ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

SELECTION OF GREEN SUPPLIERS FOR TRIGENERATION SYSTEMS USING MULTI-CRITERIA DECISION-MAKING METHODS: A CASE STUDY

M.Sc. THESIS

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Department of Civil Engineering

Construction Management Programme

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

ÇOK KRİTERLİ KARAR VERME YÖNTEMLERİNİ KULLANARAK TRİJENERASYON SİSTEMLERİ İÇİN YEŞİL TEDARİKÇİ SEÇİMİ: VAKA ÇALIŞMASI

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Alperen Yayla, a M.Sc. student of İTU Graduate School student ID 501181102, successfully defended the thesis/dissertation entitled "SELECTION OF GREEN SUPPLIERS FOR TRIGENERATION SYSTEMS USING MULTI-CRITERIA DECISION-MAKING METHODS", which he/she 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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May 2022

Alperen YAYLA
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ABBREVIATIONS

AHP	**:** Analytical Hierarchy Process
COPRAS	**:** Complex Proportional Assessment
BWM	**:** Best Worst Method
DEMATEL	**:** Decision Making Trial and Evaluation Laboratory Mode
EDAS	**:** Evaluation Based on Distance from Average Solution
MADM	**:** Multi Attribute Decision Making
MAIRCA	**:** MultiAtributive Ideal-Real Comparative Analysis
MCDM	**:** Multi Criteria Decision Making
PRO-METHEE	**:** Preference Ranking Organization Method for Enrichment of Evaluations
TOPSIS	**:** Technique for Order Preference by Similarity to Ideal Solution

SYMBOLS

CI	**:** Consistency Index of AHP
CR	**:** Consistency Ratio of AHP
$\boldsymbol{S+_i}$	**:** Distance between an alternative and ideal positive solution of TOPSIS
$\boldsymbol{S-_i}$	**:** Distance between an alternative and ideal negative solution of TOPSIS
$\boldsymbol{C+_i}$	**:** Distance between an alternative and ideal solution of TOPSIS
ϕ	**:** Net outranking flow of PROMETHEE
ϕ^+	**:** Positive outranking flow of PROMETHEE
ϕ^-	**:** Negative outranking flow of PROMETHEE
Q_i	**:** Final values of criteria functions for MAIRCA

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SELECTION OF GREEN SUPPLIERS FOR TRIGENERATION SYSTEMS USING MULTI-CRITERIA DECISION-MAKING METHODS: A CASE STUDY

SUMMARY

Due to high demand and unsustainable need for an increasing energy supply, energy efficiency has become crucial. Restricted energy markets have wide effects in areas ranging from household budgets to international relations. Also, one of the primary concerns of the twenty-first century is climate change, which is caused by increased greenhouse gas (GHG) emissions and unplanned resource consumption (UNEP, 2010). Thus, due to their high energy consumption, buildings and construction activities are on the front line of energy efficiency research. The construction industry consumes one-third of global resources, 40% of global energy, 25% of global water, and generates one-third of worldwide carbon emissions, 40% of the global waste by itself (UNEP-SBCI, 2016). Accordingly, it needs a more sustainable approach at all stages in order to reduce its negative effects on the environment. This need has increased the importance of the concept of sustainable supply chain management in construction. Also, environmental and green building grading and certification systems such as LEED, BREEAM, and Estidama provide a measurement for energy efficiency, health, and cost-saving for construction operations and buildings. Also, a lot of green building councils of countries have been started to establish to help construction stakeholders with the aim of sustainability.

One of the systems that play a vital role in increasing energy efficiency for some types of buildings is trigeneration systems that produce power, heating energy as well as cooling from a single generator or process. Also, one of the most significant purchasing steps is the selection of the most appropriate supplier (Weber et al., 1991). While the traditional supplier evaluation particularly concentrates on cost-related criteria, green supplier selection focuses on environmental requirements as a priority. Considering all of these, green suppliers have been critical in creating a successful sustainable supply chain by balancing between economic, environmental, and social pillars of sustainability. Therefore, all legal regulations and standards, green project requirements, and companies' sustainability goals make the sustainable supplier selection a complicated process and vital for green supply chain management in construction.

Considering all these, the selection of trigeneration systems in a green way is of great importance in terms of energy efficiency and sustainability. In recent years, trigeneration system procurements have been made frequently in the construction of city hospitals, which are large health complexes combining more than one hospital in Türkiye. In this context, the trigeneration selection of a health complex built in one of the big cities of Türkiye is examined as a case study. MCDM methods are used for this green selection problem. Identification of criteria is carried out as a result of literature research and expert opinions specific to the project. The three pillars of sustainability which are economic, environmental, and social aspects, form the three main criteria.

The main economic criterion includes eight sub-criteria: cost, quality, delivery, flexibility, financial ability, operation, and maintenance cost, warranty period, and partnership relations. The environmental main criterion has four sub-criteria: energy efficiency of the system, environmental protection management system of the supplier, green products, and consumption of resources. Finally, the social main criterion includes four sub-criteria: safety and health at work, employees' rights, training of employees, and respect of rights and policies. Also, the contractor of the project evaluated the offers of 7 companies from 2 different cities of Türkiye within the scope of trigeneration systems.

While AHP, DEMATEL, and BWM are used to determine the criterion weights, TOPSIS, PROMETHEE, and MAIRCA methods are used to rank the green supplier alternatives. AHP, DEMATEL, TOPSIS, and PROMETHEE are some of the most used MCDM methods, and BWM and MAIRCA are relatively newly developed and gaining popularity. Finally, the study evaluates the green suppliers of trigeneration systems for a healthcare complex and compares the different MCDM methodologies used. Constructing a framework for sustainable supplier selection in the construction sector is the main purpose of the thesis. The selection problem of sustainable suppliers takes a great place in sustainable supply chain management. Also, the most important criterion for all green building certification systems is the energy efficiency of the building. Therefore, the study aims to examine the selection problem of the trigeneration system that has a considerable impact on the energy efficiency of large healthcare complexes. Finally, it is aimed to compare different traditional and newly developed MCDM methods.

ÇOK KRİTERLİ KARAR VERME YÖNTEMLERİNİ KULLANARAK TRİJENERASYON SİSTEMLERİ İÇİN YEŞİL TEDARİKÇİ SEÇİMİ

ÖZET

Artan enerji arzına olan yüksek talep ve ihtiyaç nedeniyle, enerji verimliliği ve sürdürülebilirlik kavramları çok önemli hale gelmiştir. Kısıtlı enerji piyasaları, hane bütçelerinden uluslararası ilişkilere kadar geniş bir alana yayılan etkilere sahiptir. Ayrıca, 21. yüzyılın başlıca endişelerinden biri, artan sera gazı (GHG) emisyonları ve plansız kaynak tüketiminin neden olduğu iklim değişikliğidir (UNEP, 2010). Bu nedenle, yüksek enerji tüketimleri nedeniyle binalar ve inşaat faaliyetleri, enerji verimliliği araştırmalarının ön saflarında yer almaktadır. İnşaat sektörü, küresel kaynakların üçte birini, küresel enerjinin yüzde 40'ını, küresel suyun yüzde 25'ini tüketmekte ve dünya çapındaki karbon emisyonlarının üçte birini, küresel atıkların yüzde 40'ını tek başına üretmektedir (UNEP-SBCI, 2016). Bu nedenle inşaat sektörü çevreye olan olumsuz etkilerini azaltmak için her aşamada daha sürdürülebilir bir yaklaşıma ihtiyaç duyar. Bu ihtiyaç, inşaatta sürdürülebilir tedarik zinciri yönetimi kavramının önemini artırmıştır. Ayrıca LEED, BREEAM ve Estidama gibi çevresel ve yeşil bina derecelendirme ve sertifikasyon sistemleri, inşaat operasyonları ve binalar için enerji verimliliği, sağlık ve maliyet tasarrufu için bir ölçüm sağlar. Ayrıca, sürdürülebilirlik amacı ile inşaat paydaşlarına yardımcı olmak için birçok ülkenin yeşil bina dernekleri kurulmaya başlanmıştır. Ayrıca, yeşil tedarikçilerin yetersizliği ve yeşil tedarikçileri seçmek için yetersiz değerlendirme, yeşil tedarik zinciri yönetiminin önündeki en önemli engellerden biridir, çünkü şirketler tüm yeşil uygulamaları elde etmek için tedarikçilerin yeşil malzeme ve hizmetlerine bağımlıdır. Bu nedenle yeşil tedarikçi seçimi, inşaat sektöründe yeşil tedarik zinciri yönetimi için en önemli adımlardan biri olarak kabul edilebilir.

Bazı bina türleri için enerji verimliliğinin artırılmasında hayati rol oynayan sistemlerden biri, tek bir jeneratör veya prosesten güç, ısıtma enerjisi ve soğutma üreten trijenerasyon sistemleridir. Trijenerasyonun enerji verimliliği açısından birçok avantajı vardır. Tesis için yakıt ve enerji giderlerinin daha düşük olması için yerinde güç ve ısı üretimini yüksek verimle sunar. Ayrıca en yoğun yaz talep tarihlerinde daha az elektrik kullanır. Motordan gelen ısı, kullanım için buhar ve sıcak su üretmek için kullanılabilir ve soğutucu olarak su kullanıldığı için tehlikeli kimyasal kirleticiler yoktur. Tüm bunlar, önemli sera gazı emisyonlarını azaltarak ve binaların enerji verimliliğini artırarak LEED ve BREEAM gibi değerlendirmeli yeşil bina sertifikasına sahip bina performansının iyileştirilmesine yardımcı olur.

Ayrıca en önemli satın alma adımlarından biri de en uygun tedarikçinin seçilmesidir (Weber vd., 1991). Geleneksel tedarikçi değerlendirmesi özellikle maliyetle ilgili kriterlere odaklanırken, yeşil tedarikçi seçimi öncelikli olarak çevresel gerekliliklere odaklanır. Tüm bunları göz önünde bulundurarak yeşil tedarikçiler, ekonomik, çevresel ve sosyal olan sürdürülebilirliğin temel direkleri arasında denge kurarak başarılı bir sürdürülebilir tedarik zinciri oluşturmada kritik öneme sahiptir. Bu nedenle, tüm yasal düzenlemeler ve standartlar, yeşil proje gereksinimleri ve

şirketlerin sürdürülebilirlik hedefleri, sürdürülebilir tedarikçi seçimini inşaatta yeşil tedarik zinciri yönetimi için karmaşık ve hayati bir süreç haline getirmektedir.

Tüm bunlar göz önüne alındığında trijenerasyon sistemlerinin yeşil bir şekilde seçilmesi enerji verimliliği ve sürdürülebilirlik açısından büyük önem taşımaktadır. Türkiye'de son yıllarda birden fazla hastaneyi bir araya getiren devasa sağlık kompleksleri olan şehir hastanelerinin yapımında trijenerasyon sistem alımları sıklıkla yapılmaktadır. Bu bağlamda Türkiye'nin büyük şehirlerinden birinde inşa edilmiş bir sağlık kompleksinin trijenerasyon seçimi örnek olay olarak incelenmiştir. İnşaatı 2 yılda 2015-2017 yıllarında tamamlanmış olup, yaklaşık 350.000 m^2 üzerine inşa edilmiştir. Ana hastane, ortak bir çekirdek yapı etrafında kurulmuş 4 bloktan oluşmakta olup, toplam inşaat alanı yaklaşık 600.000 m^2'dir. Proje, USGBC'nin sürüm 3 değerlendirme sistemine göre LEED Gold sertifikasını kazanmıştır. Projede enerji verimliliğine yönelik en önemli uygulamalardan biri soğutma, ısıtma ve elektrik ihtiyaçlarını karşılayan trijenerasyon sistemidir. Sistem 5 su soğutmalı ve 2 hava soğutmalı soğutma grubu ve 4 borulu fancoil sistemi içermektedir. Projenin LEED sertifikasyon danışman firmasına göre ASHRAE 90.1-2007 standardına uygun olarak gerçekleştirilen enerji simülasyon çalışmaları sonucunda enerji verimliliğinde %42.1 tasarruf sağlanmıştır.

Bu yeşil seçim problemi için çok kriterli karar verme (ÇKKV) yöntemleri kullanılmaktadır. Kriterlerin belirlenmesi, projeye özel literatür araştırması ve uzman görüşleri sonucunda gerçekleştirilmiştir. Kapsamlı bir literatür taraması ve uzman görüşleri sonucunda 3 ana kriter altında toplam 16 alt kriter belirlenmiştir. Karar verme ekibi deneyimli dört inşaat mühendisinden oluşmaktadır. Bunlardan biri şehir hastanelerinin yapımında görev alan eski bir üst düzey yönetici ve ekibin geri kalanı müteahhitin satın alma departmanından. Tüm karar vericiler daha önce taşeronların ve mekanik sistemlerin seçiminde yer almıştır. Sürdürülebilirliğin 3 ayağı olan ekonomik, çevresel ve sosyal yönler 3 ana kriteri oluşturmaktadır. Ekonomik ana kriter; maliyet, kalite, teslimat, esneklik, finansal yeterlilik, işletme ve bakım maliyeti, garanti süresi ve ortaklık ilişkileri olmak üzere 8 alt kriteri içermektedir. Çevre ana kriteri, sistemin enerji verimliliği, tedarikçinin çevre koruma yönetim sistemi, yeşil ürünler ve kaynakların tüketimi olmak üzere 4 alt kritere sahiptir. Son olarak, sosyal ana kriter, iş sağlığı ve güvenliği, çalışan hakları, çalışanların eğitimi ve haklara ve politikalara saygı olmak üzere 4 alt kriteri içermektedir.

Çalışmanın ilk aşamasında, problemin hiyerarşisi geliştirilmiştir. Bu adımdan sonra, karar verme ekibi üyeleri, metodolojilere göre her bir hiyerarşi seviyesi için kriterleri ayrı ayrı değerlendirir. AHP'de, dört ikili karşılaştırma matrisi geometrik ortalama kullanılarak birleştirilir ve ağırlıkları hesaplamak için nihai ikili karşılaştırma matrisi elde edilir. DEMATEL'de, nihai doğrudan etki matrisi, ekip üyelerinin dört doğrudan etki matrisinin ortalaması alınarak geliştirilir. Son olarak, BWM'de tüm ekip üyeleri kendi en iyi ve en kötü vektörlerini oluşturur ve kriter ağırlıkları ayrı ayrı hesaplanır. Bu aşamadan sonra ortalama alınarak nihai ağırlıklar elde edilir. Çalışmanın ikinci aşamasında, yeşil tedarikçi seçiminin ana karar matrisi oluşturulmuştur. Alternatifler için niteliksel değerler, karar verme ekibi tarafından fikir birliği ile belirlenir. Karar matrisinin belirlenmesinden sonra alternatifleri değerlendirmek için TOPSIS, PROMETHEE ve MAIRCA yöntemleri uygulanmaktadır. Her metodoloji, AHP, DEMATEL ve BWM'den ayrı ayrı elde edilen üç kriter ağırlığını kullanır. Üç farklı kriter ağırlığı sonuçlarının üç farklı değerlendirme yöntemine uygulanması sonucunda toplam 9 farklı sıralama sonucu elde edilecektir.

Kriter ağırlıklarını belirlemek için AHP, DEMATEL ve BWM kullanılırken, yeşil tedarikçi alternatiflerini sıralamak için TOPSIS, PROMETHEE ve MAIRCA yöntemleri kullanılmıştır. AHP, DEMATEL, TOPSIS ve PROMETHEE en çok kullanılan MCDM yöntemlerinden bazılarıdır ve BWM ve MAIRCA nispeten yeni geliştirilmiş ve popülerlik kazanmaktadır. Son olarak, çalışma bir sağlık kompleksi için trijenerasyon sistemlerinin yeşil tedarikçileri değerlendirilmekte ve kullanılan farklı ÇKKV metodolojileri karşılaştırılmaktadır. Tezin temel amacı, inşaat sektöründe yeşil tedarikçi seçimi için bir çerçeve geliştirmektir. Sürdürülebilir tedarikçi seçimi sorunu, sürdürülebilir tedarik zinciri yönetiminde büyük yer tutmaktadır. Ayrıca tüm yeşil bina sertifika sistemleri için en önemli kriter binanın enerji verimliliğidir. Bu nedenle çalışma, büyük sağlık komplekslerinin enerji verimliliği üzerinde büyük etkisi olan trijenerasyon sisteminin seçim problemini incelemeyi amaçlamaktadır. Son olarak, geleneksel ve yeni geliştirilen ÇKKV yöntemlerinin karşılaştırılması amaçlanmaktadır.

Kullanılan yöntemlerin yaklaşımları farklı olduğu için kriter ağırlıklarının ve sıralamalarının farklı olması doğal bir sonuçtur. Sonuçlara göre AHP\ DEMATEL ve BWM olmak üzere tüm yöntemler sistemin enerji verimliliği oranını (Env_1) en önemli kriter olarak sıralamaktadır. AHP, tedarikçinin çevre yönetim sistemini (Env_2) ve maliyeti (Eco_1) ikinci ve üçüncü önemli kriterler olarak değerlendirirken, DEMATEL yeşil üretim (Env_3) ve kaynak tüketimini (Env_4) birinci kriterden sonra sıralar. BWM metodounda ise Maliyet (Eco_1) ve tedarikçinin çevre yönetim sistemi (Env_2) ilk kriteri takip etmektedir. AHP ve BWM yöntemlerinin kriter değerlendirmeleri birbirine çok yakındır çünkü bu iki yöntem benzer karar verme yaklaşımlarına sahiptir. Ancak DEMATEL diğerlerinden farklı bir karar verme sistemi içerdiğinden, sonuçlar da büyük ölçüde farklılık göstermektedir. AHP ve BMW yöntemlerinde çevresel ve ekonomik yönlerden alt kriterler ön plana çıkarken, DEMATEL'de ekonomik yön alt kriterlerinin önünde çevresel ve sosyal yönlerden alt kriterler yer almaktadır. Ayrıca tüm yöntemler, yeşil tedarikçi seçim problemi için en az önemli kriter olarak finansal yeteneği (Eco_5) değerlendirmektedir.

TOPSIS hesaplamaları sonucunda en iyi alternatifler olarak A2 ve A5 alternatifleri ön plana çıkmaktadır. AHP-TOPSIS ve BWM-TOPSIS kombinasyonda A2 ilk sırada yer alırken, DEMATEL-TOPSIS entegrasyonu A5'i en iyi alternatif olarak değerlendirir. PROMETHEE yöntemi, AHP, DEMATEL ve BWM'nin kullanıldığı tüm senaryolar için A5'in alternatifini en iyi seçenek olarak değerlendirir. MAIRCA yöntemi sonucunda A2 ise A5 tercih edilen alternatifler olarak belirlenmiştir. AHP-MAIRCA ve BWM-MAIRCA, A2'yi en iyi alternatif olarak, DEMATEL-MAIRCA ise A5'i en iyi alternatif olarak sıralamaktadır. Ayrıca, tüm yöntemler A7'yi en az tercih edilen alternatif olarak belirlemektedir.

1. INTRODUCTION

Due to high demand and unsustainable need for an increasing energy supply, energy efficiency has become crucial. Restricted energy markets have wide effects in areas ranging from household budgets to international relations. Also, one of the primary concerns of the twenty-first century is climate change, which is caused by increased greenhouse gas (GHG) emissions and unplanned resource consumption (UNEP, 2010). Thus, due to their high energy consumption, buildings and construction activities are on the front line of energy efficiency research. The construction industry consumes one-third of global resources, 40% of global energy, 25% of global water, and generates one-third of worldwide carbon emissions, 40% of the global waste by itself (UNEP-SBCI, 2016).

