

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**A DECISION-SUPPORT APPROACH TO IMPLEMENT
WASTEWATER RECOVERY TECHNOLOGIES THROUGH
THE CONCEPT OF CIRCULAR CITY AT FULL SCALE**

İREM ÖZTÜRK
A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
DEPARTMENT OF ENVIRONMENTAL ENGINEERING

GEBZE
2023

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ASSOC. PROF. DR. EMEL TOPUZ

GEBZE

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SUMMARY

Rising consumption hampers sustainable future without habit change. Daily water, plant, soil, and energy use exhaust resources, leaving little for future generations. This causes shortages, waste problems, and disasters. Countries and cities must initiate change. Urban migration causes waste, infrastructure, and water issues. Circular cities vital for sustainability, as linear urbanization falls short. They recover resources sustainably through reduction, reuse, recycling, and recovery, including water, nutrients, chemicals, heat, and materials.

In this thesis, wastewater resource recovery selection is provided by multi-criteria decision making. First, possible criteria and alternatives are determined in a comprehensive literature review. Then, some criteria and alternatives were eliminated depending on the missing information in the literature and expert opinions. Then, the list of criteria was classified into 4 clusters as economic, environmental, technical, and social criteria.

In the study, fuzzy Analytical Hierarchy Process, Analytical Network Process and Preference Order Technique with Similarity to Ideal Solution were used to rank the recovery technologies according to criteria and to select the best recovery technology. Alternatives evaluated in terms of criteria are listed according to their sustainability index values. In the fuzzy AHP and TOPSIS, the best wastewater source recovery technology is the membrane with a sustainability index of 4.31 and 0.54, while air stripping with an SI of 2.83 and 0.39 and precipitation with a SI of 2.65 and 0.34 are in the third place. On the other hand, according to the ANP method, the membrane (5.18) ranked first, followed by precipitation (4.55) and air stripping (4.16), respectively.

Key Words: Analytic Hierarchy Process, Analytic Network Process, Wastewater, Circular Cities, Resource Recovery, Sustainability Index.

ÖZET

Artan tüketim, alışkanlıklar değişmeden sürdürülebilir bir geleceğe ulaşmayı zorlaştırıyor. Günlük hayatta bilinçsizce kullanılan su, bitki, toprak ve enerji kaynakları gelecek nesillere az bir şey bırakıyor. Bu durum, kaynak kıtlığı, atık bertaraf sorunları ve daha sık çevresel felaketlerle sonuçlanıyor. Değişim ülkeler ve şehirlerden başlamalı. Ayrıca, hızlı kentsel göç, atık üretimi, altyapı sorunları ve su yönetimi gibi sorunları beraberinde getirmektedir. Doğrusal kentleşme yapıları bu sorunlara yetişemeyebilir, bu yüzden dairesel kentleşme büyük önem taşımaktadır. Dairesel şehirler, su, besinler, kimyasallar, ısı ve hammadde gibi kaynakları azaltma, yeniden kullanma, geri dönüşüm ve geri kazanma faaliyetleriyle sürdürülebilir bir şekilde geri kazanmaktadır.

Bu tezde, atıksudan geri kazanım teknolojisi seçimi, çok kriterli karar verme ile sağlanmaktadır. İlk olarak, kapsamlı bir literatür taramasında olası kriterler ve alternatifler belirlenir. Daha sonra literatürdeki eksik bilgiler ve uzman görüşlerine bağlı olarak bazı kriterler ve alternatifler elenmiştir. Daha sonra kriterler listesi ekonomik, çevresel, teknik ve sosyal kriterler olarak 4 kümede sınıflandırılmıştır.

Çalışmada atıksudan besin geri kazanım teknolojilerini kriterlere göre sıralamak ve en iyi geri kazanım teknolojisini seçmek için bulanık Analitik Hiyerarşi Prosesi, Analitik Ağ Süreci ve İdeal Çözüme Benzerlikle Tercih Düzeni Tekniği yöntemleri kullanılmıştır. Kriterler açısından değerlendirilen alternatifler sürdürülebilirlik indeks değerlerine göre sıralanmıştır. Bulanık AHP ve TOPSIS’de en iyi atıksudan kaynak geri kazanım teknolojisi 4.31 ve 0.54 sürdürülebilirlik indeksi ile membran iken ikinci sırada 2.83 ve 0.39 SI ile air stripping ve 2.65 ve 0.34 SI ile precipitation yer almaktadır. Öte yandan ANP yöntemine göre membran (5.18) birinci sırada yer alırken bunu sırasıyla precipitation (4.55) ve air stripping (4.16) izlemiştir.

Anahtar Kelimeler: Analitik Hiyerarşi Prosesi, Analitik Ağ Prosesi, Atıksu, Döngüsel Şehirler, Kaynak Geri Kazanımı, Sürdürülebilirlik Endeksi.

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LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations</u>	<u>Explanations</u>
<u>and Acronyms</u>	
w'	: Priority number of the factor at the hierarchy level
AHP	: Analytical Hierarchy Process
ANP	: Analytical Network Process
ELECTRE	: Elimination and Choice Translating Reality
EPA	: Environmental Protection Agency
GIS	: Geographic Information System
IWM	: Integrated Water Management
LCA	: Life Cycle Analysis
MCDA	: Multi Criteria Decision Analysis
MCDM	: Multi Criteria Decision Making
MLD	: Minimum Liquid Discharge
PROMETHE	: Preference Ranking Organization Method for Enrichment
Evaluation	
TOPSIS	: Technique for Order Preference by Similarity to Ideal Solution
VIKOR	: Vise Kriterijumska Optimizacija I Kompromisno Resenje
ZLD	: Zero Liquid Discharge

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1. INTRODUCTION

1.1. Aim and Scope

The escalation of climate change and the resulting depletion of crucial resources such as water and raw materials has propelled the adoption of sustainable practices. One of the most promising solutions is the concept of circular cities, which systematically integrate local recycling pathways to curtail resource consumption and ensure their long-term sustainability. Although these ideas are still emerging, they are gaining momentum where the challenge of identifying the most suitable technology for resource recovery remains unresolved.

As wastewater recovery gains popularity, the number of available technologies for resource recovery is increasing and there is a need to establish a decision-making methodology to recover the right resource from waste using appropriate technology. For this purpose, a method that calculates the sustainability index (SI) for resource recovery strategies is proposed in this study. Multi-criteria decision-making methods are a viable method for sustainable development and environmental decision making.

Within the aim of this thesis, an approach was proposed for the sustainability assessment of wastewater resource recovery technologies by using multi criteria decision making (MCDM) methods. The importance and applicability of various MCDM methods for the selection of resource recovery technologies were demonstrated for nutrient recovery within the scope of the thesis. Proposed approach is applied with the fuzzy AHP, ANP and TOPSIS methods, the same criteria and alternatives were analyzed in three different decision support systems and their differences were discussed. The proposed method can serve to guide the adaptation to circular cities while conventional linear wastewater treatment plants (WWTPs) are converted for resource recovery.

