria	**C$_1$** (HPD)	**C$_2$** (PMR)	**C$_3$** (DEF)	**C$_4$** (DHM)	**C$_5$** (WBD)	**C$_6$** (DER)	$\boldsymbol{D_i}$
C$_1$ (HPD)	*0*	*0.3039*	*0.4559*	*0.3039*	*0.4559*	*0*	***1.5195***
C$_2$ (PMR)	*0.3039*	*0*	*0.3799*	*0.2279*	*0*	*0*	***0.9117***
C$_3$ (DEF)	*0.3039*	*0.3039*	*0*	*0.1520*	*0.2279*	*0*	***0.9877***
C$_4$ (DHM)	*0.3039*	*0.3039*	*0.2279*	*0*	*0.1520*	*0.1520*	***1.1396***
C$_5$ (WBD)	*0.1520*	*0.3039*	*0.3799*	*0.1520*	*0*	*0.0760*	***1.0637***
C$_6$ (DER)	*0.1520*	*0.1520*	*0.1520*	*0.1520*	*0.1520*	*0*	***0.7598***
$\boldsymbol{R_i}$	***1.2156***	***1.3676***	***1.5955***	***0.9877***	***0.9877***	***0.2279***	

The total and net impacts for each criterion were calculated using the total influence matrix and are given in Table 5.6.

Table 5.6: The total effects and net effects for each criterion.

Criteria	D_i	R_i	D_i+R_i	D_i-R_i	Identity
C_1 (HPD)	*1.5563*	*1.3834*	*2.9396*	*0.1729*	*Cause*
C_2 (PMR)	*0.8646*	*1.5563*	*2.4209*	***-0.6917***	*Effect*
C_3 (DEF)	*1.0375*	*1.5563*	*2.5938*	***-0.5188***	*Effect*
C_4 (DHM)	*1.2104*	*0.8646*	*2.0750*	*0.3458*	*Cause*
C_5 (WBD)	*1.0375*	*1.0375*	*2.0750*	*0.0000*	*Cause*
C_6 (DER)	*0.8646*	*0.1729*	*1.0375*	*0.6917*	*Cause*

Table 5.6 was used to retrieve, order, and tabulate the influencing impact D_i, influenced impact R_i, level of significance $(D_i + R_i)$ and causal degree $(D_i - R_i)$ values.

A dataset of $(D_i + R_i, D_i - R_i)$ was mapped to construct the cause and effect diagram (causal diagram) using $\boldsymbol{D}$ and $\boldsymbol{R}$. With $(D_i + R_i)$ as the horizontal (X) axis and $(D_i - R_i)$ as the vertical (Y) axis, the digraph was displayed in Figure 5.2.

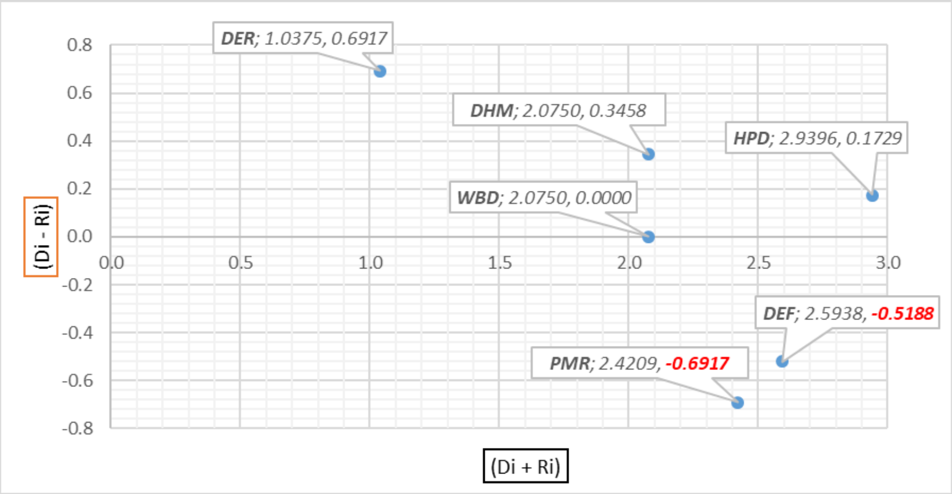


Figure 5.2: The causal diagram showing causal and effect relations among criteria.