The environmental damage caused by the construction industry is known worldwide, and governments have started to implement strict environmental regulations to reduce the negative effects of the sector. For instance, the European Union has a guideline for waste reduction on regional bases, and many countries have their own energy efficiency standards on a national base. The UK Government's strategy for construction, named Construction 2025, aims to reduce GHG emissions by 50% caused by the AEC industry until 2025, compared to a 1990 baseline. Also, the Paris Agreement, which is a legally binding international agreement signed by 192 countries and the European Union as of April 2022, aims to reduce emissions worldwide by coordinating the countries. The main goals of the agreement are to reduce the average temperature of the world increase to well below 2℃, preferably to 1.5℃, and global emissions as soon as possible (United Nations, 2015). Considering the energy consumption and environmental impacts of the construction sector, it plays a significant role in the implementation of the Paris Agreement. Accordingly, some standards and guidelines have emerged to make construction activities more sustainable and building operations. ISO 14001 is an internationally agreed environmental management system standard that helps organizations to use their resources efficiently and reduce their waste so that they can prove their sufficiency related to environmental issues. Environmental and green building grading and certification systems such as LEED, BREEAM, and Estidama provide a measurement for energy efficiency, health, and cost-saving for construction operations and buildings. Also, a lot of green building councils of countries have been started to establish to help construction stakeholders with the aim of sustainability.

The construction industry needs a more sustainable approach at all stages in order to reduce its negative effects on the environment. This need has increased the importance of the concept of sustainable supply chain management in construction. Sustainable supply chain management refers to the management of all operations aimed at reducing the environmental effect of all activities that contribute to the company's last product (Da Rocha and Sattler, 2009). Green supply chain management basically aims to enhance environmental performance as well as company performance by increasing efficiency, competitiveness, and value to stakeholders. It essentially includes the seven activities, which are green design, green purchasing and procurement, green logistics, green manufacturing, green operation, waste management, and end-of-life management (Badi and Murtagh, 2019). In the construction sector, while the information flows in order as follows; developer, architect and consultant, main contractor, sub-contractor, and supplier, the material supply chain flows in order as follows; materials, onsite construction, commissioning, and handover process (Balasubramanian and Shukla, 2017). All the mentioned regulations and standards have made green design and, therefore, the use of sustainable materials the most vital link of the construction supply chain. While green materials and mechanical systems are the most important part of the design, they also play a major role in the energy efficiency of the building throughout its lifetime.

One of the systems that play a vital role in increasing energy efficiency for some types of buildings is trigeneration systems that produce power, heating energy as well as cooling from a single generator or process. Trigeneration systems are especially effective in buildings with a steady demand for cooling, heating, and electricity throughout the year (Ziher and Poredos, 2005). Ziher and Poredos (2005) presented a study that focused on the economic benefits of a trigeneration system in one of Slovenia's biggest hospitals, and they stated that the trigeneration system could be efficient in terms of both energy and economy. Papadimitriou et al. (2021) evaluated the performance of a trigeneration system installed in a hospital building in Greece from a techno-economic standpoint. According to the findings, the efficiency of energy was still within limits, with the electrical efficiency higher than 30% and thermal efficiency at approximately 45%. The study highlighted that trigeneration systems' energy and economic performance are sustainable.

Also, one of the most significant purchasing steps is the selection of the most appropriate supplier (Weber et al., 1991). While the traditional supplier evaluation particularly concentrates on cost-related criteria, green supplier selection focuses on environmental requirements as a priority. Considering all of these, green suppliers have been critical in creating a successful sustainable supply chain by balancing between key pillars of sustainability, which are economic, environmental, and social. Therefore, all legal regulations and standards, green project requirements, and companies' sustainability goals make the sustainable supplier selection a complicated process and vital for green supply chain management in construction.

Considering all these, the selection of trigeneration systems in a green way is of great importance in terms of energy efficiency and sustainability. In recent years, trigeneration system procurements have been made frequently in the construction of city hospitals, which are large health complexes combining more than one hospital in Türkiye. In this context, the trigeneration selection of a health complex built in one of the big cities of Türkiye is examined as a case study. MCDM methods are used for this green selection problem. Identification of criteria is carried out as a result of literature research and expert opinions specific to the project. While AHP, DEMATEL, and BWM are used to determine the criterion weights, TOPSIS, PROMETHEE, and MAIRCA methods are used to rank the green supplier alternatives. AHP, DEMATEL, TOPSIS, and PROMETHEE are some of the most used MCDM methods, and BWM and MAIRCA are relatively newly developed and gaining popularity. Finally, the study evaluates the green suppliers of trigeneration systems for a healthcare complex and compares the different MCDM methodologies used. Figure 1.1 illustrates the flowchart of the study.

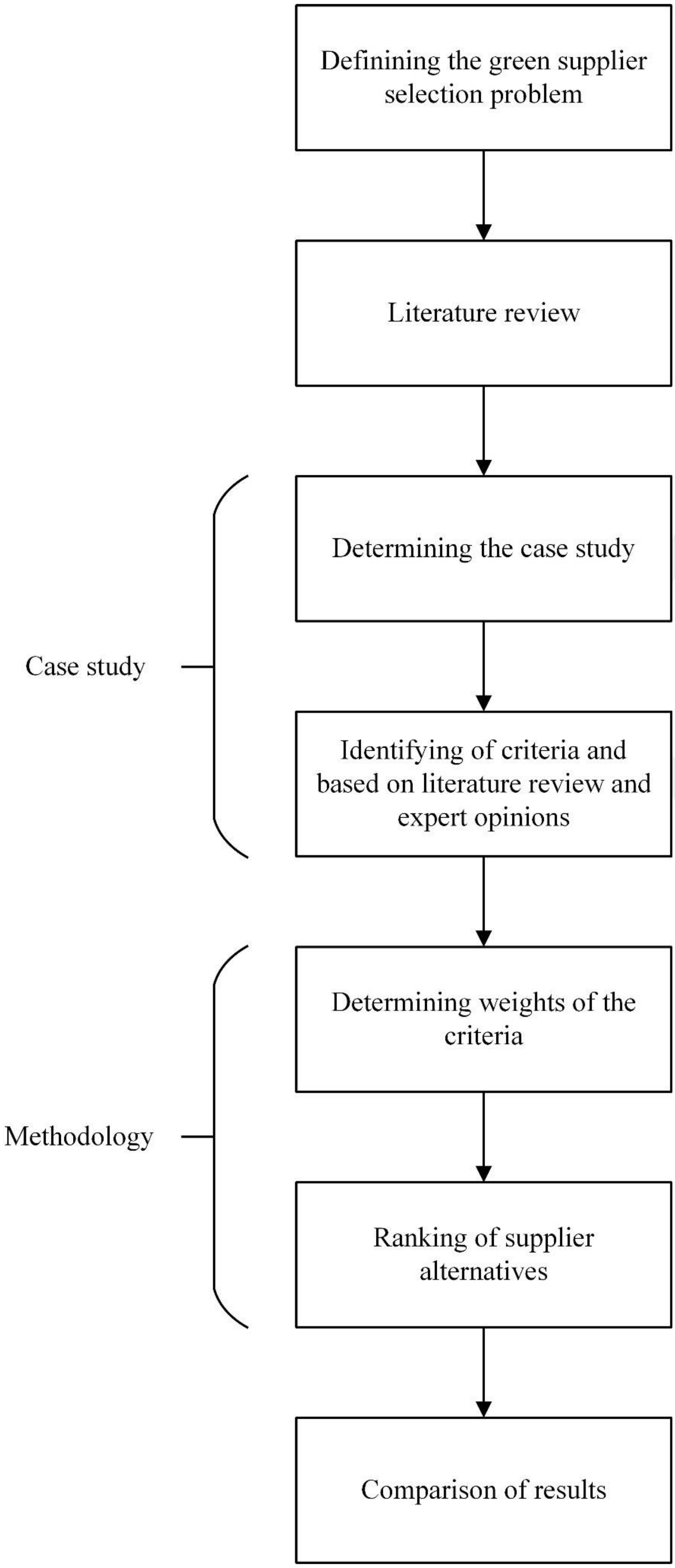

Figure 1.1 : The flowchart of the study.

1.1 Purpose of Thesis

The main goal of the thesis is to develop a framework for sustainable supplier selection in the construction sector. The selection problem of sustainable suppliers takes a great place in sustainable supply chain management. Also, the most important criterion for all green building certification systems is the energy efficiency of the building. Therefore, the study aims to examine the selection problem of the trigeneration system that has a huge impact on the energy efficiency of large healthcare complexes. Finally, it is aimed to compare different traditional and newly developed MCDM methods.

1.2 Green Supply Chain Management in Construction Industry

The construction supply chain includes various and complicated relationships among lots of parties. Also, green practices necessitate collaboration between suppliers, customers, and manufacturers throughout the supply chain in order to create and execute better solutions for businesses (Gnoni et al., 2011). In this context, green supply chain management can be defined as a set of methods and applications aiming at incorporating environmental considerations into all steps of a supply chain consisting of production, procurement, operations, logistics, and reverse logistics.

As mentioned earlier, green practices in the construction supply chain can be identified as green manufacturing, green procurement and purchasing, green design, green logistics, green operation, and management of wastes (Badi and Murtagh, 2019). There are some drivers and barriers to implementing these practices in construction. Major driving or motivating reasons and barriers for businesses to adopt green practices can be classed as external and internal (Walker et al., 2008; Walker and Jones, 2012). While external drivers can be listed as follows: stakeholder pressure, government regulation, competitor pressure, and end-customer pressure, internal drivers can be identified as follows: environmental commitment of the firm, enhancing brand image and reputation, reducing cost, and entering foreign markets (Balasubramanian and Shukla, 2017). Also, while external barriers include green supplier and professional shortage, stakeholder engagement/collaboration problems, and tight stakeholder deadlines, internal barriers involve high costs, and lack of knowledge and awareness (Balasubramanian and Shukla, 2017). Considering all these green practices, drivers, and barriers, the use of materials and the procurement process of these materials can be considered as one of the most important steps for sustainability. Green purchasing and procurement involve evaluating and selecting items and suppliers based on their environmental performance by utilizing green criteria and assessment tools (Shen et al., 2017). Also, the shortage of green suppliers and inadequate evaluation to select green suppliers is one of the most significant barriers to green supply chain management because companies depend on green materials and services by suppliers to achieve all green practices. Therefore, sustainable supplier selection can be considered as one of the most crucial steps to reach a more sustainable supply chain in the construction sector.

1.3 Green Buildings and Certification Systems

According to World Green Building Council (2022), a green building can be defined as a building that minimizes harmful effects on our climate while also having the potential to maximize positive ones. Green buildings contribute to environmental protection while also enhancing our quality of life. A building might have a number of attributes that make it green, and some of them are as follows; it uses water, energy, and other resources efficiently and may have renewable energy sources such as solar panels; it reduces pollution and waste and increase recycling and re-use; it has satisfactory indoor air quality and uses non-toxic and sustainable materials; environmental considerations are taken into account in its design, construction and operation process; its design can adopt to changes in the environment. However, different regions and countries have different climates, cultures, and traditions, as well as different environmental, economic, and social concerns, all of which influence their approach to green construction.

A variety of green building evaluation and certification frameworks have been improved by the green building councils of countries/regions or some private institutes. Among the most often used green building assessment methods are: BRE Environmental Assessment Method (BREEAM, United Kingdom), WELL (International WELL Building Institute), Leadership in Energy and Environmental Design (LEED, United States), Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan), DGNB (Germany), Green Building Council of Australia Green Star (GBCA, Australia), Hong Kong Building Environmental Assessment Method (HK BEAM), and Green Building Index

(Malaysia). The evaluation is carried out by green building council-commissioned qualified personnel. Also, the World Green Building Council was founded to provide collaboration between the green building councils throughout the world.

The BREEAM (Building Research Establishment Environmental Assessment Method) is a method for measuring the degree of sustainability of projects created by the Building Research Establishment (BRE) in 1990. The BREEAM evaluation compares construction stages, which are design, procurement, construction, and operation, to a set of goals based on performance benchmarks. Evaluation categories of the system include land use and ecology, energy, water, health and wellbeing, pollution, materials, transport, waste, and management. Each category focuses on environmental factors such as climate change adaptation, reduction in carbon emissions, and low-impact design. There are two phases of evaluation and certification as the design stage before the completion of construction to issue an interim certificate and post-construction to issue the final certificate. The BREEAM rates the projects on a scale of outstanding (>85%), excellent (>70%), very good (>55%), good (>45%), pass (>30%), and unclassified (<30%). A total of 150 points are evaluated over 31 for energy, 21 for management, 21 for health and wellbeing, 14 for materials, 13 for pollution, 12 for transport, 10 for land use and ecology, 10 for innovation, and 9 for each waste, and water consumption and efficiency. The energy category is the most important parameter with 31 points.

According to the United States Green Building Council (2022), LEED (Leadership in Energy and Environmental Design) is the most widely used evaluation and certification system to evaluate green buildings. It has been developed by the United States Green Building Council (USGBC) and involves a series of grading systems for all construction stages. LEED v4 for BD+C, which is for new construction and major renovation, evaluates projects over a total of 110 points and includes eight categories which are energy and atmosphere (33 points), location and transportation (16 points), indoor environmental quality (16 points), materials and resources (13 points), water efficiency (11 points), sustainable sites (10 points), innovation (6 points), and regional priority (4 points). The Green Building Certification Institute (GBCI) verifies and reviews projects before awarding points that correspond to a LEED certification level, and platinum with more than 80 points, gold with between 60-79 points, silver with between 50-59 points, and certified with between 40-49 points are the different levels of certification. Energy and atmosphere is the most significant category for evaluation and includes ten criteria as fundamental commissioning of building energy systems (required), fundamental refrigerant Mgmt (required), minimum energy performance (required), energy performance optimization (24 points), renewable energy usage in the site (8 points), enhanced commissioning (2 points), enhanced refrigerant Mgmt (1 point), verification and measurement (2 points), green power (1 point), and community contaminant prevention (1 point).

DGNB, which is the German Sustainable Building Council, has its own worldwide evaluation and certification system for green buildings. The system was originally presented to the market in 2009 and has been constantly expanded. The DGNB system is built on three major principles, which are life cycle assessment, holistic, and performance orientation approach taking into consideration three pillars of sustainability, ecology, economy, and sociocultural issues. The DGNB evaluation involves four certificate categories which are bronze (35%-49%), silver (50%-64%), gold (65%-79%), and platinum (80%-100%). Criteria of the system to evaluate new building projects include site quality, process quality, technical quality, sociocultural and functional quality, economic quality, and environmental quality.

1.4 Trigeneration Systems

Trigeneration systems or combined cooling, heat, and power (CCHP) have been started to use frequently in buildings that need high energy, such as hospitals, universities, and hotels. The system generates power, heating energy for spaces and water, as well as cooling from a single generator or process. The system provides higher energy efficiency by generating cold, heat, and power simultaneously (Havelsky, 1999; Hernandez-Santoyo and Sanchez-Cifuentes, 2003). Trigeneration is a step forward from cogeneration in that leftover heat from a cogeneration system is used to run a vapor absorption refrigeration system to provide cooling; the resulting process allows for combined heat and cooling from a single fuel input. Cogeneration heat can be provided in a variety of ways, including warm water.

Trigeneration has a lot of advantages in terms of energy efficiency. It presents on-site production of power and heat with high efficiency so that fuel and energy expenses become lower for the facility. It also uses less electricity during peak summer demand dates. The heat from the engine can be utilized to generate steam and hot water for use, and there are no dangerous chemical pollutants because water is utilized as the refrigerant. All of these help to improve the performance of building on evaluation green building certificates such as LEED and BREEAM by reducing significant greenhouse gas emissions and increasing the energy efficiency of buildings.

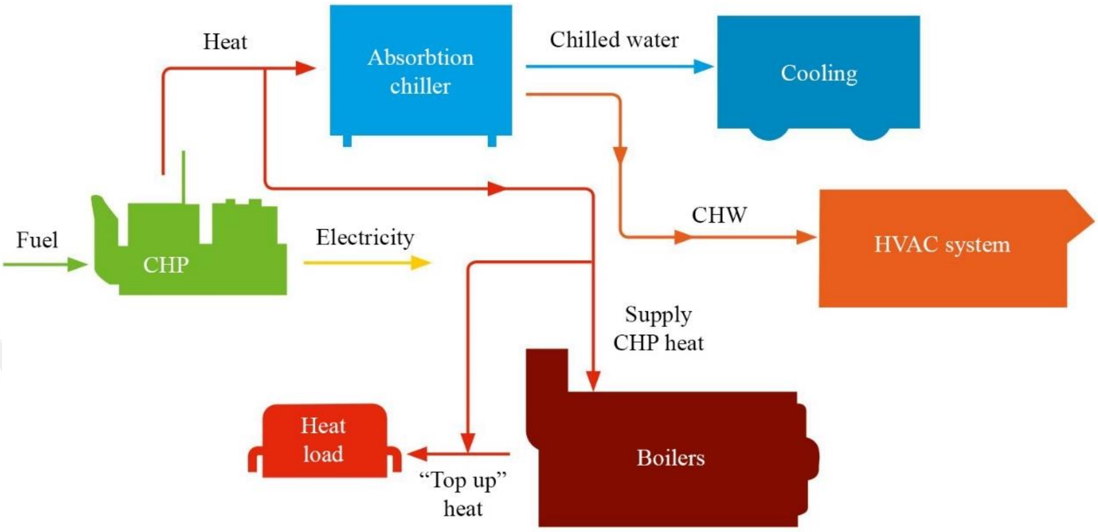

Figure 1.2 : Working scheme of the typical trigeneration system.

1.5 Contribution to the Body of Knowledge

Due to the rapid depletion of resources all over the world, energy efficiency and green buildings have become very important. Trigeneration systems are a way for large complexes to generate energy in-house rather than from the city grid. By providing energy efficiency of up to 85%, it is vital in terms of both decreasing carbon emissions and increasing sustainability in buildings. Energy efficiency is also the parameter with the highest score in all green certification systems. The selection of a trigeneration system has not been studied before. This study aims to contribute to the literature on revealing the important parameters in the selection of trigeneration systems and creating a model for sustainable supplier selection.

2. LITERATURE REVIEW

All of the relevant literature concerning green supplier selection applications in the construction industry were collected using Scopus and Google Scholar which are two of the largest academic databases to conduct scientific research. Table 1 shows the advanced search string for Scopus. The keywords were selected by considering the major aspects of the built environment. A simpler search string was used for Google Scholar, and “green supplier”, “sustainable supplier”, “green supplier selection”, “sustainable supplier selection criteria”, “construction industry”, “construction projects”, and “decision-making” keywords were identified for research. Only scientific journal articles were analyzed, and articles related to other sectors such as manufacturing, automotive, and agriculture were also excluded. After examining the abstracts of all the articles, articles related to both green supplier selection criteria and decision-making techniques were analyzed in detail. The organization of the examined studies was presented chronologically to show how the green supplier selection approach changed over time.

2.1 Green Supplier Selection in Construction Industry

Zhao and Guo (2014) proposed a study to evaluate sustainable suppliers of equipment of thermal power using an MCDM approach. The model uses a hybrid fuzzy MCDM model (fuzzy entropy-TOPSIS) for the selection problem and identifies five criteria which are environmental consciousness, equipment quotation, equipment efficiency, equipment operational costs, and delivery accuracy rate. The results show that companies can practically use the proposed method to select green suppliers in a thermal power plant project.