1.2. Goals

The direct contribution of the approach that is proposed within the scope of the thesis, when sustainable development is targeted, a special method is presented to the decision makers for the selection and application of recovered technologies for the rapid spread of circular cities. Currently, there is no comprehensive analysis of

recovery technologies by the AHP, ANP and TOPSIS method, taking into account all waste streams. It will be ensured that the concept of the circular city, in which the state, non-governmental organizations and the private sector co-exist, will be moved from a laboratory scale to a larger scale.



2. SUSTAINABLE WATER MANAGEMENT AND CIRCULAR CITIES

2.1. Conceptual Water Management

According to the conventional water management approach, wastewater was treated to protect public health. However, variety in environmental problems such as eutrophication in water resources introduced the goal of nature conservation for wastewater treatment that is achieved by nitrogen and phosphorus removal [Kehrein et al., 2020a]. Thus, according to the conventional system, most wastewater treatment plants focus on final disposal rather than material recovery from sludge [Papa et al., 2017]. In the last few decades, the increase in the demand for resources and the population growth made it inevitable to move sustainable practices. Nowadays wastewater treatment plants are perceived as resource recovery facilities and wastewater is converted into raw material and energy that provides self-sufficient energy generation capacity. Considering the sustainable development goals, wastewater is considered as a valuable resource that can be various products can be obtained from with resource recovery technologies [Chrispim et al., 2020].

Rapid urbanization, climate change, increasing demands from various sectors have made water management more complex for long time. Also, the embracement of sustainability principles in water management has brought new compulsory actions such as wastewater recovery. Therefore, there is a need for wise concepts for water management. In the field of water management, many concepts such as water efficiency, water governance, water security and water footprint have emerged in recent years [Jensen and Nair, 2019]. Overall, integrated water management approaches are shown in Figure 2.1. Water efficiency basically aims to provide more efficient use with less water. In terms of water security, risks for ecosystems are reduced to an acceptable level. Also, water governance consists of very comprehensive terms such as providing recommendations for water policies, ensuring beneficial use, and sharing information among all authorized stakeholders [Julio et al., 2021]. Water footprint contributes to sustainable management with some practices for fair water consumption [F. Liu et al., 2020]. With developing policies and comprehensive studies unconscious use and interpretation of these concepts can be prevented. In sustainable

water management and recovery, the most used approach is Integrated Water Management (IWM) [Candido et al., 2022]. Not only in IWM but also in all conceptual model's aim is to protect water resources in terms of pollution and water budget, it is necessary to reuse, recycle, recover at all stages.

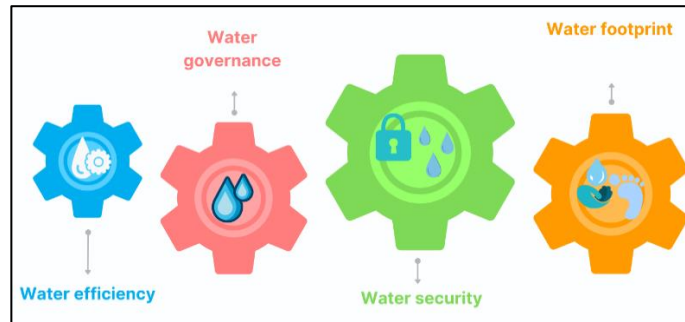


Figure 2.1: Integrated water management approaches.

Although it does not receive as much attention as water management, wastewater management has gone through challenging stages throughout history. Mismanagement of wastewater has caused numerous diseases such as cholera and typhoid through centuries [Brown, 2005]. In many parts of the world, it has been disposed into streets next to residential areas neglecting public health. Wastewater management throughout history can be examined in 5 main periods such as early history, roman period, sanitary dark age, industrial age, and age of stringent environmental standards [Lofrano and Brown, 2010] shown in Figure 2.2.

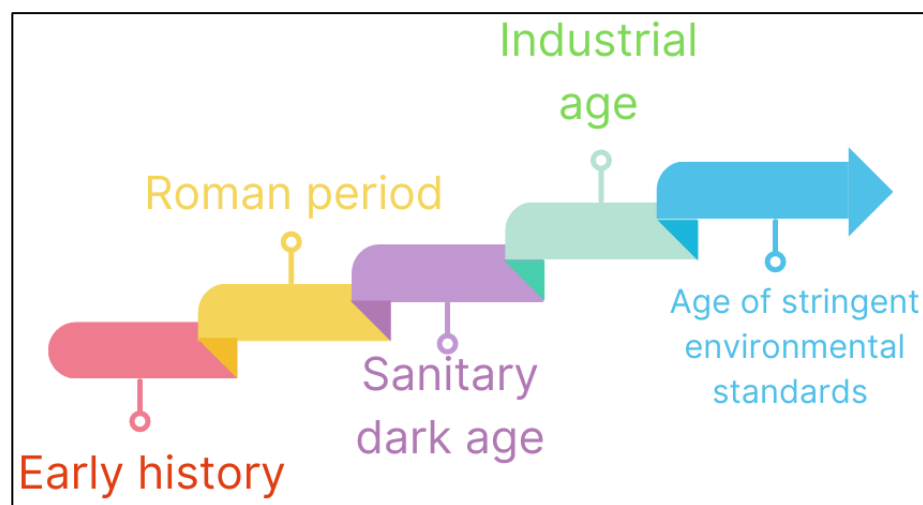


Figure 2.2: Periods of sanitation system through Roman period to present.

The history of humanity dates to 200 thousand years ago. In ancient history, human excrement was managed with holes in the ground. In Mesopotamia, the toilet systems of the houses were connected to the lines leading to the cesspools. However, as the sewage continued to spill onto the streets, asphalt levels were raised. In the Indus civilization, before the wastewater was discharged to the streets, wastewater was transmitted from a reservoir to eliminate solid phase. In Egypt, excrement collected with clay was taken into jars and dumped into the aquatic environment, streets, and pits. Modernization of sanitation dates to Greek civilization. Wastewater and storm water were collected, and wastewater was used in agricultural irrigation. The Romans established the foundation of the sewer system by developing the transmission lines and toilet systems developed by the ancient civilizations. They also collected rainwater as cleaning water in toilets before being reintroduced to the water supply [Lofrano and Brown, 2010].

After the Roman, the sanitary dark age began which would last for about a thousand years. In an unprecedented historical regression, water came to be drawn from rivers and wells and to be discharged without treatment resulting in the spread of disease. In the age of sanitary enlightenment and the industrial age dilution was believed to be the solution for contamination. States discharged wastewater into the river without pre-treatment, not taking into account the assimilation capacity of water bodies [Lofrano and Brown, 2010].

In the Age of stringent environmental standards, pollution has begun to be controlled, pollutants have been measured by various analytical methods, and end-use strategies are developed. However, they were not enough to reach secure wastewater management. Today, it is known that there are millions of people who cannot meet their sanitation needs [Lofrano and Brown, 2010].