From Figure 5.2, the causal diagram articulates the interaction between the criteria and could be a useful tool in making decisions. To filter out certain minor impacts in practice, the threshold value in this research, $\boldsymbol{\alpha}$ = **0.1773**, was derived from the mean of the elements in the matrix. The relationships in the total influence matrix, ***T*** that goes beyond the threshold value are bolded and presented in Table 5.7.

Table 5.7: The total influence matrix with relations exceeding the threshold value.

Criteria	**C₁** (HPD)	**C₂** (PMR)	**C₃** (DEF)	**C₄** (DHM)	**C₅** (WBD)	**C₆** (DER)
C₁ (HPD)	*0*	***0.3039***	***0.4559***	***0.3039***	***0.4559***	*0*
C₂ (PMR)	***0.3039***	*0*	***0.3799***	***0.2279***	*0*	*0*
C₃ (DEF)	***0.3039***	***0.3039***	*0*	*0.1520*	***0.2279***	*0*
C₄ (DHM)	***0.3039***	***0.3039***	***0.2279***	*0*	*0.1520*	*0.1520*
C₅ (WBD)	*0.1520*	***0.3039***	***0.3799***	*0.1520*	*0*	*0.0760*
C₆ (DER)	*0.1520*	*0.1520*	*0.1520*	*0.1520*	*0.1520*	*0*

These results from Table 5.7 were used to show the impact relations map (IRM) via a digraph with the direction of arrows representing the inter-criteria influence in Figure 5.3.

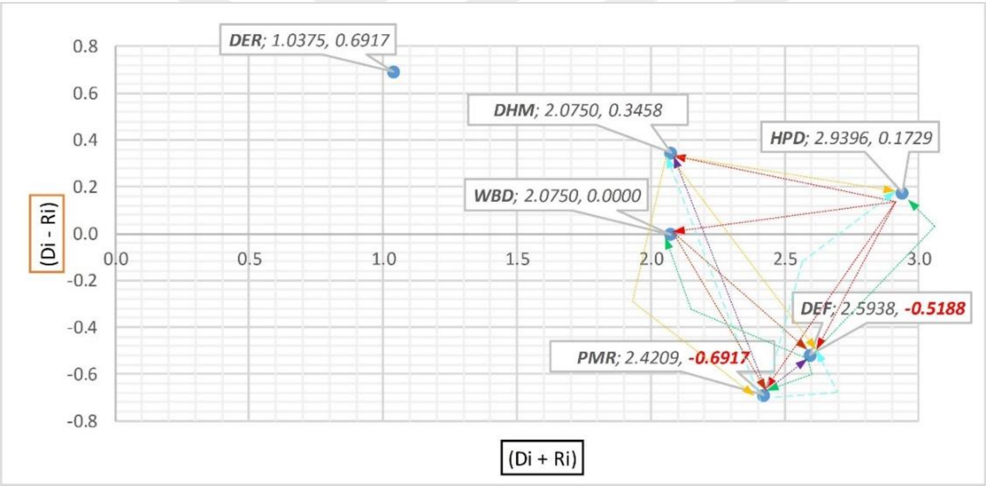


Figure 5.3: The digraph shows significant relationships in terms of linkages among criteria.

The subsequent subsection discusses the research results of the criteria influences and inter-criteria analyses as well as the DEMATEL model validation for the best choice of urban fire and emergency facilities in Istanbul.

5.4 Results and Discussion

5.4.1 Key results and findings

Further insights into analyses of the criteria interactions were generated by identification of the most important relationships among the criteria. From Table 5.7, which shows the relations exceeding the threshold limit of influence of **0.1773**, some inferences can be made. Out of the six criteria, high population density (HPD) has a significant influence on four other criteria; and PMR, DEF and DHM each have a significant influence on three other criteria. Therefore, these four criteria are the most influential contributors to the best choice of location options for facilities of fire and emergency services in cities. Conversely, DER does not significantly influence any other criteria.