Mokhlesian (2014) performed a study to put forward the contractors’ perception of green supplier selection. Semi-structured interviews are carried out with three Sweden construction companies. One key result is that there is no dramatic change in supplier selection between green and traditional projects. According to the authors, the study shows that the green expertise of both contractors and suppliers is a significant component. Therefore, contractors and suppliers must work closely together. Contractors work with their suppliers in a partnership arrangement to ensure they gain knowledge from suppliers and to strengthen their advantage over competitors. The findings of this study are expected to be utilized to fill a vacuum in the literature on the selection of suppliers in sustainable aimed projects, as well as by construction businesses considering getting engaged in green projects.

Luo et al. (2016) presented research to evaluate green suppliers for building parts using the Catastrophe Theory and Kent Index Method. The study developed four indexes for evaluation as product, enterprise, green development, and cooperation. The product index has three criteria, namely, quality, price, and time, and four sub-criteria under quality (i.e., product performance, pass rate of product sample, rate of repair and return, product performance, quality management level), three sub-criteria under the price (i.e., product price, installation cost, transportation, and procurement costs), three sub-criteria under time (i.e., flexible delivery capability, on-time delivery, early completion rate). The enterprise index includes four criteria, namely, market position, financial situation, innovation ability, and environmental conditions, and four sub-criteria under professional skill (i.e., similar project experience, contact performance, enterprise qualification, quality of personnel), three sub-criteria under market position (i.e., market share, customer satisfaction, corporate reputation), four sub-criteria under financial situation (i.e., asset-liability ratio, return on equity, circulating fund, registered capital), and three sub-criteria under innovation ability (i.e., innovative capital investment, product technical innovation rate, innovative personnel input). The green development index has three criteria, namely, environmental conditions, energy consumption level, and environmental effect, and four sub-criteria under environmental conditions (i.e., environmental management system certification, staff environmental awareness, green technology application, environmental protection investment conditions), four sub-criteria under energy consumption level (i.e., unit parts of energy consumption, unit parts of human consumption, unit parts of material consumption, other resource consumption), four sub-criteria under environmental effect (i.e., radionuclide emission, construction pollution of gas and water, construction solid waste pollution, construction noise pollution). Also, the cooperation ability index has two criteria, namely, cooperation intention and degree of cooperation, and two sub-criteria under cooperation intention (i.e., long-term cooperation intention, cooperation intention of the project), two sub-criteria under the degree of cooperation (i.e., enterprise information exchange level, corporate culture compatibility,). The study examined the selection of the best unit bathroom problem for a construction project of a China real estate company. The results show that the suggested model can successfully eliminate subjectivity in the evaluation stage of the green supplier selection problem.

Yin et al. (2017) aimed to create an MCDM model to overcome the time sequence problem. The interval-valued intuitionistic fuzzygeometric weighted Heronian means (IVIFGWHM) operator and multitarget nonlinear programming are used to evaluate green supplier alternatives. The study identifies four main criteria, namely, green technology capability, the potential for sustainable cooperation, green business operation, building materials information, and five sub-criteria under green technology capability (i.e., green R&D innovation, waste materials reclamation, green production, ecodesign of materials, green certifications), four sub-criteria under potential for sustainable cooperation (i.e., green image, enterprise reputation, the desire of green cooperation, compatibility of green culture), four sub-criteria under green business operation (i.e., compatibility of green culture, emergency response capability, financial capability, green logistics) and four sub-criteria under building materials information (i.e., materials flexibility, materials quality, green degree of materials, materials cost). The study examined a sustainable supplier selection problem of a housing construction project of a company based in China. According to the findings, the proposed model makes the green supplier selection easier and more practical.

Sahu et al. (2018) presented an MCDM framework to rank sustainable suppliers using a combination of multi-objective optimization on the basis of the simple ratio analysis (MOOSRA) and reference point approach (RPA) methods. The study mainly aims to evaluate green clay-brick suppliers, and a total of thirteen criteria are determined, namely, supply chain management, operation management, eco-design, outside environmental management, staff salary, transportation cost, production cost, energy consumption costs, air pollution treatment cost, solid waste treatment costs, water pollution treatment costs, chemical waste treatment costs, and other indirect expenses. The supply chain management criterion has three sub-criteria, which are supply in time, solving problems with suppliers, and communication with other companies, the production cost criterion has six sub-criteria, which are material procurement cost, tempering, molding, drying, firing, and sorting, the transportation cost criterion has five sub-criteria, which are loading labor charge from the plant, unloading material to contracted company, fuel to consumption, truck hire, and documentation costs, and the energy consumption criterion has three sub-criteria which are hydraulic machine power consumption cost, water supply motor consumption cost, and overall lighting and other appliance running cost. The authors stated that the model is efficient and applicable to solve many industrial decision-making problems.

Matić et al. (2019) developed a hybrid MCDM framework to evaluate suppliers from a sustainable supply chain aspect. While the full consistency method (FUCOM) is applied to determine criteria weights, the improved complex proportional assessment (COPRAS) is used for the evaluation of alternatives. The study identifies three main criteria as social, economic, and environmental pillars. The economic aspect has seven sub-criteria, which are costs/prices, partnership relations, financial ability, technology capability, delivery, quality, and flexibility, social aspect includes seven sub-criteria, which are reputation, rights of employees, training of employees, disclosing information, respect of rights and policies, and finally, local community influence, Environmental aspect also has seven sub-criteria, which are green competences, consumption of resources, eco-design, green products, pollution control, environmental protection management system, green image. The sustainable supplier selection problem of a contractor is analyzed as a case study. According to the authors, the methodology enables more accurate and reliable decisions to make the supply chain more sustainable.

Zhang et al. (2019) aimed to develop a model for a sustainable supplier evaluation for the material of buildings using a neighborhood-rough-set-based quality function deployment. The study has a total of twelve criteria which are quality assurance ability, price, timeliness of delivery, level of after-sale service, environmental certification, the environmental impact of construction, product recycling, marketing level, market position, and innovation capability, cooperation willingness, and financial condition. A real case study is implemented for a property developer to evaluate eleven green material suppliers in China. The findings state that the proposed methodology is logical and resilient for the problem.

Chen (2019) presented an evaluation model using grey relational analysis (GRA) techniques with intuitionistic fuzzy entropy-based TOPSIS method for the problem of green building material supplier selection. The study examines the problem of the best sustainable supplier selection for a real estate development company using four evaluation criteria which are price, business credit, quality, and technical capability. The evaluation model is effective and reliable according to the results.

Yazdani et al. (2020) presented a study to evaluate sustainable suppliers under legislation and risk. While the DEMATEL method is applied to examine the relationship between green suppliers' performance risk factors, the evaluation of suppliers is carried out using the EDAS method. The study used seven main criteria, which are natural distastes, unemployment rate, financial risk, government regulation, water pollution, GHG pollution, and defect in the design. A real problem of sustainable supplier selection of a construction firm in Spain was used as a case study to validate the methodology. According to the authors, the real-world case study demonstrates how risk variables are assessed and included in the green supplier selection process.

Jain and Singh (2020) developed a decision-making framework using the Fuzzy Kano philosophy along with the Fuzzy Interference System (FIS) to evaluate sustainable suppliers for large-scale sectors. While criteria clustering was performed using the fuzzy Kano model to determine criteria of "must-be", the Fuzzy Inference System (FIS) was carried out to rank the suppliers. The study identifies the three sustainability dimensions as environmental, economic, and social dimensions. Environmental sustainability includes six main criteria, which are eco-design, pollution control, green technology, hazardous material management, environmental management system, and energy management system. Economic sustainability has six main criteria, namely, quality, delivery, cost, technical capability, repair services, production facilities, and three sub-criteria under quality (i.e., quality system certificates, capability of handling abnormal quality, percentage of defective items), three sub-criteria under delivery (i.e., late delivery, early delivery, average lead time), two sub-criteria under cost (i.e., material cost, transportation cost), three sub-criteria under technical capability (i.e., number of patents, infrastructure for research and development work, the relationship between supplier and company for new technology/product development), two sub-criteria under repair services (i.e., resolved complaints, reliability and responsiveness), and two sub-criteria ınder production facilities (i.e., equipment availability, automation).

Also, social sustainability has six main criteria, namely, rights of stakeholders, human rights, social responsibility, employment practices, working conditions, health and safety of employees, and two sub-criteria under human rights (i.e., the right to collective bargaining, freedom of association), three sub-criteria under employment practices (i.e., compensation, working hours, nondiscrimination). Implementation of the proposed model examined the selection problem of Iran's steel and iron sector. The results revealed that the methodology is effective and applicable for sustainable supplier selection.

Asaad and El-Sayegh (2021) aimed to determine the important criteria to evaluate sustainable suppliers in the United Arab Emirates for the construction sector. A total of twenty criteria are obtained as a result of literature research, and a questionnaire related to these criteria is delivered to professionals from construction sectors. The study group criteria into four main categories: technical and commercial bid, company characteristics, environmental and socioeconomic. All main categories have five sub-categories; delivery time reliability, tender price, material quality, procedural compliance, and flexibility, and warranties and claims are the sub-criteria of the technical and commercial bid, technical capability and experience, supplier client relationship, resource capability, related performance history, and financial capability and stability are the sub-criteria of the company characteristics, green business operations, green certifications of material, eco-design of material, green waste material redemption and green R&D innovation are the sub-criteria of the environmental main category, and finally, health and safety, employment practices, stakeholder influence, local communities influence, green image, and reputation are the sub-criteria of the socio-economic main category. According to the results, tender price, material quality, and health and safety are the most significant criteria for selecting green supplier.

Keshavarz-Ghorabaee et al. (2020) proposed a new model to evaluate the sustainable construction suppliers based on Fermatean fuzzy sets (FFs) and weighted aggregated sum product assessment (WASPAS) to generate a solution for uncertain information situations. Seven criteria, which are pollution, green image, eco-design, reputation and management level, product flexibility, delivery efficiency, and estimated cost are determined to evaluate the fifteen construction suppliers.

Salam and Ali (2020) carried out a study to determine factors that influence sustainable supplier selection and examine how closely it relates to a company's financial situation in an emerging economy. The information was gathered from 235 purchasing specialists in the Thai supply chain. The data was investigated using partial least squares-based structural equation modeling (PLS-SEM) and PROCESS tool. According to the study, the main criteria for selecting a sustainable supplier are supplier's community focus, supplier's safety focus, supplier's human rights focus, supplier's diversity focus, supplier's ethical treatment, and supplier's environmental focus. Results showed that safety focus and human rights are the most significant factors of sustainable supplier selection. The results of the suggested approach were steady and compatible with those of certain current methods.

Shojaei and Bolvardizadeh (2020) presented a study to evaluate green suppliers in a construction project using rough AHP and TOPSIS methodology. The evaluation criterion system has five main criteria, which are (1) fundamental requirements including financial status, and similar project experience, (2) materials and equipment including design of sustainable material, a reduction of consumption for hazardous/ harmful/ toxic products in the construction, and flexibility of equipment, (3) legal approach including environmental management system, enterprise legal compatibility with the environment, and occupational health and safety (4) preventive approach including management of wastes in the sustainable construction stages, dealing with plants, plans of pollution control, and technologies for sustainability (5) managerial approach including the awareness for the environment, top managers' support for the sustainability of contractors companies, and social responsibility for a green world. The model evaluates the green suppliers of a construction project performed at Iranian State University as a case study. According to the findings, environmental management system, social responsibility for a green world, and awareness of the environment are the most significant factors for selecting the best sustainable supplier.

Liao et al. (2020) presented an MCDM model to rank building suppliers in the construction industry using Stepwise Weight Assessment Ratio Analysis (SWARA) method and the double normalization based multi-aggregation (DNMA) methodologies. The study determines two main criteria dimensions as product level and entity level. While product level dimension includes five sub-criteria as price, performance and a quality fit, logistic flexibility, variety flexibility and green degree of products, and the entity-level dimension includes three sub-criteria as development potential, corporate reputation, and information sharing degree. As a result, it is stated that the suggested approach has great applicability for solving the problem of sustainable supplier selection.

Polat and Bayhan (2020) proposed a model using the fuzzy Evaluation Based on the Distance from Average Solution (Fuzzy EDAS) method to implement in the problem of HVAC-AHU supplier selection for a green multi-purpose shopping mall project in Moscow. The efficiency level of motors, design, and supply, conformity with the energy performance of buildings directives for green production, quality of maintenance and spare parts service, quality of communication with the supplier, conformity with the specifications, delivery lead time, warranty period, and price of the product are eight criteria to evaluate suppliers. According to the results, the methodology is considered practical and applicable by professionals.

Song et al. (2021) presented an evaluation framework for supplier evaluation of prefabricated building elements using the intuitionistic fuzzy analytic hierarchy process (IFAHP), and the mechanism equation model (SEM) with the aim of sustainable development. The evaluation system of suppliers was constructed by delivering to the relevant companies of structured questionnaires after comprehensive literature research. The study identifies five main criteria, namely, after-sales system, long-term cooperation, transportation system, quality system, and economic system, and four sub-criteria under the after-sales system (i.e., after-sales tracking, problem-solving efficiency, technical support, after-sales ability), six sub-criteria under long-term cooperation (i.e., enterprise financial level, process innovation, management ability of the company, company innovation, enterprise production qualification, production equipment standards), four sub-criteria under transportation system (on-time delivery rate, traffic violation rate, flexible delivery, transport standardization), five sub-criteria under the quality system (i.e., component qualification rate, component return rate, manufacturing standardization, quality management, construction's quality problem ratio), and four sub-criteria under the economic system (i.e., storage loss, price fluctuations, component cost, shipping fee). The study evaluates the Shuangyashan prefabricated construction projects' suppliers as a case study. The findings reveal that transportation, after-sales, long-term collaboration, economy, and quality have the most influence on supplier selection, respectively.

Schiessl et al. (2021) proposed a green supplier selection methodology to evaluate the raw material manufacturers’ performance on a specific site using AHP and TOPSIS. According to the study, CO2e emission information from suppliers is important data even though the current decision-making models do not take into consideration it. The study identifies five main criteria, which are environmental sustainability, development and innovation, flexibility, quality & production, and cost. The cost criterion has two sub-criteria which are parts costs and industrialization costs. The quality and production criterion includes two sub-criteria which are the condition of machines and manufacturing technology and testing process and facilities, the flexibility criterion has two sub-criteria which are equipment development duration and supply and infrastructure, development and innovation criterion also includes two sub-criteria which are development experience and investment innovation, and finally, environmental sustainability has just one sub-criterion which are CO2e component manufacturing. The four aluminum manufacturing companies in Germany are used as a case study, and according to the findings, the suggested site-specific evaluation model increases transparency and allows for the comparison of raw material sites.

Hoseini et al. (2021) developed a hybrid fuzzy-based approach to evaluate the sustainable supplier of a construction company. While the fuzzy best-worst methodology is used to determine the criteria weights, and the weighted fuzzy inference system is applied to choose the most sustainable supplier. Social, environmental, and economic aspects form the three main criteria of the study. The economic aspect has five sub-criteria, which are cost, quality, delivery, flexibility, and service, environmental aspect includes eight sub-criteria, which are the evaluation of environmental performance, hazardous wastes, wastewater, air emissions, re-use, green certification, pollution control, and eco-labeling, and finally, the social aspect has six sub-criteria, which are safety and labor health at work, discrimination, overtime pay, working hours, insurance, and contract of workers. According to the results, the model allows professionals to replicate the decision-making process, minimize computations, and remove some uncertainties.

Chen (2021) aimed to develop a new MCDM using a Pythagorean fuzzy programming technique and a squared-distance-based approach. The proposed model is mainly used to evaluate four bridge-construction methods. Also, a green supplier selection case study was analyzed to generalize the proposed methodology. This case study involves five main criteria as usage of environmental production capital, consumption of energy, degree of environmental impact, green identity, and resource recovery and utilization. The author states that the effectiveness and adaptability of the created PF LINMAP approach are demonstrated by the application and comparative findings.

Wang et al. (2021) presented a new model to evaluate biomass furnace suppliers using the Fuzzy Analytic Hierarchy Process (FAHP) model and the Combined Compromise Solution (CoCoSo) algorithm. Reliability, responsiveness, agility, cost, and asset management efficiency are the five main criteria of the selection process. Suitable capability, right delivered quantity, and on-time order fulfillment are the three sub-criteria of reliability, order lead-time, supplier corrective action request, and decision time are the three sub-criteria of responsiveness, adaptability of supply chain upside, downside supply chain flexibility, and upside supply chain flexibility are the three sub-criteria of the agility, supply costs, supplier management costs, and transportation costs are the three sub-criteria of the cost, and finally, the cycle time of cash convention, turnover of capital and fixed asset turnover are the three sub-criteria of asset management efficiency. The findings of this research state that the study is a pioneer in the use of hybrid FAHP and CoCoSo methodologies.

Bagheri et al. (2021) proposed a new MCDM approach to assess green suppliers taking into account the risk factors under uncertainty. The study separates the selection criteria in construction projects into four main categories as sustainable technology capability, the potential for green cooperation, sustainable business operation and information of building materials. Sustainable technology capability has three sub-criteria as green certifications, ecodesign of materials, and green production, the potential for green cooperation has one sub-criterion which is the desire for green cooperation, sustainable business operation has three sub-criteria named ability of emergency response, financial capability, and green logistics, and finally, building materials information has three sub-criteria which are materials, materials flexibility, and materials quality. The study examines the four leading suppliers of a construction company in Iran. It has been determined as a result that quality and material flexibility are two critical factors to select green suppliers.

Li and Chen (2022) proposed an MCDM to evaluate the green building suppliers using the case-based reasoning (CBR) method for interval-valued probabilistic linguistic term set (IVPLTS). In this study, the process of sustainable supplier selection has three steps, which include: presenting a new score measurement and distance function for IVPLTS, constructing a system for assessing criteria, and using the proposed model to evaluate. The evaluation criterion system has five aspects which are (1) operation management, including the information sharing degree, financial ability, and quality of logistics, (2) green management, including ecological efficiency, waste recycling, green production, and environmental awareness of company, (3) cooperation potential including the ability to emergency needs, and compatibility of companies, (4) service level including flexibility, and delivery (5) product information including the price, quality, and products' environmental performance. The model evaluates twenty construction suppliers as a case study in the scope of the green transformation of the construction industry in Jiangsu, China. The results suggest that the proposed approach is more accurate in real-world situations.

Table 2.1 : Criteria employed in green supplier selection related studies.

No	Author	Year	Total Cost	Transportation Cost	Delivery	After Sales Services	Efficiency	Quality	Green Degree of Materials	Flexibility	Technology Capability	Financial Capability	Green Cooperation	Green Production	Green Certifications	Partnership Relations	Safety and Health at Work	Employees' Rights	Local community Influence	Training of Employees	Respect of Rights and policies
1	Zhao and Guo	2014	✓		✓	✓	✓														
2	Luo et al.	2016	✓	✓	✓		✓	✓													
3	Yin et al.	2017	✓	✓				✓	✓	✓		✓	✓	✓	✓						
4	Sahu et al.	2018	✓				✓		✓				✓								
5	Matić et al.	2019	✓		✓			✓		✓	✓	✓				✓	✓	✓	✓	✓	✓
6	Chen	2019	✓					✓				✓				✓					
7	Zhang et al.	2019	✓		✓	✓		✓			✓			✓		✓					
8	Jain and Singh	2019	✓	✓	✓	✓					✓					✓					
9	Polat and Bayhan	2020	✓		✓	✓	✓	✓					✓			✓					
10	Liao et al.	2020	✓		✓			✓		✓				✓							
11	Shojaei and Bolvardizadeh	2020	✓							✓		✓		✓	✓		✓				

Table 2.1 (continued) : Criteria employed in green supplier selection related studies.