In the modern era, instead of discharging the wastewater into the river or the sea without treatment, it is appropriate to finish the sewage system with wastewater treatment plants. The rapid increase in industrialization and urbanization has made the sewage problem even more complicated [Burian et al., 2000].

After rapid urbanization, the first applied treatment process is land treatment. In this system, sewage water was carried to agricultural lands. At that time, it was argued that the use of sewage water on agricultural lands had a fertilizer value. Later, this system was gradually abandoned. Because agricultural lands are decreasing around

growing and developing cities, hygiene standards decrease in lands where wastewater is treated [Tzanakakis et al., 2007].

In the 19th century, physical systems began to purify water by precipitation. Towards the end of the 19th century, chemical treatment was added to the precipitation method. At the end of the 19th century, microorganisms began to be used for organic matter removal [Tilley, 2011].

Among the natural treatment systems, stabilization ponds are the simplest soil-made shallow treatment ponds that are used instead of or in addition to conventional [traditional] treatment processes among wastewater treatment methods. Solids are decomposed by bacteria at the bottom, and suspended solids are decomposed by bacteria in suspension. Nutrients such as nitrogen and phosphorus are removed from the environment [Yıldız et al., 2013].

The activated sludge process was first applied in the early 1900s to treat the wastewater of Manchester, England. Its widespread use dates to the 1940s. The oxidation of ammonia nitrogen and phosphorus removal were solved in the biological activated sludge pool in the 1970s with various configurations [Lofrano and Brown, 2010].

Membrane systems have started a new process in obtaining higher effluent water. With the scarcity of water resources, membranes allow for direct water recovery and not only for the removal of suspended solids, but also for the removal of many bacteria and viruses from the effluent [Lofrano and Brown, 2010].

It is seen in the studies that advanced treatment methods, which provide higher treatment efficiency than the physical, chemical, biological, and advanced treatment methods used in the treatment of wastewater, are frequently used in the treatment of wastewater. Fenton, UV, radiolysis, and microwave with ozone are the advanced oxidation processes [Capodaglio, 2020].

Membranes and nanotechnologies have been developed to tolerate the increasing pollution load of water resources. New strategies have been developed for the reuse and recovery of water. Zero liquid and minimal liquid discharge approaches are the best examples of this. According to the World Water Development Report, nearly half of the world spends part of their lives in water-scarce areas [UNESCO Office Dakar and Regional Bureau for Education in Africa, 2019]. Zero liquid discharge (ZLD) and minimal liquid discharge (MLD) approaches are recommended to protect freshwater

resources and support efficient water management. Although both systems are membrane-based, ZLD also includes thermal processes [Cipolletta et al., 2021]. In the ZLD approach, the water in the closed loop is returned to the system in a closed loop with water minimization steps like source elimination, source reduction or regeneration reuse [Muhammad Yaqub and Lee, 2019]. While the efficiency is about 95% in MLD, it is close to 100% in ZLD [Panagopoulos and Haralambous, 2020]. A new era in water recovery can be started with the emerging technologies in material recovery facilities where water recovery is possible.

2.2. Water Recovery

In the last few years, rapid consumption of resources and water scarcity have emerged as a result of increased industrial activities. While considering wastewater as a valuable resource, water scarcity can be depleted over time. The recovery of treated wastewater in many activities provides significant economic, environmental, and social benefits. Water recovery action varies according to the characterization of the wastewater in building, local, industrial, or large scale [Yang et al., 2020]. In 2007, Communication on Water scarcity and Droughts has published to increase awareness of drought and water scarcity events [Of et al., 2007]. The idea of wastewater as an alternative water source is quite adopted, and national and international regulations are being developed for the beneficial use of wastewater. Also, among the United Nations Sustainability Goals, sixth goal targets a great increase in reusing and recovery of water by 2030 [United nations, 2022]. Overall, approximately 1 billion cubic meters of treated wastewater is used in countries such as Spain, Italy, Greece, Malta, Cyprus, Belgium, Germany, and the United Kingdom for activities like irrigation water, industrial use, and aquifer recharge [Of et al., 2007].

Municipal and industrial scale approaches are the sustainable tools for wastewater recovery. In municipal level, wastewater can be collected and evaluated in separate fractions as yellow, black, brown, and gray [Baykal, 2015]. In addition, rain/storm water is also collected and included in the system with the help of the roof and permeable asphalt [Sprouse et al., 2020]. In efficient resource recovery, it is prominent to collect and process the wastewater and allocate the recovered water to the end users.

Industrial wastewater management can also help reduce water scarcity and rapid consumption of resources. Especially, cooling waters constitutes the largest water demand for industries. Cooling water is widely used in many fields such as oil refineries, metal plants, cooling towers, ash irrigation and waste dilution [Hansen et al., 2018]. Regarding of water management, both municipal wastewater treatment plants and industrial wastewater recovery facilities can be integrated as industrial symbiosis. Appropriate technology selection, design, and infrastructural arrangements for cities can be provided by expert opinions and decision support tools.

While transitioning from conventional systems to green solutions, the existing wastewater network system, the status of the facility, the amount of water, its quality, cost, system configuration and some cultural parameters should be taken into account [Ma et al., 2015]. There are some improvement suggestions for modeling, improvement, management of wastewater and storm water such as instrumentation, control and automation and optimization. For example, GPS-X model is served for optimization of wastewater parameters, achieve discharge limit values and sustainable water services in water resource recovery facilities [Sweeney and Kabouris, 2020].

2.3. Technologies in Water Recovery

The use of available freshwater resources has increased due to industrial activities and rapid urbanization. Sustainable plans have been proposed to solve the problem of accessible clean water. Like European Union countries, Singapore, Israel, Australia, and California practice water reuse, and the commission issued regulation in 2018. Also, wastewater recovery has been seen as an alternative water source and it is supported by national and international strategies [Of et al., 2007]. Wastewater known as renewable resource is brought to use by many resource recovery methods [Diaz-Elsayed et al., 2019a]. Membrane processes, air stripping, precipitation, precipitation, biological and electrochemical process are the emerging technologies for resource recovery from wastewater [Larsen et al., 2021].

Today, most wastewater technologies focus on wastewater treatment rather than wastewater recovery. As shown in Figure 2.3 wastewater can be diverted into domestic, industrial, and agricultural. Heat, PHB, methane, protein and water can be recovered with physical, chemical, and biological based technologies. While nutrient and valuable materials are used in agricultural field and industrial application,

recovered water is suitable for many uses such as drinking water, toilet water, laundry, fire water or irrigation [Ma et al., 2015].