Based on the influence that each criterion has on others, an impact relations map (IRM) or influence map was created which describes how each criterion interacts with the other criteria.

The causal diagram (Figure 5.2), shows the X-axis $(D_i + R_i)$ that represents the criterion's measure of influence while the Y-axis $(D_i - R_i)$ represents the magnitude of a criterion's influence from other criteria or the intensity of the effect. Both these values characterize the criteria inter-relationships. The impact on other criteria is represented by the D_i factor, whereas the impact from other criteria is represented by the R_i value. All these variables should be considered to identify and determine the critical criteria in the planning of urban emergency facilities. According to the causal diagram in Figure 5.2, when the criterion is situated above the horizontal axis, the $(D_i - R_i)$ value is *positive* implying that the effect of this particular criterion exerted on the other criteria is greater than that received from the others. The value of the influential impact D_i is larger than the value of the affected impact R_i. Therefore, the criterion is a net causer and in turn categorized in the *cause cluster*. In contrast, when the $(D_i - R_i)$ value is *negative*, the criterion is regarded as a net receiver and subsequently classified in the *effect cluster*. Overall, the effect criteria are affected by the cause criteria thus directly influencing them in the planning of new urban fire facilities.

Furthermore, the inter-criteria effect is represented by the orientation of the arrows as depicted in Figure 5.3, which illustrates these linkages among criteria in the modified version of the diagram without the ***D*** and ***R*** values (Figure 5.4).

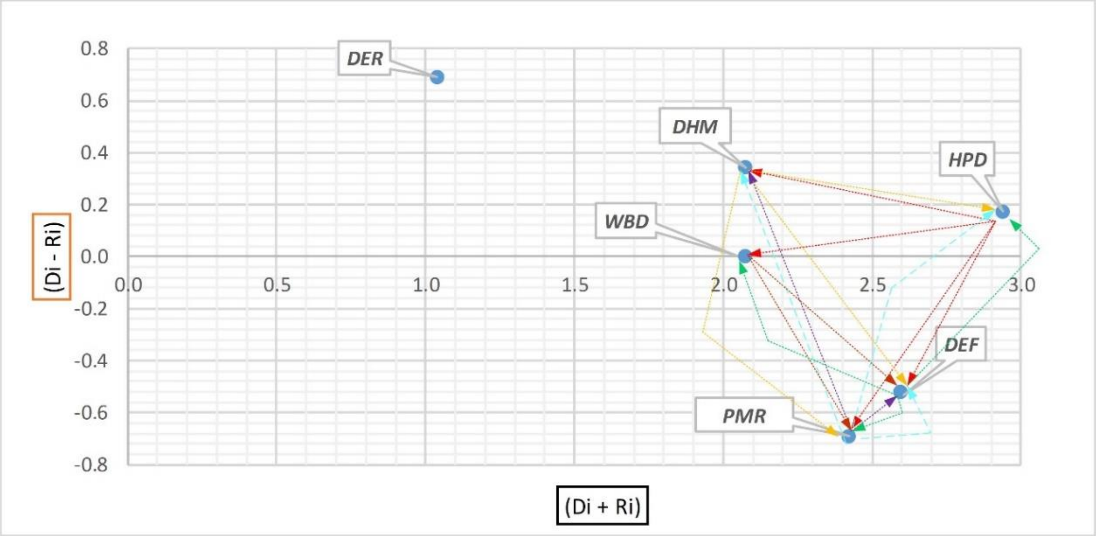


Figure 5.4: The digraph showing linkages among criteria (without D and R values).