No	Author	Year	Total Cost	Transportation Cost	Delivery	After Sales Services	Efficiency	Quality	Green Degree of Materials	Flexibility	Technology Capability	Financial Capability	Green Cooperation	Green Production	Green Certifications	Partnership Relations	Safety and Health at Work	Employees' Rights	Local community Influence	Training of Employees	Respect of Rights and policies
12	Salam and Ali	2020	✓			✓				✓		✓									✓
13	Keshavarz-Ghorabaee et al.	2020	✓		✓		✓	✓		✓				✓							
14	Asaad and El-Sayegh	2020	✓		✓			✓				✓		✓	✓						
15	Bagheri et al.	2021	✓		✓			✓				✓	✓	✓							
16	Wang et al.	2021	✓					✓		✓		✓									
17	Chen	2021	✓				✓							✓	✓						
18	Hoseini et al.	2021	✓	✓	✓	✓				✓								✓	✓	✓	✓
19	Schiessl et al.	2021	✓		✓	✓		✓		✓	✓	✓									
20	Song et al.	2021	✓	✓	✓		✓	✓													
21	Li and Chen	2022	✓	✓	✓	✓				✓			✓	✓	✓						

3. CASE STUDY

The Republic of Türkiye has invested significantly in health infrastructure in the last five years. In this context, the construction of city hospitals, which are structured as large regional health complexes, has started. Currently, there are 13 city hospitals commissioned, and 5 ongoing projects in Türkiye. The aim is to meet all kinds of health needs of the people in the region with the most advanced technological and medical facilities by having all kinds of health units within its structure. Accordingly, these facilities are designed as huge facilities consisting of a combination of multiple buildings. Also, most of these health complexes were built in accordance with modern sustainability requirements and have LEED certification. Since the high energy needs of city hospitals have made the use of trigeneration systems crucial, the sustainable supplier selection problem of a trigeneration system for one city hospital in Türkiye is selected as a case study.

3.1 Information about the Project

The case study healthcare complex is located in one of the largest cities in Türkiye. Its construction was completed in 2 years, 2015-2017, and it was built on approximately 350,000 m^2. The main hospital consists of 4 blocks built around a common core structure, and the total construction area is approximately 600,000 m^2. The project has earned the LEED Gold certification according to the version 3 evaluation system of the USGBC. Table 3.1 presents the detailed energy and atmosphere category scoreboard of the project. Within the scope of the green building, many studies have been carried out in order to ensure water efficiency, efficient use of energy and resources, selection of sustainable materials, and minimizing waste. Accordingly, one of the most important applications for energy efficiency in the project is a trigeneration system that meets cooling, heating, and electricity needs. The system includes five water-cooled and two air-cooled chillers and a 4-pipe fan-coil system. According to the LEED certification consultant firm of the project, as a result of energy simulation studies carried out in accordance with the ASHRAE 90.1-2007 standard, 42.1% savings were achieved in energy efficiency.

Table 3.1 : Detailed energy and atmosphere category scoreboard of the project

LEED Energy & Atmosphere		Awarded: 23 / 29
Codes	Criteria	Points
EAp1	Fundamental commisioning of building energy systems	Required
EAp2	Minimum energy performance	Required
EAp3	Fundamental refrigerant Mgmt	Required
EAc1	Optimize energy performance	21 / 24
EAc2	On-site renewable energy	0 / 8
EAc3	Enhanced commissioning	0 / 2
EAc4	Enhanced refrigenrant Mgmt	1 / 1
EAc5	Measurement and verification	1 / 2
EAc6	Green power	0 / 1
EAc7	Community contaminant prevention	0 / 1

The contractor of the project evaluated the offers of 7 companies from 2 different cities of Türkiye within the scope of trigeneration systems, given in Table 3.2. Firms submitted turnkey offers, including mechanical equipment, installation, and civil works. The mechanical system of the trigeneration includes natural gas generator set, natural gas system, exhaust system, engine cooling system, lubricating system, heat recovery system, ventilating system, and electrical equipment.

Table 3.2 : Green supplier alternatives of the case study project.

Name	Code	City
Alternative 1	A1	İstanbul
Alternative 2	A2	Ankara
Alternative 3	A3	İstanbul
Alternative 4	A4	İstanbul
Alternative 5	A5	Ankara
Alternative 6	A6	İstanbul
Alternative 7	A7	İstanbul

3.2 Criteria for Sustainable Supplier Selection

As a result of a comprehensive literature review and expert opinions, a total of 16 sub-criteria are identified under three main criteria. The decision-making team consists of four experienced civil engineers. One of them is a former senior executive who takes charge in the construction of city hospitals, and the rest of the team is from the procurement department of the contractor. All decision-makers have previously been involved in the selection of subcontractors and mechanical systems.

The three pillars of sustainability which are economic, environmental, and social aspects form the three main criteria. The economic main criterion includes eight sub-criteria which are cost, quality, delivery, flexibility, financial ability, operation and maintenance cost, warranty period, and partnership relations. The environmental main criterion has four sub-criteria which are energy efficiency of the system, environmental protection management system of the supplier, green products, and consumption of resources. Finally, the social main criterion includes four sub-criteria which are safety and health at work, employees' rights, training of employees, and respect of rights and policies.

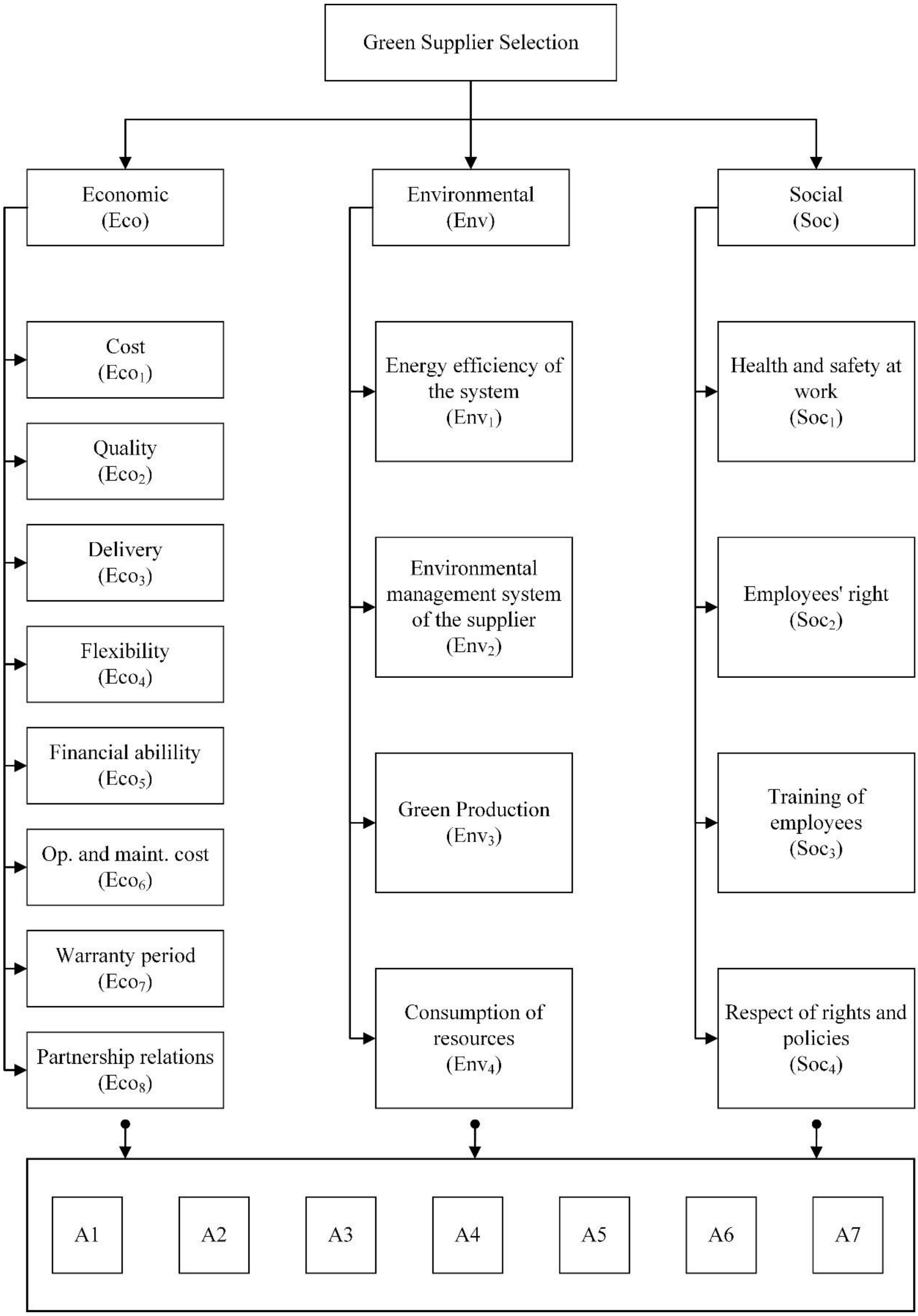

Figure 3.1 : Hierachy and criteria of the green supplier selection problem.

Table 3.3 : Explanations of the employed criteria.

Criteria	Code	Type	Explanation
Economic	Eco		
Cost	Eco_1	Cost	The final cost of the system for purchasing
Quality	Eco_2	Benefit	To what extent the system and material characteristics meet customer requirements
Delivery	Eco_3	Benefit	The capability of transporting and installing the system on time
Flexibility	Eco_4	Benefit	The capability of changing time and system properties according to customer request
Financial ability	Eco_5	Benefit	Suppliers' financial situation
Maintenance cost	Eco_6	Cost	The cost incurred by the supplier to keep the system in good working condition
Warranty period	Eco_7	Benefit	The period of time that the supplier warrant free repair and adjustment services
Partnership relations	Eco_8	Benefit	Having good relations with the supplier
Environmental	Env	Benefit	
Energy efficiency of the system	Env_1	Benefit	The energy efficiency rate of the system
Environmental management system of the supplier	Env_2	Benefit	A system that assesses an organization's environmental performance
Green Production	Env_3	Benefit	Using environmental-friendly products and materials
Consumption of resources	Env_4	Cost	The use of non-renewable resources and generating too much waste
Social	Soc	Benefit	
Health and safety at work	Soc_1	Benefit	Paying attention to health and safety at work
Employees' rights	Soc_2	Benefit	A set of legal and alleged human rights relating to labor interactions between employees and their employers.
Training of employees	Soc_3	Benefit	Employees' skills, talents, and knowledge for a certain job are improved through this approach.
Respect of rights and policies	Soc_4	Benefit	Enterprises follow all of the country's rules and regulations, accept legal duties

4. METHODOLOGY

The study uses AHP, DEMATEL, and BWM to calculate criteria weights and integrates these methods with TOPSIS, PROMETHEE, and MAIRCA to evaluate green supplier alternatives. Detailed calculations of all methods are given below separately. Also, the flowchart of the proposed methodology is shown in Figure 4.1.

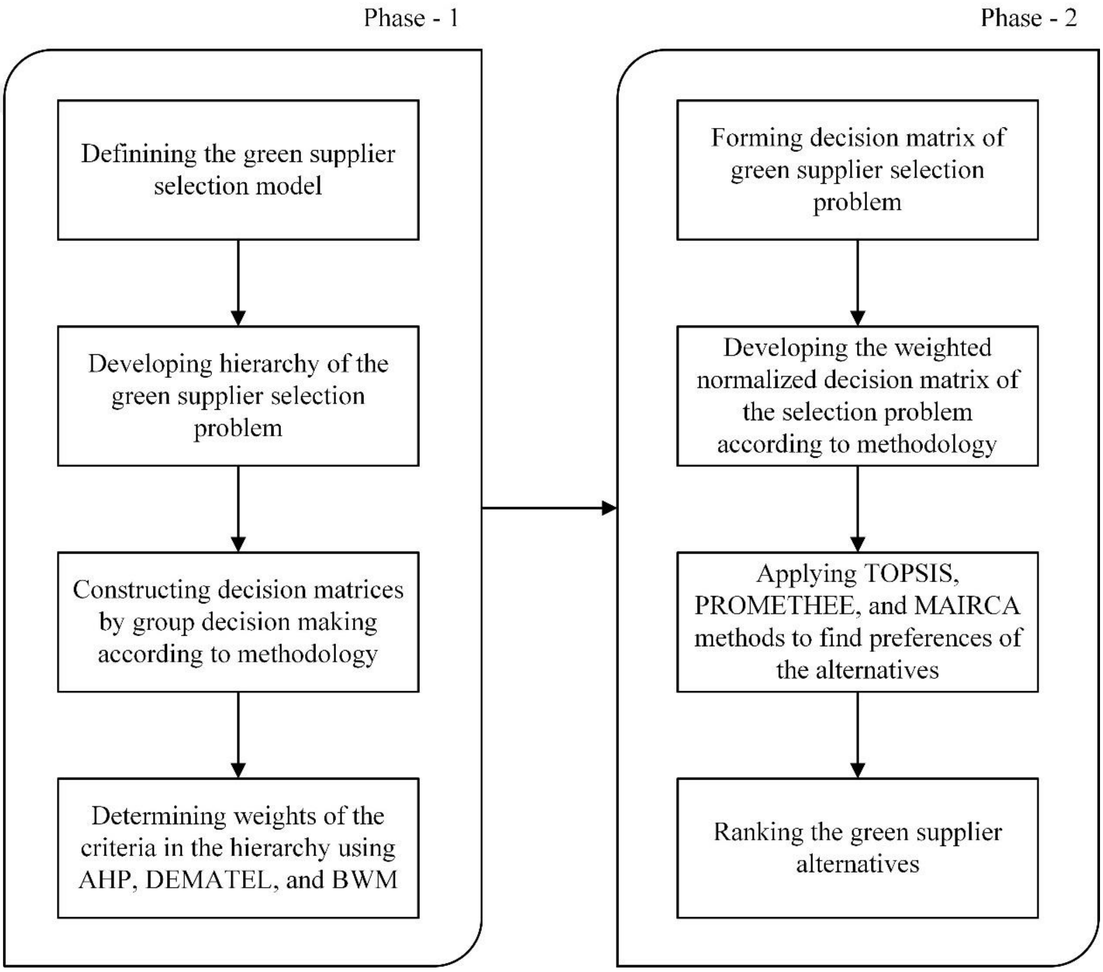

Figure 4.1 : Flowchart of the proposed methodology.

In the first stage of the study, the hierarchy of the problem is developed, as shown in Figure 3.1. After this step, decision-making team members evaluate the criteria individually for each hierarchy level according to methodologies. In AHP, four pairwise comparison matrices are combined using geometric mean, and the final pairwise comparison matrix is obtained to calculate weights. In DEMATEL, the final direct-influence matrix is developed by taking the average of four direct-influence matrices of team members. Finally, in BWM, all team members create their own best-to-others and worst-to-others vectors and criteria weights are calculated separately. After these step, final weights are obtained by taking the average.

In the second stage of the study, the final main decision matrix of green supplier selection for the defined case study is formed, given in Table 4.5. The final matrix is formed by taking an average of the decisions of four decision-makers for qualitative criteria. Table 4.1, 4.2, 4.3, and 4.4 illustrates the evaluations of decision-makers individually for alternatives, individually. After the determination of the decision matrix, TOPSIS, PROMETHEE, and MAIRCA methods are applied to evaluate alternatives. Each methodology uses three criteria weights separately obtained from AHP, DEMATEL, and BWM. As a result of applying the results of three different criteria weights to three different evaluation methods, a total of 9 different ranking results will be obtained.

Table 4.1 : DM-1's main decision matrix of green supplier selection for the defined case study.

Criteria		Criteria Types	Unit	Alternatives						
Economic				A1	A2	A3	A4	A5	A6	A7
Cost	Eco_1	Cost	M€	3.002	2.090	3.986	2.145	3.653	2.621	2.535
Quality	Eco_2	Benefit	1-9	4.000	6.000	7.000	7.000	8.000	5.000	5.000
Delivery	Eco_3	Benefit	1-9	5.000	7.000	6.000	6.000	6.000	4.000	6.000
Flexibility	Eco_4	Benefit	1-9	7.000	6.000	8.000	7.000	6.000	8.000	7.000
Finan. Abl.	Eco_5	Benefit	1-9	6.000	8.000	7.000	8.000	6.000	7.000	6.000
Maint. Cost.	Eco_6	Cost	M€	0.436	0.463	0.384	0.431	0.336	1.077	0.628
Warr. Per.	Eco_7	Benefit	1-9	9.000	8.000	8.000	10.000	9.000	8.000	8.000
Part. Rel.	Eco_8	Benefit	1-9	5.000	8.000	5.000	7.000	6.000	6.000	6.000
Environmental										
Ener. Eff.	Env_1	Benefit	%	85.000	88.000	85.000	86.000	85.000	85.000	85.000
Env. Man. Sys.	Env_2	Benefit	0,1	1.000	1.000	1.000	1.000	1.000	1.000	0.000
Gre. Pro.	Env_3	Benefit	1-9	6.000	6.000	8.000	6.000	8.000	6.000	6.000
Cons. Res.	Env_4	Cost	1-9	5.000	7.000	4.000	8.000	5.000	5.000	5.000
Social										
Heal. Safe.	Soc_1	Benefit	1-9	5.000	7.000	8.000	5.000	8.000	6.000	6.000
Emp. Rights	Soc_2	Benefit	1-9	5.000	7.000	6.000	7.000	8.000	7.000	7.000
Train. Emp.	Soc_3	Benefit	1-9	6.000	7.000	8.000	6.000	8.000	6.000	7.000
Resp. Rights	Soc_4	Benefit	1-9	7.000	7.000	8.000	7.000	8.000	8.000	7.000

Table 4.2 : DM-2's main decision matrix of green supplier selection for the defined case study.

Criteria		Criteria Types	Unit	Alternatives						
Economic				A1	A2	A3	A4	A5	A6	A7
Cost	Eco_1	Cost	M€	3.002	2.090	3.986	2.145	3.653	2.621	2.535
Quality	Eco_2	Benefit	1-9	6.000	8.000	8.000	6.000	9.000	7.000	6.000
Delivery	Eco_3	Benefit	1-9	7.000	8.000	7.000	6.000	7.000	6.000	6.000
Flexibility	Eco_4	Benefit	1-9	8.000	7.000	8.000	8.000	7.000	7.000	8.000
Finan. Abl.	Eco_5	Benefit	1-9	6.000	8.000	6.000	8.000	9.000	7.000	6.000
Maint. Cost.	Eco_6	Cost	M€	0.436	0.463	0.384	0.431	0.336	1.077	0.628
Warr. Per.	Eco_7	Benefit	1-9	9.000	8.000	8.000	10.000	9.000	8.000	8.000
Part. Rel.	Eco_8	Benefit	1-9	7.000	9.000	6.000	8.000	6.000	7.000	7.000
Environmental										
Ener. Eff.	Env_1	Benefit	%	85.000	88.000	85.000	86.000	85.000	85.000	85.000
Env. Man. Sys.	Env_2	Benefit	0,1	1.000	1.000	1.000	1.000	1.000	1.000	0.000
Gre. Pro.	Env_3	Benefit	1-9	6.000	7.000	8.000	7.000	9.000	8.000	8.000
Cons. Res.	Env_4	Cost	1-9	6.000	8.000	6.000	8.000	5.000	7.000	7.000
Social										
Heal. Safe.	Soc_1	Benefit	1-9	6.000	8.000	8.000	7.000	8.000	8.000	7.000
Emp. Rights	Soc_2	Benefit	1-9	7.000	8.000	7.000	8.000	9.000	7.000	6.000
Train. Emp.	Soc_3	Benefit	1-9	7.000	8.000	9.000	6.000	9.000	8.000	8.000
Resp. Rights	Soc_4	Benefit	1-9	7.000	8.000	7.000	7.000	8.000	7.000	6.000

Table 4.3 : DM-3's main decision matrix of green supplier selection for the defined case study.