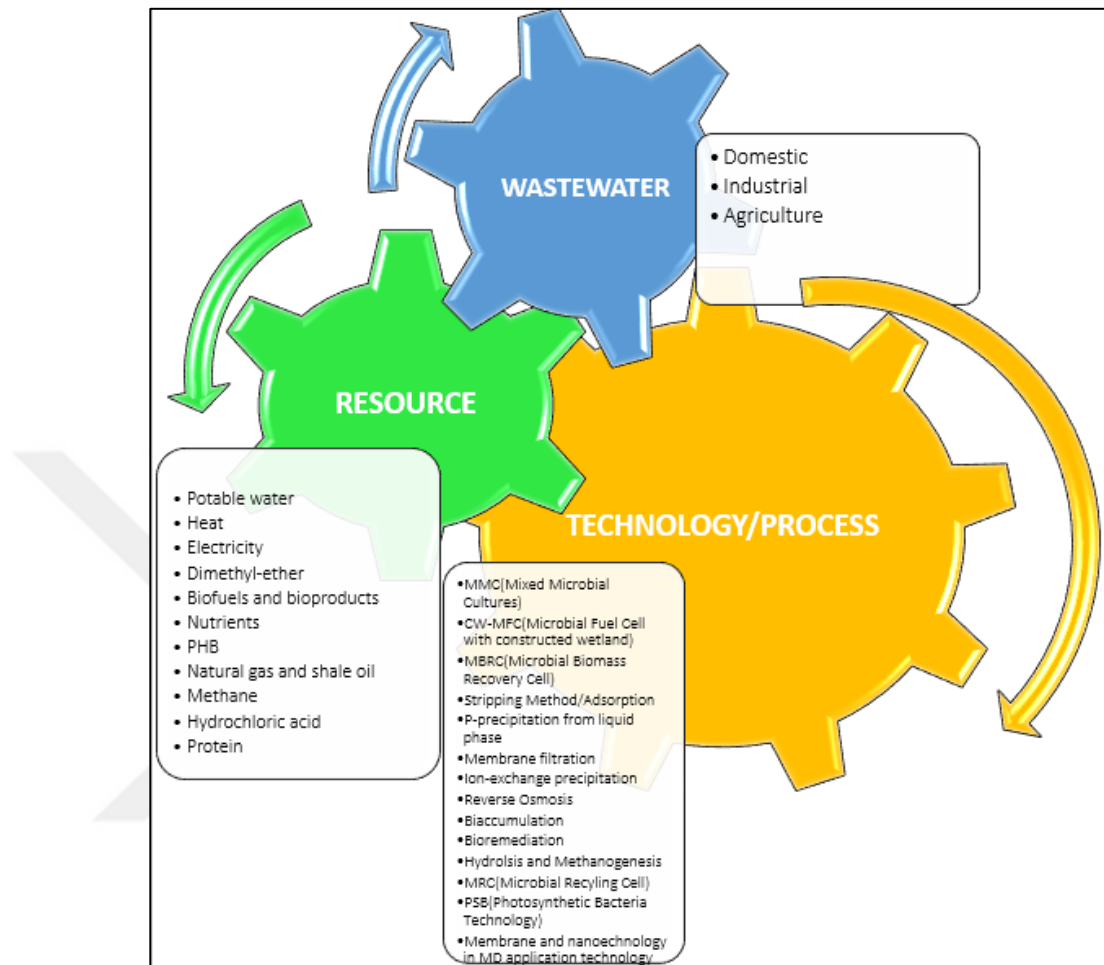


Figure 2.3: Wastewater recovery technologies and potential resources.

Due to the energy potential of wastewater, it is possible for wastewater treatment plants to be energy self-sufficient plants. Anaerobic systems are recommended for energy recovery. Anaerobic membrane bioreactor (AnMBR) is suitable to produce CH_4 from wastewater [Tomei and Angelucci, 2021]. Since microbial electrolysis cells (MECs) and microbial fuel cells (MFCs) technologies in their infancy phase, it is possible to recover energy from wastewater [Mo and Zhang, 2013], Table 2.1 indicates the potential sources can be recovered from wastewater and appropriate technology. In parallel with the wastewater treatment units, recovery technology is tried to be integrated into the existing configuration [Chrispim et al., 2020].

In terms of water recovery, treated water can be used as potable purpose and non-potable purpose such as flushing water. Membrane distillation, reverse osmosis,

nano filtration, and forward osmosis are membrane separation technologies [Xie et al., 2016a]. Working principles and pre-treatment requirements are changed according to process itself. Moreover, evaporation and lyophilisation are the other miscellaneous technologies. There are advantages and disadvantages of each technology. For membrane distillation, evaporation and lyophilisation, energy requirement is the limiting factor [Diaz-Elsayed et al., 2019a].

Material recovery such as P bio fertilizer and polyhydroxyalkanoate from wastewater is possible by biological methods such as microalgae-based wastewater recovery [Lu et al., 2021] and enhanced biological phosphorous removal (EBPR) [Perera et al., 2019]. In addition to biological methods, electrochemical methods are applicable for recovery of some valuable metals. The typical electrochemical methods are electrochemical oxidation, electrochemical reduction, electrocoagulation and electrodialysis [Y. Liu et al., 2021]. Efficient recovery is possible with the integration of two or more technologies, rather than recovery from a single technology.

Table 2.1: Resource recovery technologies and potential resources from wastewater.

Recovered material	Technology	References
Pigments, Single cell protein (SCP)	Purple non-sulfur bacteria (PNSB)	[Lu et al., 2021]
Phosphorous	Precipitation	[Carillo et al.,2020]
Nutrient	Enlarged microbial nutrient recovery cell (EMNRC)	[Sun et al.,2019]
Water	Membrane	[Chang et al.,2019] [Goh et al.,2022]
Nitrogen	Struvite precipitation, Air stripping	[Hoek et al.,2018]
Ammonium, phosphate, volatile fatty acids and water	Microbial desalination cells (MDCs)	[Liu et al.,2020]
Nutrient	Forward osmosis (FO)	[Jafarinejad,2021]
Methane	Microbial fuel cell (MFC)	[Wei et al.,2020]
Nutrient	Electrodialysis (ED)	[Xie et al.,2015]
Metal	Photo-electrochemical, Sono-electrochemical	[Yang et al.,2021]

Overall, integration of water recovery technologies is fundamental in sustainable water management in cities. Since studies are in lab or pilot scale, scaling up operations are essential in all technologies.

2.4. Sustainability

Rapid consumption of natural resources due to population growth and industrialization and climate change are global environmental concerns that lead to authorities contributing to international strategies. As healthy ecosystems and natural environments are essential for the survival of humans and other organisms, the concept of sustainability emerged. It has been integrated into the management of natural resources with global actions in order to ensure the continuity of natural resources such as air, water and soil. The modern use of the concept of sustainability is difficult to define precisely. There are various definitions of this concept which can be applied in many countries in different fields of activity of life.