It can be observed from Figure 5.4 that HPD has the most influence on all other criteria, whereas PMR and DEF are impacted by a lot of other criteria. The inter-relationships among the various criteria for optimally selecting fire stations and urban emergency facilities in Istanbul were analysed in this study. From Table 5.6 and the generated digraph presented in Figures (5.2) and (5.3), the criteria's cause and effect linkages have been revealed. Based on Figures (5.3) and (5.4), the causal criteria, in terms of their levels of significance, can be ordered as HPD ≻ DHM ≻ WBD ≻ DER. By further discussing the cause and effect directional arrows from the digraph in Figures (5.3) and (5.4), HPD and DHM have mutual interactions where either one of the criteria will affect the other. Concurrently, mutual influences occur between the pairs of “HPD and DEF” and “HPD and PMR”. However, PMR and DEF are net receivers and are both influenced by four (4) criteria. The PMR criterion is influenced by the HPD, DHM, DEF, and WBD criteria while the DEF criterion is influenced by the HPD, DHM, WBD and PMR criteria. On the other hand, HPD and DHM are net causes and thus affect four (DHM, WBD, PMR, DEF) and three (HPD, PMR, DEF) criteria, respectively. That is, the HPD criterion is the most essential in selecting an urban fire facility preceded by the DHM criterion. Notably, the DER criterion is neither influenced nor influences any other criteria. Furthermore, the HPD is at the peak of the causative group, inferring that it is the most critical parameter considered in urban emergency facility planning. The density of population is higher in areas with close access to main roads, existing fire stations, industrialised areas with a lot of factories and settlements with wooden buildings; and is thus influenced by the relevant criteria. The DHM is the second most important criterion in the causal class, and it has a huge impact on the other population and closeness variables because highly industrialised regions with a higher concentration of hazardous products from factories have a large population and easy access to major road networks. The other least influential criteria in the causal group are the WBD and the DER.

The criteria in the effect group are the PMR and the DEF. These criteria are the most affected by the other criteria and the most influenced. Distances and access to the main road network are significantly affected by the population density, closeness to existing fire stations, presence of settlement areas with wooden buildings and highly industrial zones/factories. The DEF is largely influenced by the population, hazardous material density in factories/industrial facilities, access to the main road networks, and the presence of old historical buildings made of wood.

From the analyses of the most essential criteria within the causal cluster, it can be inferred that these criteria have a direct impact on the rest of the criteria and their performance can directly affect the planning objective of selecting new urban fire facilities. Correspondingly, it is difficult to move the cause cluster criteria as opposed to the effect cluster criteria (Hori & Shimizu, 1999). Moreover, when contrasted to the effect criteria, the cause criteria are considered to be the most underlying and stable (Vardopoulos, 2019) affecting the integral planning model and therefore should be given more special attention by assigning them a higher priority (Wu & Chang, 2015).

The results of the DEMATEL analysis can be validated using previous studies as further described in the following subsection.

5.4.2 Validation of model results from the applied MCDA techniques

The findings of the DEMATEL analysis were validated using previous studies conducted by Nyimbili & Erden (2020a, c, 2021). In their research focussing on the metropolitan city of Istanbul, GIS-based Fuzzy AHP, Entropy-AHP and Group Decision-Making (GDM) with Best-Worst Method (BWM) (Rezaei, 2015) techniques were implemented for the appropriate selection of new urban fire and emergency infrastructure needed to reduce fire response time to under five minutes. Using the six evaluation criteria established from the screening process, the relevant criteria weights were determined from which the subsequent preference rankings were identified as shown in Table 5.8.

Table 5.8: Criteria rankings and importance by preference ordering from previous studies for DEMATEL model validation.

MCDM Technique	**DM Group**	**Criteria rankings and importance by preference ordering**
AHP	Both academicians and practitioners	DHM ≻ HPD ≻ PMR ≻ WBD ≻ DEF ≻ DER
FAHP	Both academicians and practitioners	DHM ≻ HPD ≻ PMR ≻ WBD ≻ DEF ≻ DER
Entropy-AHP	Both academicians and practitioners	HPD ≻ DHM ≻ PMR ≻ WBD ≻ DEF ≻ DER
BWM	Both academicians and practitioners	DHM ≻ HPD ≻ PMR ≻ DEF ≻ WBD ≻ DER
BWM (GDM approach)	Academicians only	DHM ≻ HPD ≻ PMR ≻ DEF ≻ WBD ≻ DER
	Practitioners only	HPD ≻ DHM ≻ PMR ≻ WBD ≻ DEF ≻ DER