Criteria		Criteria Types	Unit	Alternatives						
Economic				A1	A2	A3	A4	A5	A6	A7
Cost	Eco_1	Cost	M€	3.002	2.090	3.986	2.145	3.653	2.621	2.535
Quality	Eco_2	Benefit	1-9	4.000	8.000	6.000	7.000	8.000	5.000	4.000
Delivery	Eco_3	Benefit	1-9	6.000	8.000	5.000	4.000	7.000	5.000	7.000
Flexibility	Eco_4	Benefit	1-9	7.000	5.000	8.000	8.000	5.000	8.000	7.000
Finan. Abl.	Eco_5	Benefit	1-9	8.000	6.000	9.000	8.000	9.000	4.000	6.000
Maint. Cost.	Eco_6	Cost	M€	0.436	0.463	0.384	0.431	0.336	1.077	0.628
Warr. Per.	Eco_7	Benefit	1-9	9.000	8.000	8.000	10.000	9.000	8.000	8.000
Part. Rel.	Eco_8	Benefit	1-9	7.000	8.000	6.000	7.000	6.000	6.000	6.000
Environmental										
Ener. Eff.	Env_1	Benefit	%	85.000	88.000	85.000	86.000	85.000	85.000	85.000
Env. Man. Sys.	Env_2	Benefit	0,1	1.000	1.000	1.000	1.000	1.000	1.000	0.000
Gre. Pro.	Env_3	Benefit	1-9	6.000	8.000	8.000	6.000	8.000	7.000	6.000
Cons. Res.	Env_4	Cost	1-9	7.000	7.000	6.000	8.000	4.000	6.000	7.000
Social										
Heal. Safe.	Soc_1	Benefit	1-9	6.000	7.000	8.000	7.000	8.000	6.000	5.000
Emp. Rights	Soc_2	Benefit	1-9	7.000	6.000	6.000	7.000	8.000	8.000	6.000
Train. Emp.	Soc_3	Benefit	1-9	7.000	8.000	9.000	7.000	8.000	6.000	7.000
Resp. Rights	Soc_4	Benefit	1-9	8.000	7.000	8.000	8.000	8.000	7.000	7.000

Table 4.4 : DM-4's main decision matrix of green supplier selection for the defined case study.

Criteria		Criteria Types	Unit	Alternatives						
Economic				A1	A2	A3	A4	A5	A6	A7
Cost	Eco_1	Cost	M€	3.002	2.090	3.986	2.145	3.653	2.621	2.535
Quality	Eco_2	Benefit	1-9	7.000	6.000	8.000	6.000	8.000	7.000	7.000
Delivery	Eco_3	Benefit	1-9	6.000	7.000	6.000	6.000	7.000	5.000	5.000
Flexibility	Eco_4	Benefit	1-9	7.000	5.000	8.000	8.000	5.000	7.000	8.000
Finan. Abl.	Eco_5	Benefit	1-9	7.000	8.000	7.000	8.000	8.000	6.000	5.000
Maint. Cost.	Eco_6	Cost	M€	0.436	0.463	0.384	0.431	0.336	1.077	0.628
Warr. Per.	Eco_7	Benefit	1-9	9.000	8.000	8.000	10.000	9.000	8.000	8.000
Part. Rel.	Eco_8	Benefit	1-9	5.000	9.000	6.000	8.000	6.000	8.000	7.000
Environmental										
Ener. Eff.	Env_1	Benefit	%	85.000	88.000	85.000	86.000	85.000	85.000	85.000
Env. Man. Sys.	Env_2	Benefit	0,1	1.000	1.000	1.000	1.000	1.000	1.000	0.000
Gre. Pro.	Env_3	Benefit	1-9	7.000	7.000	8.000	7.000	8.000	6.000	6.000
Cons. Res.	Env_4	Cost	1-9	7.000	7.000	5.000	7.000	4.000	6.000	5.000
Social										
Heal. Safe.	Soc_1	Benefit	1-9	5.000	8.000	9.000	6.000	8.000	7.000	7.000
Emp. Rights	Soc_2	Benefit	1-9	6.000	7.000	8.000	6.000	9.000	8.000	6.000
Train. Emp.	Soc_3	Benefit	1-9	6.000	7.000	9.000	6.000	8.000	5.000	6.000
Resp. Rights	Soc_4	Benefit	1-9	7.000	7.000	8.000	7.000	9.000	8.000	7.000

Table 4.5 : The final main decision matrix of green supplier selection for the defined case study.

Criteria		Criteria Types	Unit	Alternatives						
Economic				A1	A2	A3	A4	A5	A6	A7
Cost	Eco_1	Cost	M€	3.002	2.090	3.986	2.145	3.653	2.621	2.535
Quality	Eco_2	Benefit	1-9	5.250	7.000	7.250	6.500	8.250	6.000	5.500
Delivery	Eco_3	Benefit	1-9	6.000	7.500	6.000	5.500	6.750	5.000	6.000
Flexibility	Eco_4	Benefit	1-9	7.250	5.750	8.000	7.750	5.750	7.500	7.500
Finan. Abl.	Eco_5	Benefit	1-9	6.750	7.500	7.250	8.000	8.000	6.000	5.750
Maint. Cost.	Eco_6	Cost	M€	0.436	0.463	0.384	0.431	0.336	1.077	0.628
Warr. Per.	Eco_7	Benefit	1-9	9.000	8.000	8.000	10.000	9.000	8.000	8.000
Part. Rel.	Eco_8	Benefit	1-9	6.000	8.500	5.750	7.500	6.000	6.750	6.500
Environmental										
Ener. Eff.	Env_1	Benefit	%	85.000	88.000	85.000	86.000	85.000	85.000	85.000
Env. Man. Sys.	Env_2	Benefit	0,1	1.000	1.000	1.000	1.000	1.000	1.000	0.000
Gre. Pro.	Env_3	Benefit	1-9	6.250	7.000	8.000	6.500	8.250	6.750	6.500
Cons. Res.	Env_4	Cost	1-9	6.250	7.250	5.250	7.750	4.500	6.000	6.000
Social										
Heal. Safe.	Soc_1	Benefit	1-9	5.500	7.500	8.250	6.250	8.000	6.750	6.250
Emp. Rights	Soc_2	Benefit	1-9	6.250	7.000	6.750	7.000	8.500	7.500	6.250
Train. Emp.	Soc_3	Benefit	1-9	6.500	7.500	8.750	6.250	8.250	6.250	7.000
Resp. Rights	Soc_4	Benefit	1-9	7.250	7.250	7.750	7.250	8.250	7.500	6.750

4.1 AHP

AHP, which is a strong tool to manage quantitative and qualitative multi-criteria parameters for decision-making problems, was invented by Saaty (1980). AHP helps decision-makers judge more easily by dividing complicated problems into more understandable small parts. The method includes basically six main procedures, which are (1) defining the problem and specifying the purpose, (2) constructing the hierarchical framework, (3) forming a matrix for pairwise comparison, (4) performing judgment among criteria, (5) synthesizing pairwise comparisons, and finally, (6) checking for consistency.

The hierarchy is established from the highest level to the lowest level, with purpose, criteria, and alternatives, respectively. After the hierarchy, criteria comparison is performed using a standardized nine-point measuring scale by constructing a pairwise matrix. The set of criteria, *C*, is as follows.

$$C = \{C_j \mid j = 1,2, \dots, n\} \tag{4.1}$$

The outcome of the n criteria pairwise comparison matrix can be described in a $(n \times n)$ evaluation matrix *A*, where each member $a_{ij}(i, j = 1, 2, \dots, n)$ is the weights of the criteria:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nm} \end{bmatrix} \tag{4.2}$$

Where, $a_{ii} = 1$, $a_{ji} = {}^{1}/_{a_{ij}}$, $a_{ji} \neq 0$.

To calculate the weighting for each criterion and alternative, the combination of all of the pairwise comparison matrices is created. There are two key phases in this procedure: To create a normalized pairwise comparison matrix, each member of a pairwise comparison matrix is divided by its column total. The priority vector is then developed by taking the average of the items in each row of the normalized pairwise comparison matrix. Nextly, the consistency index, *CI*, and ratio, *CR*, of the comparison are found as follows.

$$CI = (\lambda_{max} - n)/(n - 1) \tag{4.3}$$

where, λ_{max} is the principal eigenvalue of the weighted sum matrices obtained by multiplying pairwise comparison matrices by priority vectors.

$$CR = CI/RI \tag{4.4}$$

where, RI is the random index of AHP.

If the CR is less than 0.1, the evaluation and results are considered acceptable. Otherwise, the judgment is assumed as inconsistent, and the pairwise comparisons should be reevaluated.

4.2 DEMATEL

The Geneva Research Centre of the Battelle Memorial Institute was the first to develop the DEMATEL approach to illustrate the relationship of intricate causal interactions using digraphs or matrices (Gabus and Fontela, 1972). It is particularly effective in examining the cause and effect relations among decision-making parameters as a type of structural modeling technique. The DEMATEL may be used to examine and solve hard and entangled issues by demonstrating dependency between pieces and contributing in the construction of a map depicting relative links within them. This approach uses matrices to translate relationships into a cause and effect group, as well as an impact relation diagram to determine the important aspects of a complex structural system. As a result, it's a practical and helpful technique for analyzing the interdependent interactions among elements in a difficult system. The conventional DEMATEL's formulation processes can be stated as follows (Tzeng et al., 2007)

Step 1: Create the Z direct-influence matrix for the group. To evaluate the relationships between n factors $F = \{F_1, F_2, \ldots, F_n\}$ in a system, m experts in a decision group, $E = \{E_1, E_2, \ldots, E_m\}$, rate the direct influence of that factor, F_i, has on factor, F_j. The scale is based on *0-4* integer scale. While 0 means "no influence", 4 means "very strong influence". The direct-influence matrix $Z_k = \left[z_{ij}^k\right]_{n\times n}$ provided by the kth expert is then be constructed, with all primary diagonal components equal to zero and z_{ij}^k representing decision-maker E_k assessment of the degree to which factor influences the other. The group direct-influence matrix $Z = [z_{ij}]_{n\times n}$ will be obtained by combining the opinions of the *m* experts.

$$z_{ij} = \frac{1}{m}\sum_{k=1}^{m} z_{ij}^{k}, \quad i,j = 1,2,\dots,n. \tag{4.5}$$

Step 2: Calculate *X*, the normalized direct-influence matrix. $X = [x_{ij}]_{n\times n}$ can be obtained by utilizing the group direct-influence matrix Z.

$$X = {}^{Z}/_{s} \tag{4.6}$$

$$s = max\left(\begin{matrix} max \\ 1 \le i \le n \end{matrix}\sum_{j=1}^{n} z_{ij}, \begin{matrix} max \\ 1 \le i \le n \end{matrix}\sum_{i=1}^{n} z_{ij}\right) \tag{4.7}$$

All members of *X* satisfy the conditions $0 \le x_{ij} \le 1$, $0 \le \sum_{j=1}^{n} x_{ij} \le 1$, and at least one *i* such that $0 \le \sum_{j=1}^{n} z_{ij} \le s$.

Step 3: Create the T-matrix of total influence. $T = [t_{ij}]_{n\times n}$ is derived by using the matrix *X*, and adding the direct effects and all of the indirect effects with

$$T = X + X^2 + \cdots + X^h = X(1 - X)^{-1}, \text{ when } h \to \infty \tag{4.8}$$

where I is the symbol of identity matrix.

Step 4: Create an influential relationship map, *IRM*. The following formulas are used to define the vectors *R* and *C*, which reflect the rows and columns' sum from the matrix *T*:

$$R = [r_i]_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} \tag{4.9}$$

$$C = [c_i]_{1\times n} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n} \tag{4.20}$$

where r_i represents the sum of the direct and indirect effects dispatching from the factor F_i to the other factors in the matrix T. Similarly, in the T, c_j is the jth column sum, which represents the total of indirect and direct impacts that factor F_j receives from the others.

Let $i = j$ and $i, j \in \{1, 2 \ldots \ldots, n\}$; the horizontal axis vector $(R + C)$ labeled "Prominence" depicts the intensity of the factor's provided and received influences. That is, $(R + C)$ denotes the degree to which the component plays a major role in the system. Similarly, the "Relation" vertical axis vector $(R - C)$ depicts the net influence that the factor has on the system. If $(r_j - c_j)$ is positive, the factor F_j has a net influence on the other factors and can be classified as a cause; if $(r_j - c_j)$ is negative, the factor F_j is influenced by the other factors on a global level and should be classified as an effect. Finally, by mapping the dataset of $(R + C, R - C)$, an *IRM* may be generated, which gives useful information for decision-making.

4.3 BWM

The Best Worst Method (BWM), which has been a popular MCDM method recently, is developed by Rezaei (2015). BWM needs less data than similar existing approaches because a full pairwise comparison matrix is not formed in the method. It delivers more reliable findings because of its organized pairwise comparison system. It is also seen as easy by decision-makers because it is extremely similar to how they make a decision in the human judgement process. The description of all the steps of the method is below.

Step 1: Identify criteria set for a decision. In this step, each hierarch level's decision criteria are determined.

Step 2: Identify the best and worst criteria. Decision-makers choose the best and worst criteria among all.

Step 3: Identifying the preference of the best criterion. Based on a 9-point evaluation scale, a rating of priorities for the best decision (B) over all other decision criteria (1: B is equally important to j; 9: B is highly more important than j) is carried out. As a result, the best-to-others (BO) vector is obtained as follows.

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn}) \tag{4.13}$$

where, a_{Bj} represents the preference of B over j and $a_{BB} = 1$.

Step 4: Identifying the preference of the worst criterion. Based on a 9-point evaluation scale, a rating of priorities for the worst decision (W) over all other decision criteria (1: j is equally important to W; 9: j is extremely more important than W) is carried out. As a result, others-to-worst (OW) vector is obtained as follows.

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T \tag{4.12}$$

where, a_{jW} represents the preference of j over W and $a_{WW} = 1$.

Step 5: Calculate the weights. The criteria weights, $w_1^*, w_2^*, \ldots, w_n^*$, are calculated so that the maximum absolute differences $\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$ for all j will be minimum, or equivalently:

$$\begin{gathered} \min \max_{j} \{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\} \\ \text{s.t.} \\ \sum_j w_j = 1, w_j \geq 0 \; for \; all \; j \end{gathered} \tag{4.43}$$

Equation X equals the following linear problem:

$$\begin{gathered} min \; \xi^L \\ s.t. \\ |w_B - a_{Bj}w_j| \leq \xi^L, \text{ for all j} \\ |w_j - a_{jW}w_W| \leq \xi^L, \text{ for all j} \\ \sum_j w_j = 1 \\ w_j \geq 0, \text{ for all j} \end{gathered} \tag{4.54}$$

Solving equation 4.54, the weights $(w_1^*, w_2^*, \ldots, w_n^*)$ and optimal objective function ξ^{L*} are calculated.

The consistency index (ξ^{L*}) measures how consistent the pairwise comparisons offered by the decision-makers. Values near *0* indicate that the pairwise comparisons have a high level of consistency.

4.4 TOPSIS

TOPSIS is an analysis method for an MCDM problem established by Ching-Lai Hwang and Yoon in 1981 (Hwang and Yoon, 1981), with updates by Yoon in 1987 and Hwang, Lai, and Liu in 1993 (Yoon, 1987; Hwang et al., 1993). The main idea of the TOPSIS is that the preferred option has the minimum geometric distance from the positive ideal and the maximum geometric distance from the negative ideal solution (Assari et al, 2012; Yoon and Hwang, 1995). The steps of the TOPSIS is as follows.

Firstly, an evaluation matrix is established with m options and n criteria. Each member x_{ij} represents the intersection of each criterion and alternative and $(x_{ij})_{m\times n}$ matrix obtained. Secondly, the normalised form of the $(x_{ij})_{m\times n}$ matrix, which is $R = (r_{ij})_{m\times n}$, is derived using the following equation.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}}, i = 1, 2, \ldots, m, j = 1,2, \ldots, n \tag{4.65}$$

Then, multiplying the normalized decision matrix by its associated weights gives the normalized weighted decision matrix. The following formulas are used to calculate the normalized weighted value v_{ij}.

$$v_{ij} = r_{ij} \times w_{ij} \tag{4.76}$$

$$w_{ij} = {W_j}\Big/{\sum_{k=1}^{n} W_k}, \quad j = 1, 2, \ldots, n \tag{4.87}$$

Where, $\sum_{i=1}^{n} w_i = 1$, and W_j is the original weight assigned to the v_{ij}.

The third step is to determine the positive or most ideal solutions, given in Equation 4.18, as well as the negative ideal solutions, given in Equation 4.19. The decision-maker achieves the greatest extreme value of any choices for benefit criteria.

Meanwhile, the decision-maker must achieve the minimum value among all possibilities for cost criteria.

$$A+= \{(\max v_{ij} | \in J), (\min v_{ij} | \in J'), i = 1, 2, 3, \dots, M\} \\ = \{v +_1, v +_2, \dots, v +_n\} \tag{4.98}$$

$$A-= \{(\max v_{ij} | \in J), (\min v_{ij} | \in J'), i = 1, 2, 3, \dots, M\} \\ = \{v -_1, v -_2, \dots, v -_n\} \tag{4.109}$$

where,

$$J = \{j = 1, 2, 3, \dots., N \mid j \; associated \; with \; benefit \; criteria\} \tag{4.20}$$

$$J' = \{j = 1, 2, 3, \dots., N \mid j \; associated \; with \; cost \; criteria\} \tag{4.21}$$

The difference between each option to the positive ideal (PIS) and negative ideal solutions (NIS) is measured in the fourth step. Furthermore, in the Euclidean sense, $S +_i$, and $S -_i$ denote the distance between each alternative and the ideal positive and ideal negative solutions, respectively.

$$S +_i = \sqrt{\left(\sum_{j=1}^{n} \left(v_{ij} - v +_j\right)^2\right)} \tag{4.22}$$

$$S -_i = \sqrt{\left(\sum_{j=1}^{n} \left(v_{ij} - v -_j\right)^2\right)} \tag{4.23}$$

Fifth, using Equation 4.24, determining how close an option A_i is to the optimal answer $A +$. The options are arranged in descending order, with the best option having the smallest distance to the ideal solution and hence the greatest separation from the negative-ideal solution.

$$C +_i = \frac{s_i}{(s +_i) + (s -_i)}, and \; 0 \leq c +_i \leq 1 \tag{4.24}$$

4.5 PROMETHEE

Professor Jean-Pierre Brans (CSOO, VUB Vrije Universiteit Brussel) first developed the essential principles of the Promethee approach in 1982 (Brans, 1982). Additions like GAIA is added with the improvement of the methodology (Mareschal and Brans, 1988). The Gaia descriptive technique lets the decision-maker to visualize the major elements of a choice problem Promethee is a prescriptive strategy that gives the decision-maker both entire and partial rankings of the activities (Brans and Vincke, 1985). After determining the decision-making problem, alternatives, criteria, and criteria weights using different methods, PROMETHEE includes six steps for evaluation of alternatives as follows (Brans, Mareschal 2005).