Environmental Protection Agency (EPA) defines sustainability as leaving productive nature to future generations, creating conditions for survival and well-being [Web 1, 2023]. Sustainability term began with the 1983 United Nations (UN) Commission on Environment and Development, also known as the Brundtland Commission. According to UN Brundtland Commission, sustainability was described as meeting the basic needs of the present, without promoting barriers for future generations in 1987 [Wwap, 2017]. Moreover, the Brundtland report highlighted that environment and development should be considered inseparable. In 1992, Agenda 21 illustrated that sustainability consist of three pillars of economy, society, and environment [Wwap, 2017]. After, United Nations Framework Convention on Climate Change (UNFCCC) is committed to taking action plans to prevent the negative effects of greenhouse gases considering the sustainable development. A framework has been established to reduce the anthropogenic impacts of climate change and improve the lives of populations [IDEP, 2012]. Then, the 2030 Agenda popularized the concept of sustainable development by deriving it from the term sustainability. Historical development of the concept of sustainability is shown in Figure 2.4. Sustainability Development Goals [SDG] designed as a balancing element with 169 targets and 17 Sustainable Development Goals with 3-pillar sustainability [United Nations

Environment Programme, 2015]. Goal 6,7,12,13, 14 and 15 are related with environmental protection and management [United Nations, 2022].

After the embracement of Sustainable Development Goals at international area, waste and wastewater management has evolved to be based on circular economy principles. However, the prominent step in implementing sustainability and its components is seen as the circular economy [Sodiq et al., 2019]. In circular economy, the main goal is not getting value from resource by recycling or reuse but also prevent and reduce the consumption of materials. Therefore, circular economy principles serve well for achieving the SDGs [Joensuu et al., 2020]. Renewable City Projects which offer long-term green solutions with cooperative solution proposals are an example of sustainability in cities. It develops budget-friendly dynamics by providing sustainable products and services by being minimally dependent on external sources in a closed loop [Säumel et al., 2019].

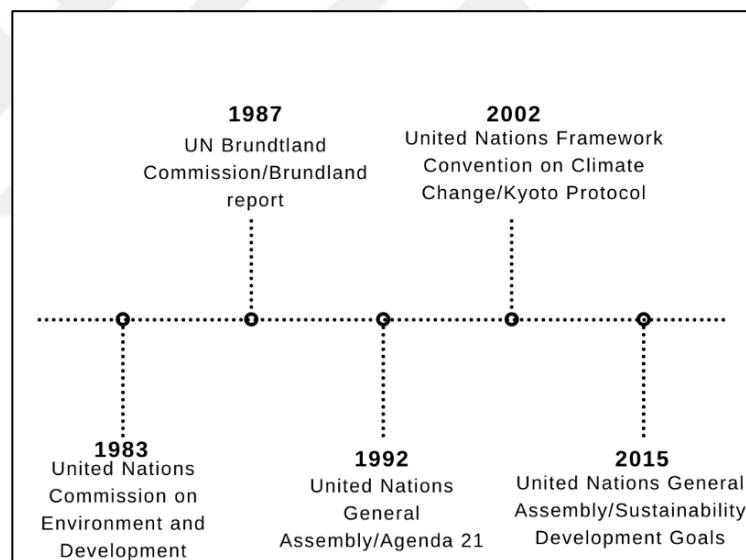


Figure 2.4: Historical development of the concept of sustainability.

2.5. Sustainability Index

Sustainability has been applied by different institutions in the management of various problems with integrated methods. Depending on the subject covered, its content changes. Since sustainability term has arisen in the 1980's, its application on fields such as environment and water management gained popularity after 2015 by

regulations and actions. While the sustainability index used to measure sustainability is based on three basic pillars, these pillars have very complicated components.

In the developing city grid, some practices have been developed to make the water supply sustainable and stable. Global Water Partnership offers practices for water management and encourages cities to implement water efficient technologies [Ma et al., 2015]. In this sense, sustainability of water management practices such as recycling, recovery and reuse in cities is discussed. Sustainability indices are an essential metrics that can be preferred to increase system efficiency and provide a holistic perspective. Comprehensive studies are needed to measure sustainability. Some concepts are being developed to express sustainability [Juwana et al., 2012]. In case where multiple complex ideas cannot be expressed, indicators play an important role in making explanations. Sub-indicators make up indicators, and indicators make up the components. Components come together to form indexes or composite indicators [Giuseppe Munda, 2009],[Juwana et al., 2012].

In order to assist decision makers, the sustainability index is used as an auxiliary element in water management. There are global and regional water sustainability indices. Global water sustainability indexes can be listed Water Poverty Index, Sustainability Index for water resources planning and management, WASH Performance Index, Index of water service quality, Index of Drinking Water Adequacy Equity and Index for water and sanitation. On the other hand, regional water sustainability indexes are Sustainability Index for Integrated Urban Water Management (SIIUWM), Sustainable Water Governance Index, Arab Water Sustainability Index, Sustainable Water Management Index, Water, Sanitation and Hygiene Index and Canadian Water Sustainability Index [Mvongo et al., 2021],[Juwana et al., 2012]. Each index has same goal for measuring sustainability, yet their formulations and application areas can be changed. The Water Poverty Index [WPI] is useful to measure water stress in different levels. The Index of Drinking Water Adequacy [IDWA] is used to monitor performances of countries regarding of water supply potential [Mvongo et al., 2021]. Sustainability Index for water resources planning and management which depends on reliability and resilience of the system is developed for basin management [Sandoval-Solis et al., 2011]. The Equity Index (EI) is composed of Structural Index (SI), Process Index (PI) and Outcome Index (OI) and its purpose is informing public for their water rights [Luh et al., 2013]. The Water,

Sanitation and Hygiene (WASH) Performance Index also similar to EI in terms of representativeness [Mvongo et al., 2021]. Index of water service quality depends on Analytical Hierarch Process and its purpose to compute quality of service. Among the regional water sustainability indexes, Canadian Water Sustainability Index and Arab Water Sustainability Index are country based and specific to region. On the other hand, Sustainability Index for Integrated Urban Water Management (SIUWM), Sustainable Water Governance Index and Sustainable Cities Water Index are more comprehensive and focusing water improvement strategies.

In the management of water resources, the concept of sustainability index which aims to establish the holistic harmony of the system has emerged. Although it is considered a concept, it can be formulated mathematically. Sustainability index is frequently used in multi-criteria group decision making problems [Srdjevic and Srdjevic, 2017]. For example, AHP and Morphological Analysis (MA) are intended to aid in decision making by evaluating manufactured products. Sustainability factors have been evaluated from the design process to the production phase. The highest value was chosen from the final sustainability index values [Hassan et al., 2012]. In circular city approach, the AHP method was used to evaluate possible recovery scenarios in terms of energy sustainability. The regional energy development possibilities of Latvia were evaluated through the sustainability development index [Slišāne et al., 2020].

In addition to energy and product evaluation, the sustainability index is also widely used in terms of water management. Sustainability assessment tools are used in order to balance the integrity and sustainability of water resources at regional and global scales [Juwana et al., 2012], [Mvongo et al., 2021], [Silva et al., 2020], [Srdjevic and Srdjevic, 2017].

In general, in the integrative and systematic approach of recycling, recovery and reuse activities in cities, governments and managements are evaluating all economic, social, environmental, and technical aspects to ensure sustainability. While shifting strategies applying, presenting a final sustainability index is critical in decision-making processes.