The results from the MCDM techniques implemented in previous research (Nyimbili & Erden 2020a, c, 2021) correlate well with the DEMATEL analysis findings. From all the MCDA methods examined, it can be observed that the most important and influential criteria for optimal planning of new urban emergency infrastructure across all groups of decision-makers are the DHM and HPD. These two criteria are ranked at the top of the causal group while the least important criterion evaluated is the DER, which is also the lowest-ranked in the causal group according to the findings of the DEMATEL analyses, therefore, validating the model.

6. CONCLUSIONS

In essence, this research set out to apply the GIS-based MCDA techniques of BWM, integrated AHP-Entropy, fuzzy AHP and the DEMATEL to optimally select new urban emergency and fire facilities in Istanbul required to reduce the emergency response time to within 5 minutes in view of the upsurge in fire risk for improved mitigation planning. The high fire risk situation prevalent in Istanbul is largely caused by the rising urban population and increasing demand for access to socio-economic and infrastructural services, thereby underscoring the need for adequate planning of emergency and fire protection services. By merging value judgments with geographic data, GIS-based MCDA methods were proposed to improve the quality of decision-making (Malczewski, 2006), crucial in solving the complex planning of emergency facilities problem that involves multiple criteria and stakeholders. Fire, medical, police, and ambulance services all form part of the urban emergency services systems and require precise spatial planning for resource allocation. In the event of large-scale disasters and emergencies such as earthquakes, floods, and landslides, fire stations also serve as emergency medical communication and regional control centres. Consequently, locating these facilities requires a collaborative effort from experts and decision-makers, planners, fire brigade and emergency response personnel, as well as interaction with other stakeholders such as local communities impacted by the decision. In this respect, Istanbul province comprising about 960 subdistricts was selected as the case study region for each published paper as a section of this thesis.

The first study proposed a hybrid model of the recently developed BWM combined with GIS. For the emergency facility planning decision problem, the multiple attribute group decision-making (MAGDM) framework that aimed at reaching a group satisfactory solution was suggested to support the inclusion of opposing viewpoints of two DM groups consisting of academicians and fire brigade practitioners. The three main stages of the MAGDM process included: *structuring and construction*, *assessment* and *selection* or *ranking* stage. Statistical techniques such as the *one-sample t-test, one-way ANOVA*, and *Tukey's HSD* test were used to analyze the expert groups' preferences and draw meaningful conclusions from the study. The *sample t-*

test was carried out to establish whether the criteria weight values within each DM group varied significantly and having established that indeed there were significant differences, a *one-way analysis of variance* (*ANOVA*) was conducted to determine if there was an overall significant difference between any of the criteria weights across the DM groups. Subsequently, to locate and uncover these specific differences between the criteria mean in both expert groups, a post-hoc test called *Tukey's Honest Significant Difference* (*HSD*) test was applied. Furthermore, a statistical metric termed *Kendall's coefficient of concordance, W* was used in this study to examine the measure of consensus or dependability in the DM process which was found to be high or in good agreement among the fire brigade personnel DM groups as opposed to the academician group which had more divergent views due to non-homogeneity of expert background and disciplines. According to the study, the DHM and HPD were perceived as the most important by the academician and fire brigade participants, respectively while in both DM groups, the DER was deemed the least important criterion. The BWM model results for each of the two DM groups were determined to be consistent and reliable with respect to the consistency ratios (CRs), aggregated weight comparison analysis and rankings as per model validation using the AHP method. During the GIS processing and analyses, a *reclassification* procedure of *natural breaks* (*jenks*) and *weighted sum overlay* was applied to each of the six criteria map layers resulting in two separate composite raster suitability maps for new optimal urban fire emergency station areas, each representative of the academician and fire brigade expert groups. A comparison of the two map outputs was done statistically to assess the spatial variability using the *Kappa statistic* (calculated at 0.66) and inferred that there was a high correlation and similarity. This indicated a high agreement level between the two DM groups and demonstrated the value and usability of the generated maps for relevant authorities and policy-makers regarding emergency facility design and service management.