Step 1: Identify the preference function. It converts the difference between two alternatives' assessments into a preference degree ranging from zero to one. There are six different types of functions which are usual, U-shape, V-shape, level, linear, and Gaussian. Gaussian. PROMETHEE's preference structure is built on pairwise comparisons, which is the difference between two alternatives' evaluations on a given criterion is considered:

$$P_j(a,b) = F_j\left[d_j(a,b)\right], j = 1, 2, \dots, k \tag{4.25}$$

where, $P_j(a,b)$ indicates the preference of alternative an over alternative b on each criterion j as a function of the $d_j(a,b)$, calculated as follows.

$$d_j(a,b) = g_j(a) - g_j(b) \tag{4.26}$$

where, $g_j(a)$, and $g_j(b)$ are the evaluation of alternatives on the criterion j.

Step 2: Calculate the threshold values for the criteria. Three different threshold values, are the value of a strict preference threshold (p), the Gaussian threshold (s), and the value of an indifference threshold (q). The maximum deviation that can be considered negligible on that criterion is called the indifference threshold q. The smallest deviation to deem decisive in choosing one choice over another is known as the preference threshold p. The intermediate value between p and q gives the Gaussian threshold.

Step 3: Determine aggregated preference indices. $\pi(a, b)$ indicates the degree to which a is preferred over b

$$\pi(a, b) = \sum_{j=1}^{k} P_j(a, b) w_j \tag{4.27}$$

Step 4: Determine outranking flows. This step covers the PROMETHEE I partial ranking. Calculations of outranking flows are carried out by comparing each alternative *a* to other alternatives in *A*. The positive and negative outranking flows are calculated as follows.

$$\phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x) \tag{4.28}$$

$$\phi^-(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a) \tag{4.29}$$

While the positive outranking flow shows to what extent a dominates all other alternatives of *A*, the negative outranking flow shows to what extent a is dominated by all other alternatives of *A*.

$$\begin{aligned}
&\text{aPb if: } \phi^+(a) > \phi^+(b), and\ \phi^-(a) < \phi^-(b); or \\
&\qquad \phi^+(a) > \phi^+(b), and\ \phi^-(a) = \phi^-(b); \\
&\text{aIb if: } \phi^+(a) = \phi^+(b), and\ \phi^-(a) < \phi^-(b); \\
&\text{aRb if: } \phi^+(a) = \phi^+(b), and\ \phi^-(a) > \phi^-(b); or \\
&\qquad \phi^+(a) < \phi^+(b), and\ \phi^-(a) < \phi^-(b);
\end{aligned} \tag{4.30}$$

where, P, I, and R means preference, indifference, and incomparability, respectively.

Step 5: Determine outranking flow. This step covers the PROMETHEE II complete ranking. ϕ(a) indicates the net outranking flow and is calculated as follows.

$$\phi(\mathrm{a}) = \phi^+(a) - \phi^-(a) \tag{4.311}$$

The alternative with the higher net flow is thought to be the better option.

Step 6: Perform a geometric analysis. The interactive aid (GAIA) plane is obtained as a result of this step. It shows the relative position of the alternatives graphically. The matrix of normed flows is subjected to Principal Component Analysis (PCA):

$$\phi_j(a) = \frac{1}{n-1}\sum_{b \neq a}[P_j(a,b) - P_j(b,a)] \tag{4.32}$$

4.6 MAIRCA

MAIRCA was first introduced to the literature in 2014 (Pamučar et al., 2014). The key premise of the MAIRCA approach is that the difference between ideal and empirical weights can be determined. A summation of these difference for each criterion gives the alternatives' overall gap. The best alternative will have the smallest total gap value. The six steps of the MAIRCA approach are as follows.

Step 1: The initial decision matrix, X, is created. The matrix includes the criteria weights $(x_{ij}, i = 1, 2, \dots, n; j = 1, 2, \dots, m)$ for alternatives, $A_1, A_2, \dots, A_m$.

$$X = \begin{array}{c} \\ A_1 \\ A_2 \\ \cdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{array} \tag{4.33}$$

Step 2: Alternative selection P_{Ai} is used to determine preference. The DM is unaffected by the process of alternative selection. In fact, he has no preference for any of the options presented. The essential assumption is that DM disregards the probabilities of any alternative option. Because the DM considers the alternatives as having an equal chance of appearing, the desire to select one of them from m potential options is:

$$P_{A_i} = \frac{1}{m};\ \sum_{i=1}^{m} P_{A_i} = 1 \tag{4.34}$$

where, m denotes the total number of choices.

With the provided probability, we assume the DM is risk agnostic in the decision-making analysis. In that situation, according to the selection of specific alternatives, all preferences are equal.

$$P_{A_1} = P_{A_2} = \cdots = P_{A_m} \tag{4.35}$$

Step 3: Theoretical evaluation matrix, T_P, with format $n \times m$ is generated (n is the total criteria number, m is the total number of alternatives). The elements of the theoretical evaluation matrix, t_{Pij} , are calculated by multiplying preferences according to alternatives P_{A_i} and criteria weights, $w_i, i = 1, 2, \dots, n$.

$$
\begin{array}{ll}
T_P = & \begin{array}{c} \\ P_{A_1} \\ P_{A_2} \\ \cdots \\ P_{A_m} \end{array}
\begin{array}{c} \begin{array}{cccc} w_1 & w_2 & \cdots & w_n \end{array} \\ \begin{bmatrix} t_{p11} & t_{p12} & \cdots & t_{p1n} \\ t_{p21} & t_{p22} & \cdots & t_{p2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{pm1} & t_{pm2} & \cdots & t_{pmn} \end{bmatrix} \end{array} \\
= & \begin{array}{c} \\ P_{A_1} \\ P_{A_2} \\ \cdots \\ P_{A_m} \end{array}
\begin{array}{c} \begin{array}{cccc} w_1 & w_2 & \cdots & w_n \end{array} \\ \begin{bmatrix} P_{A_1}w_1 & P_{A_1}w_1 & \cdots & P_{A_1}w_n \\ P_{A_2}w_1 & P_{A_2}w_2 & \cdots & P_{A_1}w_n \\ \cdots & \cdots & \cdots & \cdots \\ P_{A_m}w_1 & P_{A_m}w_2 & \cdots & P_{A_m}w_n \end{bmatrix} \end{array}
\end{array}
\tag{4.36}
$$

Since decision-makers considers the alternatives as having an equal chance of appearing, all preferences, P_{A_i}, are same for all alternatives. Then, it can be obtained:

$$
\begin{array}{ll}
T_P = & \begin{array}{c} \\ P_{A_i} \end{array}
\begin{array}{c} \begin{array}{cccc} w_1 & w_1 & \cdots & w_1 \end{array} \\ \begin{bmatrix} t_{p1} & t_{p2} & \cdots & t_{pm} \end{bmatrix} \end{array} \\
= & \begin{array}{c} \\ P_{A_i} \end{array}
\begin{array}{c} \begin{array}{cccc} w_1 & w_1 & \cdots & w_n \end{array} \\ \begin{bmatrix} P_{A_i}w_1 & P_{A_i}w_2 & \cdots & P_{A_i}w_n \end{bmatrix} \end{array}
\end{array}
\tag{4.37}
$$

where t_{pi} is theoretical evaluation, and n is the total criteria number,

Step 4: Real evaluation matrix is determined.

$$
T_r = \begin{array}{c} \\ A_1 \\ A_2 \\ \cdots \\ A_m \end{array}
\begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} t_{r11} & t_{r12} & \cdots & t_{r1n} \\ t_{r21} & t_{r22} & \cdots & t_{r2n} \\ \cdots & \cdots & \cdots & \cdots \\ t_{rm1} & t_{rm2} & \cdots & t_{rmn} \end{bmatrix} \end{array}
\tag{4.38}
$$

The higher criterion value is preferable for the benefit type of criteria.

$$
t_{rij} = t_{pij}\left(\frac{x_{ij} - x_i^-}{x_i^+ - x_i^-}\right) \tag{4.39}
$$

The smaller criterion value is preferable for the cost type of criteria.

$$
t_{rij} = t_{pij}\left(\frac{x_{ij} - x_i^+}{x_i^- - x_i^+}\right) \tag{4.40}
$$

where, x_{ij}, x_i^+, x_i^- are the elements of *X*, the initial decision making matrix. While $x_i^+ = \max(x_1, x_2, \ldots, x_m)$ are the maximum criterion values, $x_i^- = \min(x_1, x_2, \ldots, x_m)$ are the minimum criterion values.

Step 5: The total gap matrix, *G*, is calculated. Members of the matrix are computed as the difference between theoretical, t_{pij} , and real, t_{rij}, assessments.

$$G = T_p - T_r = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ g_{m1} & g_{m1} & \cdots & g_{mn} \end{bmatrix} \tag{4.412}$$

where, $g_{ij} \in \left[0, (t_{pij} - t_{rij})\right]$, so:

$$g_{ij} = \begin{cases} 0, & if\ t_{pij} = t_{rij} \\ t_{pij} - t_{rij} & if\ t_{pij} > t_{rij} \end{cases} \tag{4.42}$$

Since the alternative with the least difference between the theoretical, t_{pij}, and real assessment, t_{rij}, is selected, it is preferable if g_{ij} goes to zero ($g_{ij} \to 0$). If the theoretical evaluation value of the alternative A_i for the criterion C_i equals the real evaluation value $t_{pij} = t_{rij}$, then the gap for the alternative A_i for the criterion C_i is $g_{ij} = 0$. In fact, for the criterion C_i, the alternative A_i is the best option A_i^+. If the criterion's alternative A_i has a theoretical evaluation value of t_{pij} and a real ponder value of t_{rij} 0, then the gap for the alternative is 0. The condition C_i's C_i is $g_{ij} = t_{pij}$. In fact, the alternative A_i is the poorest, A_i^- , for the criterion C_i.

Step 6: For each alternative, criteria functions' final values, Q_i, are calculated. The values of the functions' criteria are derived from the gaps summation, g_{ij}, for the alternatives, or simply the the matrix elements' sum, *G*, in columns.

$$Q_i = \sum_{j=1}^{n} g_{ij}\, , i = 1, 2, \ldots, m \tag{4.43}$$

5. RESULTS

5.1 Results of the AHP

Calculations are made for each hierarchy level, and all results are listed below. Table 5.1 shows the final pairwise comparison matrix and calculated weights of the three main criteria of the problem. According to decision-makers, the most important main criteria is the economic (Eco) aspect of sustainability with a weight of 0.450. Environmental (Env) and social (Soc) aspects follow the economic criterion with the weights of 0.379 and 0.171, respectively. Table 5.2 lists the final pairwise comparison matrix and sub-criteria weights of the economic main criterion. The three most important criteria are cost (Eco1), quality (Eco2), and warranty period (Eco7), with the weights of 0.250, 0.201, and 0.162, respectively. The least important criterion is the partnership relations (Eco8) with a weight of 0.062.

Table 5.1 : Final pairwise comparison matrix and calculated AHP weights of main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	1.000	1.189	2.632	0.450
Env	0.841	1.000	2.213	0.379
Soc	0.380	0.452	1.000	0.171

CR=0.001

Table 5.2 : Final pairwise comparison matrix and calculated AHP weights of sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	1.000	1.189	2.590	3.663	5.439	2.449	1.682	3.500	0.250
Eco_2	0.841	1.000	2.340	2.991	4.091	1.732	1.189	3.162	0.201
Eco_3	0.386	0.427	1.000	1.414	2.000	0.639	0.577	1.495	0.090
Eco_4	0.273	0.334	0.707	1.000	1.189	0.687	0.408	1.107	0.067
Eco_5	0.184	0.244	0.500	0.841	1.000	0.359	0.286	0.707	0.047
Eco_6	0.408	0.577	1.565	1.456	2.783	1.000	0.760	2.213	0.121
Eco_7	0.595	0.841	1.732	2.449	3.500	1.316	1.000	2.783	0.162
Eco_8	0.286	0.316	0.669	0.904	1.414	0.452	0.359	1.000	0.062

CR=0.013

The energy efficiency of the system (Env_1) and the environmental management system of the supplier (Env_2) are the two most significant sub-criteria of the environmental aspect of the selection problem. They cover more than 60% of the environmental criterion with the weights of 0.385 and 0.300, respectively, as listed in Table 5.3.

Table 5.3 : Final pairwise comparison matrix and calculated AHP weights of sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	1.000	1.414	2.449	2.213	0.385
Env_2	0.707	1.000	2.000	2.000	0.300
Env_3	0.408	0.500	1.000	1.000	0.155
Env_4	0.452	0.500	1.000	1.000	0.160
					CR=0.007

Health and safety at work (Soc_1), with a weight of 0.357, and employees' rights (Soc_2), with the weight of 0.361, are the leading sub-criteria for the social main criterion, as shown in Table 5.4.

Table 5.4 : Final pairwise comparison matrix and calculated AHP weights of sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	1.000	1.414	1.565	2.213	0.357
Soc_2	0.707	1.000	1.189	1.682	0.261
Soc_3	0.639	0.841	1.000	1.414	0.224
Soc_4	0.452	0.595	0.707	1.000	0.158
					CR=0.001

Table 5.5 lists the combined final weights of all main aspects and sub-criteria. The final weights of the sub-criteria are calculated by multiplying the weights of the main aspects and sub-criteria weights obtained in their own hierarchy level. According to the AHP results, the two most important criteria are the energy efficiency rate (Env_1), and the environmental management system of the supplier (Env_2), with weights of 0.146, and 0.114, respectively. The cost (Eco_1) sub-criteria is the third most significant sub-criterion for the selection problem, with a weight of 0.113. Also, financial ability

(Eco_5), respect for rights and policies (Soc_4), and partnership relations (Eco_8) are the least important criteria with the weight of 0.021, 0.027, and 0.028, respectively.

Table 5.5 : The combined final AHP weights of all main and sub-criteria.

Final Weights	
Economic	0.450
Eco_1	0.113
Eco_2	0.091
Eco_3	0.041
Eco_4	0.030
Eco_5	0.021
Eco_6	0.054
Eco_7	0.073
Eco_8	0.028
Environmental	0.379
Env_1	0.146
Env_2	0.114
Env_3	0.059
Env_4	0.060
Social	0.171
Soc_1	0.061
Soc_2	0.045
Soc_3	0.038
Soc_4	0.027

5.2 Results of DEMATEL

Calculations of each hierarchy level and all results are shown below. Table 5.6 shows the final direct-influence matrix and calculated weights of the three main criteria of the problem. The Economic (Eco) aspect of sustainability comes into prominence with the weight of 0.355, and environmental (Env) and social (Soc) aspects follow the economic criterion with the weight of 0.331 and 0.314, respectively.

Table 5.6 : The final direct-influence matrix and calculated DEMATEL weights of main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	0.000	3.000	2.250	0.360
Env	1.500	0.000	1.750	0.343
Soc	0.750	1.250	0.000	0.297

Table 5.7 lists the final direct-influence matrix and sub-criteria weights of the economic main criterion. According to the results, cost (Eco_1) and quality (Eco_2) are the two most essential sub-criteria for the economic aspect. Also, financial ability (Eco_5), 0.186, and (Eco_3), 0.151, flexibility are the two least significant sub-criteria with the weight of 0.083 and 0.085, respectively.

Table 5.7 : The final direct-influence matrix and calculated DEMATEL weights of sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	0.000	2.000	1.250	1.250	0.750	1.500	1.750	1.500	0.186
Eco_2	2.750	0.000	0.250	0.500	0.250	2.250	1.250	0.500	0.151
Eco_3	1.000	0.250	0.000	1.250	0.500	0.000	0.500	0.750	0.085
Eco_4	1.000	0.250	1.000	0.000	0.500	0.500	0.250	1.000	0.101
Eco_5	1.250	1.000	0.250	1.000	0.000	0.000	0.500	0.750	0.083
Eco_6	1.500	1.750	0.000	0.000	0.000	0.000	1.250	0.250	0.129
Eco_7	1.750	1.250	0.000	0.250	0.750	2.000	0.000	1.000	0.136
Eco_8	1.000	0.750	1.750	2.000	0.750	1.000	1.000	0.000	0.129

Although all sub-criteria are close to each other, energy efficiency rate comes to the fore as the most important criterion with the weight of 0.266 in the environmental aspect, as shown in Table 5.8. Also, the environmental management system, 0.228, is the least important criterion according to the results.

Table 5.8 : The final direct-influence matrix and calculated weights of sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	0.000	2.000	2.500	1.250	0.266
Env_2	0.250	0.000	0.750	0.750	0.228
Env_3	0.000	1.000	0.000	1.750	0.256
Env_4	0.250	1.500	1.750	0.000	0.250

While respect for rights and policies, with the weight of 0.262, is the most significant sub-criterion of the social main criterion, training of employees, with the weight of

0.238, is the least one as listed in Table 5.9. Table 5.10 lists the final weights of all criteria resulting from DEMATEL. The two most important criteria are the energy efficiency rate (Env1) and green production (Env3), with weights of 0.088 and 0.085, respectively. All environmental sub-criteria have higher weights than the other sub-criteria. On the other hand, financial ability (Eco5) and delivery (Eco3) have the smallest weights with 0.030 and 0.031, respectively.

Table 5.9 : The final direct-influence matrix and calculated weights of sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	0.000	1.250	3.250	2.000	0.244
Soc_2	2.000	0.000	1.750	3.500	0.256
Soc_3	3.000	1.750	0.000	1.000	0.238
Soc_4	2.000	3.750	2.250	0.000	0.262

Table 5.10 : The combined final BWM weights of all main and sub-criteria.

Final Weights	
Economic	0.360
Eco_1	0.067
Eco_2	0.054
Eco_3	0.031
Eco_4	0.036
Eco_5	0.030
Eco_6	0.046
Eco_7	0.049
Eco_8	0.047
Environmental	0.343
Env_1	0.091
Env_2	0.078
Env_3	0.088
Env_4	0.086
Social	0.297
Soc_1	0.073
Soc_2	0.076
Soc_3	0.071
Soc_4	0.078

5.3 Results of the BWM

Table 5.11 and Table 5.12 lists the best-to-others and worst-to-others vectors of the decision-makers for the main criteria. While the first three decision-makers select the economic aspect as the best option, the other decision-maker selects the environmental aspect the first. On the other hand, the social aspect is selected as the least important main criterion by all of the decision-makers.

Table 5.11 : Best-to-others vectors of all main criteria.

Best to Others			
DM-1	Eco	Env	Soc
Eco	1	2	4
DM-2	Eco	Env	Soc
Eco	1	1	2
DM-3	Eco	Env	Soc
Eco	1	2	3
DM-4	Eco	Env	Soc
Env	2	1	3

Table 5.12 : Others-to-worst vectors of all main criteria.

Others to Worst							
DM-1	Social	DM-2	Social	DM-3	Social	DM-4	Social
Eco	4	Eco	2	Eco	3	Eco	2
Env	2	Env	2	Env	2	Env	3
Soc	1	Soc	1	Soc	1	Soc	1

Table 5.13 and Table 5.14 shows the best-to-others and worst to others vectors of the decision-makers for the sub-criteria of the economic main criterion. All of the decision-makers select the cost (Eco1) criterion as the most significant. The first two decision-makers choose financial ability (Eco5) as the worst sub-criterion. While flexibility (Eco4) is chosen as the worst by the DM-3, the partnership relations (Eco8) are selected by the DM-4.