2.6. Circular Cities

Today, half of the world's population is oriented towards cities [Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, 2019]. The acceleration of life in cities has brought along problems such as waste generation, infrastructure problems and water managements [Oberascher et al., 2022]. Since linear and traditional urbanization structures may not be sufficient for pressures, circularity is of great importance for the creation of a sustainable environment [Arbolino et al., 2018]. According to the report published by the United Nations, it has been suggested that circular of urban metabolism an accelerating factor for the Sustainable Development Goals of the 2030 Agenda [united nations, 2022]. The circular city concept constitutes a development plan in which all economic, environmental, technological, and social components are evaluated [Prendeville et al., 2018]. According to the New Urban Agenda, circular cities are flexible city structures that can withstand challenges and encourage transformations [Wwap, 2017]. As Figure 2.5 [Horn and Proksch, 2022] shows, there are many frameworks for sustainability, industrial operations, and biological systems in circular cities.

Framework Association	Framework name	Selected for the following CC related qualities
Sustainable development	Sustainability Sustainable Development.	Regenerative
Nexus Perspectives	Food-Water-Energy nexus (FWE) Water-Energy (WE) Energy-Water-Carbon (EWC) Land Carbon (LC).	Symbiotic
Economy	Circular Economy Blue Economy	Circular, symbiotic
Biological systems and Ecosystems	Bioeconomy (BE) Circular Bioeconomy (CBE) Eco-localism	Regenerative Circular
Industrial Systems	Industrial Ecology Industrial Metabolism	Circular, symbiotic
Urban systems	Circular City Urban Ecology	Regenerative Circular

Figure 2.5: Reviewed frameworks for circular city approach in cities.

There are many articles in the literature on circular cities [Babí Almenar et al., 2021, [Williams, 2019]. While some of them dealt with one city only cities de Ferreira and Fuso-Nerini (2019) and Prendeville et al. (2017) examined European countries such as Barcelona, Glasgow, Rotterdam in different urban contexts [de Ferreira and Fuso-Nerini, 2019, [Prendeville et al., 2018]. According to research, the circularity rate of the world is currently only 8.6% [Web 2,2022].

Circular cities generally consist of resource interactions, city dwellers and urban space. In circular cities, resources such as water, nutrients, chemicals, heat, and raw materials can be recovered sustainably through reduction, reuse, recycling, and recovery activities [Skar et al., 2020], [Williams, 2019].

2.7. History of Circular Cities

In terms of environment, problems created by the linear economy, ecology and waste are observed in the simplest form in urban space. The improvement of agricultural structures in the 18th and 19th centuries and the industrial revolution gained momentum after it radically changed the way of production and consumption. As a result of this transformation, agricultural relations have gained functionality on a deeper and different plane in the urban plane [Yalçın and Negiz, 2020]. Today's economic structure is based on a linear economic structure that functions as a take-make-dispose model. In this model, some natural resources such as water, fossil fuels, and mines are taken and processed, and when the life of the product it is transformed into ends up, it becomes waste. With the transition from agricultural production to industrial production at the global level, there has been a jump in resource use. At the beginning of the 21st century, 68 billion tons of materials were used, has used resources 10 times the amount of the past 100 years [Jonas et al., 2014]. Environmental and ecological problems such as global warming, acid rain, soil, sea, and air pollution have reached serious dimensions today. Studies on the sustainable use of natural resources have gained momentum.

The most serious factor affecting resource use in cities has been the industrial revolution. Before the industrial revolution, the population living in rural areas flocked to the cities with the industrial revolution, and the cities became the places of production and consumption. Cities have become the centers of industrial society where capital is centralized and concentrated. In addition, they have turned into basic

places where production and consumption take place with dense population. Cities, where the linear economic approach is concretely constructed, face problems such as infrastructure, unplanned urbanization, environmental problems, inadequate and unhealthy housing that arise in the face of social and economic change. Due to the world's growing population and current economic, political, and social conditions, humanity is currently 1.75 times faster than the ecosystems of our planet can be regenerated. In other words, there is a need for almost a second world in response to production and consumption habits. Although these cities make up only 2% of the Earth's surface; It has a position that consumes 75% of the world's resources and produces 75% of all waste. Again, 60-80% of greenhouse gases occur in cities [Ellen MacArthur Foundation].

2.8. Water Recovery in Circular Cities

Historically, water-based systems played a major role in the main points of the culture and changes of humanity and protected people from disasters. The Romans managed water resources with channels, aqueducts, and waterways, which played a major role in their development. Water is a very important resource not only for its use in homes, but also for ecological continuity. Today, water has become an interdisciplinary concept and has been a significant factor in protecting climate, increasing its life, increasing the use of resources and energy [Carmon and Shamir, 2010]. There is a certain water cycle on the planet we live in. From this point of view, water-sensitive planning and design principles are guiding to recycle water in the cities. When water-sensitive design and planning principles are adopted and implemented, the water cycle in cities in the future is managed and improved. In addition to storm water, gray and black water are also recovered. Internationally, United Nations Water and United Nations Inter-Agency underline the great importance of water management in creating self-sufficient and sustainable cities. In Europe, there are many listed proposals in this context in the informative text of the European Adaptation to Climate Change, and these proposals aim to make cities self-sufficient through water management [Rentizelas et al., 2018].

In cities, water recovery takes place in many ways. Many methods are proposed for the management of rainwater in cities. Permeable pavements, stream buffers, greenways, leach strips, rain gardens and infiltration ditches are green solutions that

combine the city and nature. There are examples around the world where water recovery has been implemented in various configurations. In Germany, wastewater and storm water management is based on a holistic ecological concept. Black water which comprises from urine and feces is conveyed to the central anaerobic digester by vacuum sewage systems, rainwater from roofs and water from confined spaces is collected in small gutters and infiltrated and mixed into groundwater from distribution ditches [Germer, 2009]. In Singapore, used water is reused with the NEWater concept. The Singapore Green Plan 2030, or Green Plan, is a whole nation movement to advance Singapore's national agenda for sustainable development.



3. MULTI CRITERIA DECISION MAKING TECHNIQUES

3.1. Analytic Hierarchy Process

Decision-making methods are a process that provide more effective decision making in complex decision problems in an organized way. Flow of the decision making is comprised from identifying the problem, developing criteria, and defining importance of them, generating alternatives, evaluating alternatives according to expert opinions and deciding [Gabriel et al., 2014]. There can be some considerations while achieving robust decision making. In determining the problem, there must be sufficient awareness [Gabriel et al., 2014]. Multi-criteria decision-making process can be complicated because many criteria including quantitative and qualitative factors may conflict with each other. Various models and software programs may minimize the risks and facilitates decision making. Many decision-making models have been defined and implemented. Depending on purpose, various approaches are available such as Analytical Hierarchy Process (AHP), Analytical Network Process (ANP), Fuzzy AHP, Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE), Elimination et Choix Traduisant la Realité (ELECTRE), Fuzzy TOPSIS, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [Masdari and Khezri, 2021]. Although these methods have methodological similarities, each has advantages and disadvantages. For example, the AHP method is a flexible method that can be preferred to sort and prioritize criteria. Also, the TOPSIS method is a more preferred method in the selection of alternatives. However, it cannot reveal the difference between the two alternative solutions, positive and negative. On the other hand, the VIKOR method calculates the ideal solution ratio by specifying the best- and worst-case scenarios. However, it is complicated to use when there is a conflict situation [Jamwal et al., 2021]. ELECTRE is used to rank alternatives and analyze data in the decision matrix. Also, PROMETHEE is a method for ranking and choosing among various alternatives, even within the complexity and conflicting criteria [Iphar and Alpay, 2019]. Multi criteria decision making analysis (MCDA) allows the social, economic, environmental, and technical criteria to be easily

evaluated and the developed method to be used by many decision-making groups [Hoang and Fogarassy, 2020].