In the second paper, a hybrid AHP-Entropy and GIS model is applied which uses a combinative weighting strategy, considers both subjective and objective weighted approaches and is used to produce more accurate criteria weight outcomes. The estimation of criteria weights is required in most MCDA issues to reflect the relative importance of each criterion to other criteria affecting choice alternatives and outcomes. Without depending on subjective information from experts or DMs, *entropy* *weights*, hence called *objective weights*, can estimate the amount of meaningful information provided by the index based on disparities between attribute values. The primary advantage of the entropy technique over subjective-based weighting methods is that it eliminates human influence in the weighting process, allowing for objective determination of the criteria weights (Ding et al., 2017). Though entropy weights can portray useful information, it is necessary to incorporate the expertise and depth of knowledge of the decision-makers, to reflect the practical problem situation by integrating the subjectivity of the AHP and the objectivity of the entropy weight method (EWM) for reliability and effectiveness enhancement of the weights evaluation process. In the study, after these criteria weights were derived, the following main GIS processing and analyses were implemented: *data standardization and extraction, buffer analysis, network analysis, overlay analysis* and *spatial sensitivity analysis* (SA) for numerical model calibration and testing the robustness of the final decision solution. The *one-at-time* (OAT) SA technique was used to estimate the sensitivity of the criteria weights by altering one input criterion at a time whilst maintaining constant values for all other criteria to investigate the resultant impact on the model outputs visually in a GIS environment. From the AHP-Entropy model results, the criteria established to have the strongest influence on the urban fire facility site selection problem were the HPD and DHM, with weight values of 29.3% and 27.6%, respectively, which also coincided with the areas of high urban fire risk on the reclassified final raster suitability map generated. In the study conclusion, results from the map suitability indices, whose fire risk classification ranges from moderate to very high, indicate that about 206.6 km^2 of the study coverage area representing almost a third (28.1%), is at risk of urban fires and should therefore be given the highest priority for new urban fire station infrastructure construction and fire protection service coverage.

In the third paper, fuzzy AHP in combination with GIS is used based on a triangular membership function to simulate the subjective expert assessments for the six criteria preferences for urban fire station suitability mapping in Istanbul. İn this paper, the fuzzy extension of the AHP techniques has been proposed to improve on the inherent weakness of imprecision in linguistic assessments of the conventional AHP method. Human preferences using crisp numbers for assessments have been more accurately transformed to overcome these uncertainties and limitations by the use of fuzzy set theory. In this approach, triangular fuzzy numbers (TFNs) based on a triangular membership function, are utilized instead of crisp numbers to obtain fuzzy pairwise comparison measurements from which the weights are derived. The method of the *geometric mean* was used to compute the fuzzy AHP weights of the criteria. Defuzzification of the fuzzy weights into crisp numerical weight values was performed using the *centre of area* (COA) method and thereafter, *normalized* into final weights to be applied to each of the criterion map layers in GIS by use of the *weighted overlay* function. The reliability and validity of the final fuzzy AHP weights were checked using consistency ratios (CRs) and by another MCDA method of BWM and found to be comparable and consistent. The DHM, HPD, and PMR criteria were found to be the most important parameters in urban fire station site selection, with weights of 33.3%, 24.4%, and 15.2%, respectively. The resultant suitability raster map showing 34 recommended new fire station sites was then produced. A three-level prioritization analysis ranging high (20 sites), medium (9 sites) and low (5 sites), was performed on these proposed new sites based on resource constraints for planning construction. Other special considerations taken into account for the planning of these new sites included night and day population distribution especially in tourist and trading/commercial centres, increasing volume of migrant populations and the presence of wooden building infrastructure such as the district with a group of islands called Adalar on the Asian side of Istanbul.