Table 5.13 : Best-to-others vectors of sub-criteria of the economic aspect.

Best to Others								
DM-1	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8
Eco_1	1	2	3	5	6	2	2	4
DM-2	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8
Eco_1	1	1	3	4	5	2	2	2
DM-3	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8
Eco_2	1	1	5	5	5	3	2	5
DM-4	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8
Eco_1	1	1	2	3	5	3	2	6

Table 5.14 : Others-to-worst vectors of sub-criteria of the economic aspect.

Others to Worst							
DM-1	Eco_5	DM-2	Eco_5	DM-3	Eco_4	DM-4	Eco_8
Eco_1	6	Eco_1	5	Eco_1	5	Eco_1	6
Eco_2	3	Eco_2	4	Eco_2	6	Eco_2	5
Eco_3	2	Eco_3	2	Eco_3	2	Eco_3	5
Eco_4	2	Eco_4	2	Eco_4	1	Eco_4	3
Eco_5	1	Eco_5	1	Eco_5	2	Eco_5	1
Eco_6	3	Eco_6	4	Eco_6	4	Eco_6	2
Eco_7	4	Eco_7	4	Eco_7	4	Eco_7	5
Eco_8	2	Eco_8	2	Eco_8	2	Eco_8	1

All decision-makers select the energy efficiency rate (Env1) as the most important sub-criterion of the environmental aspect, as given in Table 5.15. While consumption of resources (Env4) is chosen as the worst by DM-1, DM-2, and DM-4, DM-3 selects the green production (Env3), given in Table 5.16

Table 5.15 : Best-to-others vectors of sub-criteria of the environmental aspect.

Best to Others				
DM-1	Env_1	Env_2	Env_3	Env_4
Env_1	1	2	3	3
DM-2	Env_1	Env_2	Env_3	Env_4
Env_1	1	1	2	2
DM-3	Env_1	Env_2	Env_3	Env_4
Env_1	1	1	3	2
DM-4	Env_1	Env_2	Env_3	Env_4
Env_1	1	2	2	2

Table 5.16 : Others-to-worst vectors of sub-criteria of the environmental aspect..

Others to Worst							
DM-1	Env$_4$	DM-2	Env$_4$	DM-3	Env$_3$	DM-4	Env$_4$
Env$_1$	3	Eco$_1$	2	Eco$_1$	3	Eco$_1$	2
Env$_2$	2	Eco$_2$	2	Eco$_2$	2	Eco$_2$	2
Env$_3$	1	Eco$_3$	1	Eco$_3$	1	Eco$_3$	1
Env$_4$	1	Eco$_4$	1	Eco$_4$	1	Eco$_4$	1

For the social main criterion, health and safety at work (Soc1) is selected as the best sub-criterion by all the decision-makers, listed in Table 5.17. On the other hand, DM-1 and DM-4 choose the employees' rights as the least important criterion. While DM-2 chooses the respect of rights and policies (Soc4) as the worst, DM-3 selects the training of employees (Soc3) as given in Table 5.18.

Table 5.17 : Best-to-others vectors of sub-criteria of the social aspect.

Best to Others				
DM-1	Soc$_1$	Soc$_2$	Soc$_3$	Soc$_4$
Soc$_1$	1	2	1	2
DM-2	Soc$_1$	Soc$_2$	Soc$_3$	Soc$_4$
Soc$_1$	1	1	1	2
DM-3	Soc$_1$	Soc$_2$	Soc$_3$	Soc$_4$
Soc$_1$	1	2	3	2
DM-4	Soc$_1$	Soc$_2$	Soc$_3$	Soc$_4$
Soc$_1$	1	1	2	2

Table 5.18 : Others-to-worst vectors of sub-criteria of the social aspect.

Others to Worst							
DM-1	Soc$_2$	DM-2	Soc$_4$	DM-3	Soc$_3$	DM-4	Soc$_2$
Soc$_1$	2	Soc$_1$	2	Soc$_1$	3	Soc$_1$	2
Soc$_2$	1	Soc$_2$	2	Soc$_2$	2	Soc$_2$	2
Soc$_3$	1	Soc$_3$	2	Soc$_3$	1	Soc$_3$	2
Soc$_4$	1	Soc$_4$	1	Soc$_4$	2	Soc$_4$	1

Table 5.19 lists the final weights of the all criteria as a result of the best worst methodology. The most significant main criterion is economic aspect with the weight of 0.451, and environmental and social aspects follow it with the weights of 0.380 and,

0.169, respectively. Energy efficiency rate, wşth the weight of 0,146, and the cost, with the weight of 0.111, are the two most important sub-criterion for the green trigeneration supplier selection problem. On the other hand, financial ability and flexibility are determined as the least significant sub-criteria with the weights of 0.020 and 0.029, respectively, as a result of the best worst method.

Table 5.19 : The combined final BWM weights of all main and sub-criteria.

Final Weights	
Economic	0.451
Eco_1	0.111
Eco_2	0.097
Eco_3	0.043
Eco_4	0.029
Eco_5	0.020
Eco_6	0.053
Eco_7	0.064
Eco_8	0.033
Environmental	0.380
Env_1	0.146
Env_2	0.107
Env_3	0.057
Env_4	0.070
Social	0.169
Soc_1	0.058
Soc_2	0.044
Soc_3	0.037
Soc_4	0.030

5.4 Comparison of Criteria Weights

Since the approaches of the methods used are different, it is a natural result that the criteria weights and rankings are different. Table 5.20 shows all sub-criteria weights according to AHP, DEMATEL, and BWM. According to the results, all methods rank the energy efficiency rate of the system (Env_1) as the most significant criteria. AHP evaluates the environmental management system of the supplier (Env_2) and cost (Eco1) as the second and third important criteria, DEMATEL ranks the green production (Env_3) and consumption of resources (Env_4) after the first criterion, and cost (Eco_1) and the environmental management system of the supplier (Env_2) follows the efficiency rate in BWM. The criteria evaluations of the AHP and BWM methods are very close to each other because these two methods have similar decision-making approaches. However, since DEMATEL includes a different decision-making system than the others, the results also differ greatly. While sub-criteria from environmental and economic aspects came to the fore in AHP and BMW methods, environmental and social aspects' sub-criteria take place in front of the sub-criteria of the economic aspect in DEMATEL. Also, all methods rank the financial ability (Eco_5) as the least important criterion for the green supplier selection problem.

Table 5.20 : Comparison of sub-criteria weights according to the methods.

AHP			DEMATEL			BWM		
Env1	0.146	1	Env1	0.091	1	Env1	0.146	1
Env2	0.114	2	Env3	0.088	2	Eco1	0.111	2
Eco1	0.113	3	Env4	0.086	3	Env2	0.107	3
Eco2	0.091	4	Env2	0.078	4	Eco2	0.097	4
Eco7	0.073	5	Soc4	0.078	5	Env4	0.070	5
Soc1	0.061	6	Soc2	0.076	6	Eco7	0.064	6
Env4	0.06	7	Soc1	0.073	7	Soc1	0.058	7
Env3	0.059	8	Soc3	0.071	8	Env3	0.057	8
Eco6	0.054	9	Eco1	0.067	9	Eco6	0.053	9
Soc2	0.045	10	Eco2	0.054	10	Soc2	0.044	10
Eco3	0.041	11	Eco7	0.049	11	Eco3	0.043	11
Soc3	0.038	12	Eco8	0.047	12	Soc3	0.037	12
Eco4	0.03	13	Eco6	0.046	13	Eco8	0.033	13
Eco8	0.028	14	Eco4	0.036	14	Soc4	0.030	14
Soc4	0.027	15	Eco3	0.031	15	Eco4	0.029	15
Eco5	0.021	16	Eco5	0.030	16	Eco5	0.020	16

5.5 Results of the Alternative Rankings

Evaluation of alternatives using TOPSIS, PROMETHEE, and MAIRCA methods are performed using all three different criteria weights obtained as a result of AHP, DEMATEL, and BWM. Table 5.20, Table 5.21, and Table 5.22 list calculation results and ranking of alternatives as a result of TOPSIS, PROMETHEE, and MAIRCA, respectively. Also, Figure 5.1, 5.2, and 5.3 illustrates the ranking distributions of alternatives according to TOPSIS, PROMETHEE, and MAIRCA, respectively.

As a result of TOPSIS calculations, alternatives of A2 and A5 come to the forefront as the best alternatives. While the AHP-TOPSIS and BWM-TOPSIS combination ranks the A2 as the first, DEMATEL-TOPSIS integration evaluates the A5 as the best alternative. According to the AHP-TOPSIS results, alternatives of A4 and A5 follow the A2, and A7 is determined as the worst alternative. DEMATEL-TOPSIS integration determines the alternatives of A2 and A3 as the second and third alternatives, respectively, and selects the A7 as the least suitable alternative for the problem. Finally, alternatives of A24 and A5 are chosen as second and third alternatives, respectively, by BWM-TOPSIS combination. Like other combinations, BWM-TOPSIS also determines the A7 as the worst option.

PROMETHEE method evaluates the alternative of the A5 as the best option for all scenarios of using AHP, DEMATEL, and BWM. A2 is selected as the second alternative by AHP-PROMETHEE and BWM-PROMETHEE combinations. Also, AHP-DEMATEL evaluates the A3 as the second alternative. While AHP-PROMETHEE and BWM-PROMETHEE determine the alternative of A7 as the least preferable option, the DEMATEL-PROMETHEE combination selects the A1 as the worst option.

As a result of the MAIRCA method, A2 and A5 are determined as the preferable alternatives. AHP-MAIRCA and BWM-MAIRCA rank A2 as the best alternative, and DEMATEL-MAIRCA ranks A5 as the best. While the AHP-MAIRCA and BWM-MAIRCA combinations evaluate the alternatives of A5 and A4 as the second and third, in the DEMATEL-MAIRCA integration A2 and A3 follow the best alternative. Also, all methods determine the A7 as the least preferable alternative.

Considering all methodology, PROMETHEE ranks the alternative of A5 as the most suitable alternative. MAIRCA evaluates A2 as the best option for the scenarios where criteria weights are determined by AHP and BWM. In the scenario where the criteria are calculated by AHP and BWM, TOPSIS chose A2 as the best alternative, while in the other two scenarios where DEMATEL is used, A5 was chosen as the most suitable option.

Table 5.21 : Ranking of alternatives as a result of TOPSIS.

AHP - TOPSIS					DEMATEL - TOPSIS					BWM - TOPSIS				
Alternatives	$S+_i$	$S-_i$	$C+_i$	Rank	Alternatives	$S+_i$	$S-_i$	$C+_i$	Rank	Alternatives	$S+_i$	$S-_i$	$C+_i$	Rank
A2	0.016	0.060	0.787	1	A5	0.016	0.048	0.744	1	A2	0.017	0.057	0.770	1
A4	0.019	0.059	0.751	2	A2	0.020	0.043	0.685	2	A4	0.021	0.056	0.728	2
A5	0.024	0.058	0.709	3	A3	0.020	0.044	0.684	3	A5	0.023	0.057	0.711	3
A1	0.027	0.054	0.668	4	A4	0.025	0.042	0.627	4	A1	0.027	0.051	0.655	4
A3	0.029	0.056	0.655	5	A1	0.026	0.039	0.601	5	A3	0.029	0.054	0.652	5
A6	0.033	0.051	0.609	6	A6	0.030	0.036	0.547	6	A6	0.033	0.049	0.599	6
A7	0.052	0.027	0.341	7	A7	0.040	0.021	0.347	7	A7	0.050	0.027	0.353	7

Table 5.22 : Ranking of alternatives as a result of PROMETHEE.

AHP - PROMETHEE					DEMATEL - PROMETHEE					BWM - PROMETHEE				
Alt.	ϕ	ϕ^+	ϕ^-	Rank	Alt.	ϕ	ϕ^+	ϕ^-	Rank	Alt.	ϕ	ϕ^+	ϕ^-	Rank
A5	0.449	0.625	0.176	1	A5	0.498	0.676	0.178	1	A5	0.380	0.590	0.210	1
A2	0.318	0.595	0.277	2	A3	0.229	0.534	0.304	2	A2	0.318	0.587	0.270	2
A4	0.174	0.499	0.325	3	A2	0.212	0.538	0.326	3	A3	0.107	0.437	0.330	3
A3	0.086	0.441	0.355	4	A6	-0.055	0.389	0.444	4	A4	0.043	0.438	0.395	4
A6	-0.192	0.309	0.501	5	A4	-0.065	0.382	0.446	5	A6	-0.105	0.337	0.443	5
A1	-0.355	0.225	0.580	6	A7	-0.395	0.231	0.626	6	A1	-0.370	0.201	0.572	6
A7	-0.479	0.184	0.663	7	A1	-0.424	0.198	0.622	7	A7	-0.371	0.225	0.596	7

Table 5.23 : Ranking of alternatives as a result of MAIRCA.

AHP - MAIRCA			DEMATEL - MAIRCA			BWM - MAIRCA		
Alt.	Q_i	Rank	Alt.	Q_i	Rank	Alt.	Q_i	Rank
A2	0.047	1	A5	0.040	1	A2	0.047	1
A5	0.051	2	A2	0.058	2	A5	0.051	2
A4	0.064	3	A3	0.060	3	A4	0.066	3
A3	0.070	4	A4	0.076	4	A3	0.070	4
A6	0.090	5	A6	0.090	5	A6	0.091	5
A1	0.094	6	A1	0.099	6	A1	0.095	6
A7	0.108	7	A7	0.109	7	A7	0.108	7

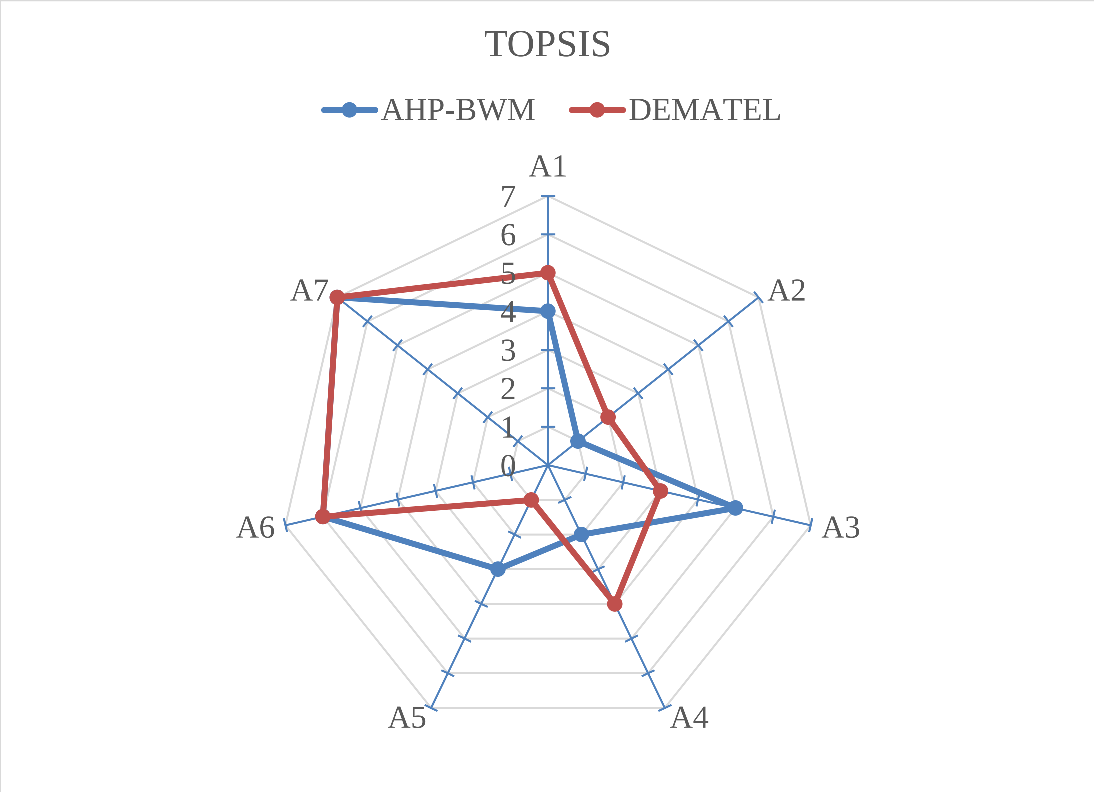

Figure 5.1 : Radar diagram of the TOPSIS results.

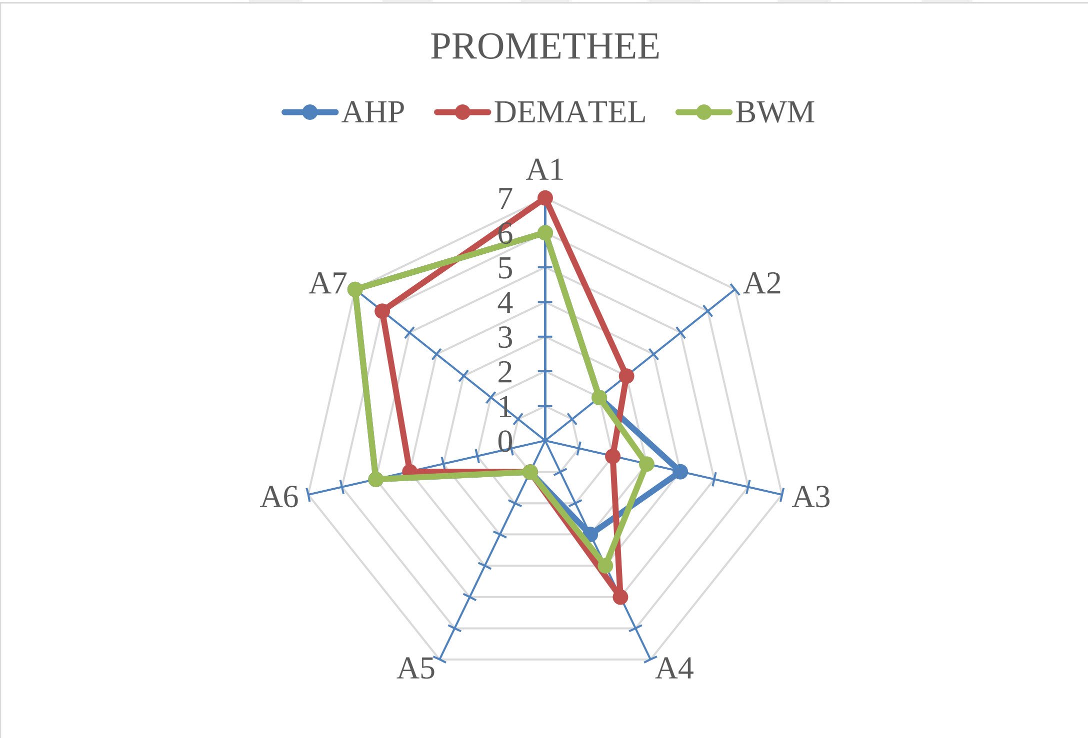

Figure 5.2 : Radar diagram of the PROMETHEE results.