According to Web of Science literature search, AHP is the most commonly used method with approximately 22 thousand studies. AHP was developed by Thomas Saaty in the 1971. AHP is a multi-criteria process and is created by prioritizing and matching alternatives derived under various criteria [Saaty, 2006]. According to Saaty, AHP is comprising of decomposition, comparative judgement, and synthesizing steps [T. L. Saaty, 1990]. In the decomposition phase, a hierarchy is created according to the problem to be decided, and the highest level of the hierarchy is the goal. The criteria are listed one below the other, from general to specific. Then, the criteria are scored according to their impact on aim. After, in the second step since the decision-making process with AHP is basically based on a numerical scale, pairwise comparisons are made to understand the importance of criteria for the decision. The numerical scale ranges from 1 to 9. The number 1 indicates the equality of importance between the two phenomena, while the 9 indicates that one criterion is extremely important than the other [Saaty and Tran, 2007]. In the synthesis of priorities, linear structure is established by weights and priority values to decide an alternative. Final scores are obtained by using the priority weights and scores. Finally, alternatives are ranked according to the ultimate scores.

AHP is common method that is used in various areas such as agriculture, energy, electronics industry, fuel sector, educational institutions, textile, banking, and environmental management [Dos Santos et al., 2019]. Especially in environmental engineering science AHP is an indispensable tool in the field of environmental impact, waste management, sustainable manufacturing, remediation, energy, air quality and water quality management [Mardani et al., 2017].

The AHP method is emerging as a useful and dominant method for solving the full spectrum of multi-criteria problems in smart cities [Milošević et al., 2021]. AHP is integrated with other decision-making tools such as Quality Function Development, meta-heuristics, SWOT analysis, mathematical programming, GIS and Data Envelopment Analysis [Ho and Ma, 2018a]. The integrated application of AHP and GIS program is a very useful support design system in the field of environmental engineering, especially in choosing the appropriate site. For example, it provides options for selection by considering many factors for land selection in agriculture

[Zolfaghary et al., 2021]. In another study, with the integration of AHP and gray relation analysis (GRA), the optimum alternative for zero liquid discharge option in the industry can be selected [Shende et al., 2021]. At the same time, another integration is the sustainability assessment of power plants using AHP and LCA together in Mexico [Bohra and Anvari-Moghaddam, 2021].

The usage of AHP can be proper for the water management in circular cities. Wastewater treatment and infrastructural management requires the consultation of many stakeholders due to its complicated nature that leads to involvement of multi criteria. The length and inadequacy of the decision-making process for water management issues in circular cities is due to the lack of information [Mosleh and Negahban-Azar, 2021]. Fuzzy set theory is used to transform the undefined into meaningful criteria [Fetanat et al., 2021]. While eigenvalue method is used in crisp numbers, lambda-max technique is used for fuzzy numbers to solve AHP [Bohra and Anvari-Moghaddam, 2021]. In general, AHP is comprising of four main steps shown in Figure 3.1.

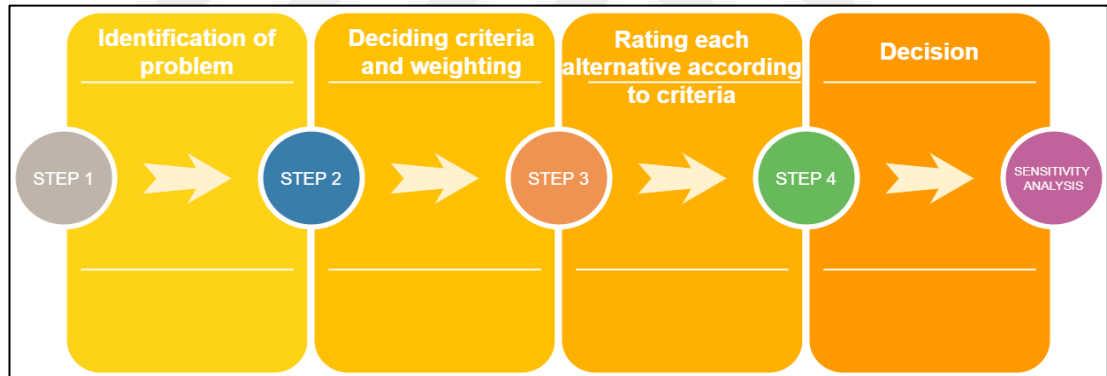


Figure 3.1: Main steps of Analytical Hierarchy Process.

3.1.1. Hierarchy

The decision-making process starts with a problem or purpose. In the next step, the options are determined. The determination of the criteria requires extensive study. The combination of all these forms the hierarchy. Pair wise comparisons are determined after hierarchy is formed [Ishizaka and Labib, 2011].

In general, MCDM methods have common aspects such as alternatives and attributes. The options namely the alternatives are considered limited, they are scanned, and their priorities are sorted. The decision-making problem is linked to many

criteria. Each main criterion can also be divided into several sub-criteria. A hierarchical order can be established for a dozen or more criteria. It is possible to choose criteria that have the same meaning with each other, as well as the selection of criteria that conflict each other. At the stage where the hierarchy is given its final shape, the criteria can be revised and reconstructed. In the hierarchy where numerical and verbal criteria are together, the unit of each criterion is diverse [T. L. Saaty, 2003].

AHP from MCDM techniques includes linked substantive stages. In the first stage, hierarchical order is provided to separate grouping of the defined system elements in a way that facilitates the evaluation. According to the purpose, hierarchically related decision elements emerge. Main decision-making elements are criteria and alternatives [Taherdoost, 2017]. In AHP, elements at each level are considered independently of each other. As problem gets more complex, number of sub elements can be increases. Figure 3.2 indicates the structure of hierarchy.