This thesis consisted of three published articles. Regarding the aim of the thesis, each paper evaluates a GIS-based MCDA methodology for effectively planning new urban emergency and fire facilities in Istanbul province, Turkey, to reduce the fire response times to within five minutes for fire risk mitigation. In achieving this main objective, four MCDA techniques of fuzzy AHP, Entropy-AHP, BWM and DEMATEL method were explored and assessed for model construction, comparison and validation of model resultant weights as part of the sub-objectives. The influencing criteria for effective urban emergency facility planning were determined and utilizing the *Delphi* technique, the decision-maker (DM) preferences were captured from surveys conducted. The varying criteria weights based on pairwise comparisons from the respective experts' judgements were evaluated using the different GIS-based MCDA methodologies with the key focus, being to identify the most important criteria required for urban emergency facility site selection. Procedures within a GIS environment, that included input criteria map layer data processing and analysis leading to the final production of raster suitability maps were performed that show the high urban fire risk areas which are also feasible sites for new urban emergency facilities. In this regard, 34 new sites to be built were also recommended based on prioritization analysis from low to high in consideration of resource constraints. GIS capabilities were utilized to carry out a spatial *sensitivity analysis* (SA) to test the constructed model's robustness from combined weight variations, visually. Further, an assessment was carried out of the diverging views from the perspectives of two DM groups in the developed multiple attribute group decision-making (MAGDM) framework, comprising fire brigade personnel and academic professionals.

Finally, using the DEMATEL method in this thesis, the inter-relationships and criteria interactions as well the validation of the MCDA modelling process results of the BWM, AHP-Entropy and fuzzy AHP techniques, were evaluated. According to the studies from the three published papers utilizing the GIS-based BWM, AHP-Entropy and fuzzy AHP models, the suitable criteria for the optimal planning of emergency facilities were comprehensively examined. Thereon, the expert preferences of the criteria influences were acquired using the GDM approach of the DEMATEL technique. The criteria interactions and the cause and effect group inter-relationships were subsequently evaluated to generate a diagram of causality and consequence aside from a *digraph* to visually illustrate the causal linkages using directional arrows. The results of the study suggest that the HPD and the DHM criteria are at the top of the causal group implying that they are the most influential and significant for suitably planning urban emergency facilities. These criteria should be given the highest priority in the planning process. The optimal selection of a suitable site must be located in areas with a high population density and is likely to be close to the main road network infrastructure (PMR), where there are existing fire and emergency facilities (DEF), in highly industrialized zones with a high density of hazardous materials from factories (DHM) and settlement areas made up of a high density of wooden building structures (WBD). The HPD criterion is therefore affected by these preceding criteria. The DHM criterion is ranked second within the causal group and has a considerable effect on the HPD and PMR criteria. In highly industrialized areas with a large number of factories and warehouses, the density of hazardous materials (DHM) is high. These areas also have large population densities (HPD) and have good access to the main road and transportation networks (PMR). The effect group criteria are the most affected and influenced by the other criteria and consist of the PMR and the DEF.

The DEMATEL model results presented in this thesis, with regard to the criteria importance levels have therefore been used to validate the study results in the three published papers that utilized other MCDA methods such as AHP, Fuzzy AHP, Entropy-AHP and BWM. The contribution of this research is that the complexity of the interrelationships and interdependence of the criteria required for planning new emergency facilities in megacities and urban environments that are similar in profile to Istanbul has been modelled. Linkages among the criteria have been established and these criteria, are clustered into the cause and effect groups in terms of their levels of influence, priority and how they impact directly or indirectly on the entire emergency planning and fire risk mitigation process.

The research outcomes in this thesis, therefore, have an immense practical benefit at both local and national levels towards enhancing the integrated planning of fire risk reduction and mitigation strategies with a special focus on rapidly growing cities and megacities. The complex nature of the fire risk landscape and mitigation planning as part of disaster and emergency management risk reduction strategies is further reinforced in this study and as a result, all stakeholders must be involved, and policies must be integrated to reduce vulnerability, build resilience, and achieve sustainable development.

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