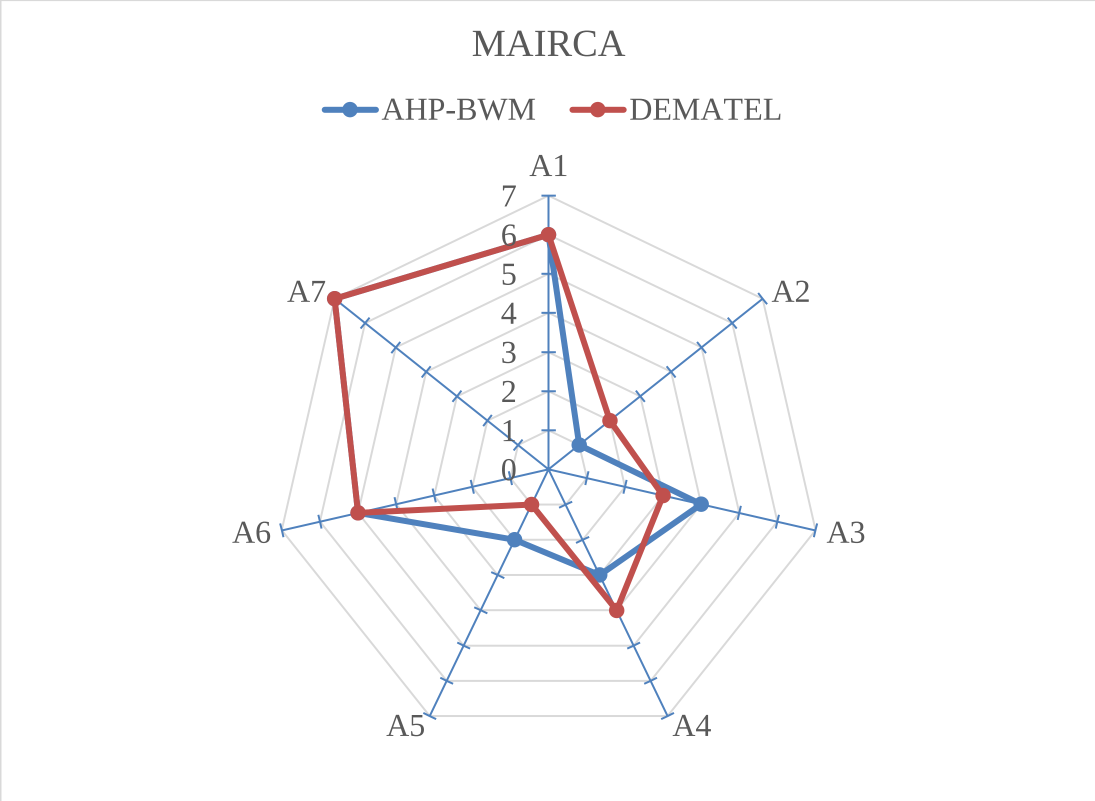

Figure 5.3 : Radar diagram of the MAIRCA results.

6. CONCLUSION

One-third of global resources, 40% of global energy, 25% of global water is consumed, and one-third of worldwide carbon emissions, 40% of the global waste is produced by construction industry (UNEP-SBCI, 2016). To limit its adverse impacts on the environment, the building sector has to take a more sustainable approach at all stages. The notion of green supply chain management in construction has become more important as a result of this necessity. As a result, several standards and rules have arisen to make construction activities and building operations more sustainable. ISO 14001 is an internationally recognized environmental management system standard that assists organizations in maximizing resource efficiency and reducing waste in order to demonstrate their environmental compliance. LEED, BREEAM, and Estidama are environmental and green building grading and certification systems that give a measurement for energy efficiency, health, and cost savings in construction processes and structures. In addition, a number of national green building councils have been formed to assist construction players in achieving sustainability.

The major purpose of the thesis is to provide a framework for selecting green suppliers in the construction industry. The problem of selecting sustainable suppliers occupies a prominent position in green supply chain management. The building's energy efficiency is also the most significant factor for all green building certification methods. As a result, the study will look into the trigeneration system selection challenge, which has a significant impact on the energy efficiency of large healthcare facilities. Finally, different classic and recently designed MCDM approaches will be compared. In light of these factors, choosing a green trigeneration system is critical for energy efficiency and long-term sustainability. Trigeneration systems, which produce power, heating energy, and cooling from a single generator or process, are one of the systems that play a critical role in boosting energy efficiency for certain types of buildings. Buildings with a consistent demand for cooling, heating, and electricity throughout the year benefit most from trigeneration systems (Ziher and Poredos, 2005).

In recent years, trigeneration system procurements have become more common in the construction of city hospitals in Türkiye, which are large health complexes that combine many institutions. The trigenerational selection of a health facility established in one of Turkey's major cities is investigated as a case study in this context. For this green selection challenge, multi-criteria decision-making (MCDM) approaches are applied. Criteria are determined as a consequence of literature study and expert opinions relevant to the project. The main criteria include the economic, environmental, and social aspects of sustainability. The economic main criterion has eight sub-criteria which are cost, quality, delivery, flexibility, financial ability, operation and maintenance cost, warranty period, and partnership relations. The environmental main criterion consists of four sub-criteria which are energy efficiency of the system, environmental protection management system of the supplier, green products, and consumption of resources. Finally, the social main criterion has four sub-criteria which are safety and health at work, employees' rights, training of employees, and respect of rights and policies. While the criterion weights are determined using AHP, DEMATEL, and BWM, the green supplier alternatives are ranked using TOPSIS, PROMETHEE, and MAIRCA. Some of the most extensively used MCDM methods include AHP, DEMATEL, TOPSIS, and PROMETHEE, while BWM and MAIRCA are relatively new and gaining popularity. Finally, the study examines the different MCDM approaches used to evaluate green trigeneration system vendors for a healthcare complex.

This study also includes some limitations. Fuzzy systems that better reflect human decision making is not used. It is aimed to use more advanced MCDM methods and fuzzy methods in future studies. This study contributes to the body of knowledge on identifying the important parameters in the selection of trigeneration systems and developing a model for green supplier selection.

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APPENDICES

APPENDIX A: Tables of AHP
APPENDIX B: Tables of DEMATEL

APPENDIX A

Table A.1 : DM-1's pairwise comparison matrix and calculated AHP weights for the main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	1.000	2.000	4.000	0.557
Env	0.500	1.000	3.000	0.320
Soc	0.250	0.333	1.000	0.123
				CR=0.054

Table A.2 : DM-2's pairwise comparison matrix and calculated AHP weights for the main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	1.000	1.000	2.000	0.400
Env	1.000	1.000	2.000	0.400
Soc	0.500	0.500	1.000	0.200
				CR=0.000

Table A.3 : DM-3's pairwise comparison matrix and calculated AHP weights for the main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	1.000	2.000	3.000	0.539
Env	0.500	1.000	2.000	0.297
Soc	0.333	0.500	1.000	0.164
				CR=0.274

Table A.4 : DM-4's pairwise comparison matrix and calculated AHP weights for the main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	1.000	0.500	2.000	0.312
Env	2.000	1.000	2.000	0.490
Soc	0.500	0.500	1.000	0.198
				CR=0.160

Table A.5 : DM-1's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	1.000	2.000	3.000	3.000	5.000	3.000	2.000	3.000	0.277
Eco_2	0.500	1.000	2.000	2.000	2.000	1.000	2.000	2.000	0.158
Eco_3	0.333	0.500	1.000	1.000	2.000	0.500	1.000	2.000	0.098
Eco_4	0.333	0.500	1.000	1.000	2.000	1.000	0.500	2.000	0.098
Eco_5	0.200	0.500	0.500	0.500	1.000	0.500	0.500	1.000	0.058
Eco_6	0.333	1.000	2.000	1.000	2.000	1.000	1.000	2.000	0.126
Eco_7	0.500	0.500	1.000	2.000	2.000	1.000	1.000	2.000	0.122
Eco_8	0.333	0.500	0.500	0.500	1.000	0.500	0.500	1.000	0.063

CR=0.095

Table A.6 : DM-2's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	1.000	1.000	3.000	4.000	5.000	2.000	2.000	2.000	0.229
Eco_2	1.000	1.000	3.000	4.000	4.000	1.000	0.500	2.000	0.173
Eco_3	0.333	0.333	1.000	1.000	1.000	0.500	0.333	0.500	0.059
Eco_4	0.250	0.250	1.000	1.000	1.000	0.333	0.333	0.500	0.051
Eco_5	0.200	0.250	1.000	1.000	1.000	0.200	0.200	0.500	0.044
Eco_6	0.500	1.000	2.000	3.000	5.000	1.000	1.000	2.000	0.160
Eco_7	0.500	2.000	3.000	3.000	5.000	1.000	1.000	2.000	0.188
Eco_8	0.500	0.500	2.000	2.000	2.000	0.500	0.500	1.000	0.096

CR=0.094

Table A.7 : DM-3's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	1.000	1.000	5.000	5.000	7.000	2.000	2.000	5.000	0.260
Eco_2	1.000	1.000	5.000	5.000	7.000	3.000	2.000	5.000	0.275
Eco_3	0.200	0.200	1.000	2.000	2.000	0.333	0.333	1.000	0.058
Eco_4	0.200	0.200	0.500	1.000	0.500	0.333	0.333	0.500	0.039
Eco_5	0.143	0.143	0.500	2.000	1.000	0.333	0.333	0.500	0.043
Eco_6	0.500	0.333	3.000	3.000	3.000	1.000	1.000	3.000	0.131
Eco_7	0.500	0.500	3.000	3.000	3.000	1.000	1.000	3.000	0.137
Eco_8	0.200	0.200	1.000	2.000	2.000	0.333	0.333	1.000	0.058

CR=0.099

Table A.8 : DM-4's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	1.000	1.000	1.000	3.000	5.000	3.000	1.000	5.000	0.202
Eco_2	1.000	1.000	1.000	2.000	5.000	3.000	1.000	5.000	0.191
Eco_3	1.000	1.000	1.000	2.000	4.000	2.000	1.000	5.000	0.177
Eco_4	0.333	0.500	0.500	1.000	2.000	2.000	0.500	3.000	0.095
Eco_5	0.200	0.200	0.250	0.500	1.000	0.500	0.200	1.000	0.040
Eco_6	0.333	0.333	0.500	0.500	2.000	1.000	0.333	2.000	0.069
Eco_7	1.000	1.000	1.000	2.000	5.000	3.000	1.000	5.000	0.191
Eco_8	0.200	0.200	0.200	0.333	1.000	0.500	0.200	1.000	0.037

CR=0.031

Table A.9 : DM-1's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	1.000	2.000	3.000	3.000	0.455
Env_2	0.500	1.000	2.000	2.000	0.263
Env_3	0.333	0.500	1.000	1.000	0.141
Env_4	0.333	0.500	1.000	1.000	0.141
					CR=0.013

Table A.10 : DM-2's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	1.000	1.000	2.000	2.000	0.333
Env_2	1.000	1.000	2.000	2.000	0.333
Env_3	0.500	0.500	1.000	1.000	0.167
Env_4	0.500	0.500	1.000	1.000	0.167
					CR=0.000

Table A.11 : DM-3's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	1.000	1.000	3.000	2.000	0.362
Env_2	1.000	1.000	2.000	2.000	0.326
Env_3	0.333	0.500	1.000	1.000	0.148
Env_4	0.500	0.500	1.000	1.000	0.163
					CR=0.025

Table A.12 : DM-4's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	1.000	2.000	2.000	2.000	0.392
Env_2	0.500	1.000	2.000	2.000	0.279
Env_3	0.500	0.500	1.000	1.000	0.165
Env_4	0.500	0.500	1.000	1.000	0.165
					CR=0.075

Table A.13 : DM-1's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	1.000	2.000	1.000	2.000	0.286
Soc_2	0.500	1.000	0.500	1.000	0.286
Soc_3	1.000	2.000	1.000	1.000	0.286
Soc_4	0.500	1.000	1.000	1.000	0.143
					CR=0.075

Table A.14 : DM-2's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	1.000	1.000	1.000	2.000	0.455
Soc_2	1.000	1.000	1.000	2.000	0.263
Soc_3	1.000	1.000	1.000	2.000	0.141
Soc_4	0.500	0.500	0.500	1.000	0.141
					CR=0.000

Table A.15 : DM-3's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	1.000	2.000	3.000	3.000	0.329
Soc_2	0.500	1.000	2.000	2.000	0.329
Soc_3	0.333	0.500	1.000	1.000	0.200
Soc_4	0.333	0.500	1.000	1.000	0.142
					CR=0.075

Table A.16 : DM-4's pairwise comparison matrix and calculated AHP weights for the sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	1.000	1.000	2.000	2.000	0.357
Soc_2	1.000	1.000	2.000	2.000	0.261
Soc_3	0.500	0.500	1.000	2.000	0.224
Soc_4	0.500	0.500	0.500	1.000	0.158
					CR=0.000

APPENDIX B

Table B.1 : DM-1's direct-influence matrix and calculated DEMATEL weights for the main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	0.000	3.000	3.000	0.370
Env	1.000	0.000	2.000	0.313
Soc	0.000	1.000	0.000	0.317

Table B.2 : DM-2's direct-influence matrix and calculated DEMATEL weights for the main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	0.000	3.000	2.000	0.330
Env	1.000	0.000	2.000	0.349
Soc	1.000	2.000	0.000	0.321

Table B.3 : DM-3's direct-influence matrix and calculated DEMATEL weights for the main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	0.000	3.000	2.000	0.361
Env	2.000	0.000	2.000	0.349
Soc	1.000	1.000	0.000	0.290

Table B.4 : DM-4's direct-influence matrix and calculated DEMATEL weights for the main criteria.

Criteria	Eco	Env	Soc	Weights
Eco	0.000	3.000	2.000	0.385
Env	2.000	0.000	1.000	0.352
Soc	1.000	1.000	0.000	0.263

Table B.5 : DM-1's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	0.000	2.000	1.000	1.000	1.000	1.000	2.000	2.000	0.211
Eco_2	3.000	0.000	0.000	0.000	0.000	2.000	1.000	0.000	0.149
Eco_3	1.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.067
Eco_4	1.000	0.000	1.000	0.000	0.000	0.000	0.000	1.000	0.082
Eco_5	1.000	1.000	0.000	1.000	0.000	0.000	1.000	1.000	0.085
Eco_6	2.000	2.000	0.000	0.000	0.000	0.000	1.000	0.000	0.129
Eco_7	2.000	1.000	0.000	0.000	0.000	2.000	0.000	1.000	0.137
Eco_8	1.000	1.000	2.000	2.000	1.000	1.000	1.000	0.000	0.140

Table B.6 : DM-2's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	0.000	3.000	2.000	2.000	0.000	2.000	2.000	1.000	0.182
Eco_2	2.000	0.000	1.000	1.000	1.000	3.000	1.000	1.000	0.165
Eco_3	1.000	1.000	0.000	1.000	0.000	0.000	0.000	1.000	0.084
Eco_4	1.000	1.000	1.000	0.000	2.000	1.000	1.000	1.000	0.129
Eco_5	1.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.059
Eco_6	1.000	2.000	0.000	0.000	0.000	0.000	2.000	0.000	0.137
Eco_7	2.000	1.000	0.000	1.000	1.000	2.000	0.000	1.000	0.136
Eco_8	1.000	1.000	1.000	2.000	0.000	1.000	1.000	0.000	0.108

Table B.7 : DM-3's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	0.000	1.000	0.000	0.000	1.000	2.000	1.000	1.000	0.174
Eco_2	3.000	0.000	0.000	1.000	0.000	2.000	1.000	1.000	0.139
Eco_3	1.000	0.000	0.000	1.000	1.000	0.000	1.000	1.000	0.091
Eco_4	1.000	0.000	1.000	0.000	0.000	0.000	0.000	1.000	0.081
Eco_5	2.000	1.000	1.000	1.000	0.000	0.000	0.000	1.000	0.105
Eco_6	1.000	2.000	0.000	0.000	0.000	0.000	1.000	1.000	0.136
Eco_7	2.000	1.000	0.000	0.000	1.000	2.000	0.000	1.000	0.130
Eco_8	1.000	0.000	2.000	2.000	1.000	1.000	1.000	0.000	0.145

Table B.8 : DM-4's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the economic aspect.

Eco.	Eco_1	Eco_2	Eco_3	Eco_4	Eco_5	Eco_6	Eco_7	Eco_8	Weights
Eco_1	0.000	2.000	2.000	2.000	1.000	1.000	2.000	2.000	0.189
Eco_2	3.000	0.000	0.000	0.000	0.000	2.000	2.000	0.000	0.140
Eco_3	1.000	0.000	0.000	2.000	1.000	0.000	1.000	1.000	0.099
Eco_4	1.000	0.000	1.000	0.000	0.000	1.000	0.000	1.000	0.099
Eco_5	1.000	2.000	0.000	1.000	0.000	0.000	1.000	1.000	0.094
Eco_6	2.000	1.000	0.000	0.000	0.000	0.000	1.000	0.000	0.111
Eco_7	1.000	2.000	0.000	0.000	1.000	2.000	0.000	1.000	0.136
Eco_8	1.000	1.000	2.000	2.000	1.000	1.000	1.000	0.000	0.131

Table B.9 : DM-1's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	0.000	2.000	3.000	1.000	0.282
Env_2	1.000	0.000	1.000	1.000	0.241
Env_3	0.000	1.000	0.000	2.000	0.249
Env_4	0.000	1.000	1.000	0.000	0.228

Table B.10 : DM-2's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	0.000	2.000	2.000	2.000	0.290
Env_2	0.000	0.000	0.000	0.000	0.240
Env_3	0.000	1.000	0.000	1.000	0.205
Env_4	1.000	2.000	2.000	0.000	0.265

Table B.11 : DM-3's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	0.000	2.000	2.000	1.000	0.226
Env_2	0.000	0.000	1.000	1.000	0.242
Env_3	0.000	1.000	0.000	2.000	0.263
Env_4	0.000	2.000	2.000	0.000	0.269

Table B.12 : DM-4's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the environmental aspect.

Environmental	Env_1	Env_2	Env_3	Env_4	Weights
Env_1	0.000	2.000	3.000	1.000	0.269
Env_2	0.000	0.000	1.000	1.000	0.199
Env_3	0.000	1.000	0.000	2.000	0.282
Env_4	0.000	1.000	2.000	0.000	0.250

Table B.13 : DM-1's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	0.000	2.000	2.000	1.000	0.225
Soc_2	2.000	0.000	2.000	4.000	0.288
Soc_3	3.000	2.000	0.000	1.000	0.221
Soc_4	2.000	4.000	2.000	0.000	0.266

Table B.14 : DM-2's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	0.000	1.000	4.000	3.000	0.278
Soc_2	2.000	0.000	1.000	3.000	0.220
Soc_3	4.000	1.000	0.000	1.000	0.242
Soc_4	2.000	4.000	2.000	0.000	0.260

Table B.15 : DM-3's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	0.000	1.000	3.000	1.000	0.219
Soc_2	2.000	0.000	2.000	4.000	0.279
Soc_3	3.000	3.000	0.000	1.000	0.246
Soc_4	2.000	4.000	2.000	0.000	0.257

Table B.16 : DM-4's direct-influence matrix and calculated DEMATEL weights for the sub-criteria of the social aspect.

Social	Soc_1	Soc_2	Soc_3	Soc_4	Weights
Soc_1	0.000	1.000	4.000	3.000	0.253
Soc_2	2.000	0.000	2.000	3.000	0.230
Soc_3	2.000	1.000	0.000	1.000	0.252
Soc_4	2.000	3.000	3.000	0.000	0.265

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Yayla, A., Kayakutlu, G. and Kayalica, M.O.,** 2021. Life Cycle Assessment with BIM Towards Sustainable Energy Policy-Making: The Case of Urban Transformation in Istanbul. International Journal of Sustainable Construction Engineering and Technology, 12(3), pp.142-154.