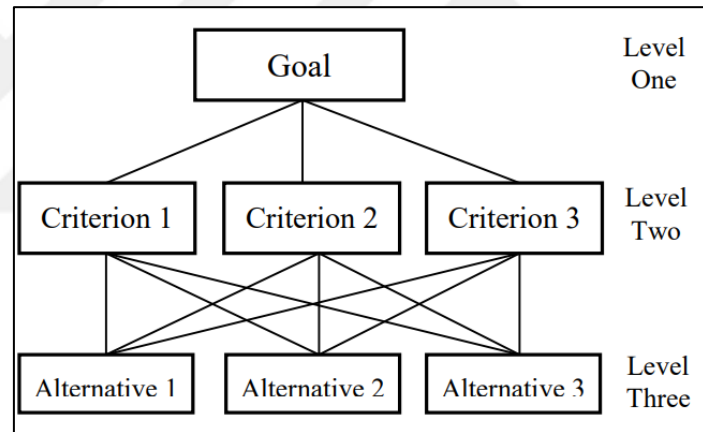


Figure 3.2: Hierarchical structure of decision-making problem.

3.1.2. Comparison Matrix

Comparison matrices are the major component of decision-making step after determining the criteria, matrices are created by placing the criteria on horizontal and vertical columns. In the matrix, a row and a column fall on each criterion. Therefore, all possible combinations of criteria and binary comparisons can be seen in each square matrix [Jagoda et al., 2020]. While making pairwise comparisons, each grid area is scored based on a scale, considering the importance of the criteria. According to the scale, criteria with equal importance are assigned a score of 1, while 9 indicates that one criterion is more important than the other [Ishizaka and Labib, 2011]. While

scoring the matrix, scoring is done for the upper right corner based on the diagonal of the matrix. The lower left corner of the matrix under the diagonal is found by inverting the numbering in the upper right corner. The opposite relationship between the two criteria is found by taking the inverse of the fraction.

When the numbering of the matrix is completed, by using linear algebra equations, weight vectors are created according to the importance weight of each criterion. In the calculation step, first the geometric mean is found. Unlike the arithmetic mean, the geometric mean is value found the multiplication of values [Krejčí and Stoklasa, 2018]. In ordering by weighted vector, the reliability of results depends on consistency of compared data sets [R. W. Saaty, 1987].

The only way to assign meaningful quantities to entities is to compare them with other entities. A scale can be derived from these measurements by making comparisons between elements. In order to make process meaningful, it is necessary to make comparisons according to the purpose. There are two different comparisons, relative and absolute [R. W. Saaty, 1987]. Relative comparison is the comparison of options in pairs according to a common criterion. The process is called pairwise comparison in Analytical Network Process. Especially, in decision problems involving abstract criteria, relative comparison is often necessary to compare criteria. Pairwise comparison is the making of judgments based on knowledge and experience to provide data on the contributions of elements to the criteria [T. L. Saaty, 1990]. Pairwise comparisons performed in the analytical hierarchy process and the analytical network process are represented by a matrix. A pairwise comparison matrix is a square matrix in which values symmetric about the square are inverse of each other with respect to multiplication [T. L. Saaty, 1990]. Dominance is a characteristic that should be taken into account when comparing elements in pairs according to a common feature they have or their contribution to the fulfillment of a criterion. The dominance of an element means that it is more important than the other element and is more preferred. For example, while the dominance of the x_1 element over x_2 is measured by w_1/w_2 , in this case the inverse relation x_2, x_1 is expressed as $1/(w_1/w_2)$. Accordingly, the ideal comparison matrix is shown as shown in Figure 3.3.

$$A = \begin{matrix} & \begin{matrix} x_1 & x_2 & \dots & x_n \end{matrix} \\ \begin{matrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{matrix} & \begin{pmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \dots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & w_n/w_n \end{pmatrix} \end{matrix}$$

Figure 3.3: Comparison matrix.

Decision making involves swapping the weights assigned to judgments with some arithmetic operation. In multi-criteria problems, the type of arithmetic operations applied on the weights is important [T. L. Saaty, 1990]. There are four types of scales such as nominal, ordinal, interval and ratio on which measurements and arithmetic operations can be performed [T. Saaty, 2006]. Nominal scale is a form of measurement generally performed by assigning labels to objects. It is used for the purpose of gaining a certain identity and does not give any preference or order information about the element it represents. Ordinal scale is the scale consisting of the ordering of all the elements of interest with decreasing or increasing numbers. Although the numerical orders give an idea of the quantitative performance of the element, they are not very useful as lack of information about the performance difference between the element above or below. In the interval scale, in addition to the meaning of the first two factors in the measurement process according to the interval, the performance difference between the elements becomes meaningful. On the other hand, the ratio scale is the most used method in terms of measure by means of ratios. Due to their characteristic's ratio scales are the only tool that can be used for modeling decision theories involving dependency [T. L. Saaty, 2003].

In the analytical network process, judgments are made in integer form and rankings are derived on a ratio scale of superiorities. These temporal scales are weighted and converted into scales that are equal in size and quality. These are also used to rank the options. Saaty (1987) put forward a basic scale consisting of numbers that indicate how many times the larger of the two elements is more dominant than the smaller one, according to a common feature or criteria they have when making

comparisons [R. W. Saaty, 1987]. This scale shown in Table 3.1 consists of integers between 1 and 9.

Table 3.1: Basic scale.

Number	Explanation
1	Two elements are of equal importance
3	One element is slightly important than the other element.
5	One element is important than the other
7	One element is more important than the other
9	One element is extremely more important than the other
2,4,6,8	Intermediate values

3.1.3. Fuzzy Inference

The concept of fuzzy logic was first introduced in 1965 by Lotfi A.Zadeh. Fuzzy logic can be defined as a rigid mathematical order established for the expression of uncertainties and working with uncertainties. As it is known, statistics and probability theory work with certainties but real world is mostly full of uncertainties. Therefore, it is necessary to work with uncertainties in order to understand the ability of human beings to draw conclusions [Zadeh, 2008].

The central concept of fuzzy theory is mathematical fuzzy sets. The main difference between fuzzy logic and mathematics is that mathematics in the usual sense allows only extreme values. This is why it is difficult to model and control complex systems using classical mathematical methods, because the data must be complete. Fuzzy logic frees the person from this obligation and provides a more qualitative definition [Zadeh, 1994].

Numerical variable values are displayed graphically with the help of points on a plane, but linguistic values are represented as fields with fuzzy boundaries. Therefore, the event can be more presentative in this way and finds different application areas [Zadeh, 2008]. Kaur and Singh (2019) show that fuzzy logic is used in image processing, robotics, management, agriculture, education, healthcare and software engineering [Kaur and Singh, 2019].

Fuzzy sets are represented by two methods like classical sets. The first is the representation in which the elements are ordered according to the degree of membership, and the other is in the form of mathematically defining the membership functions. The membership function type in fuzzy sets can be triangular, trapezoidal, Gaussian and bell-shaped. For example, if a triangle membership function is expressed with three parameters as a_1 , b and a_2 ; The following formula Equation 3.1 can be applied [Milošević et al., 2021].

$$\mu(x; a_1, b, a_2) = \begin{cases} \text{if } a_1 \leq x \leq b & [x - a_1]/[b - a_1] \\ \text{if } b \leq x \leq a_2 & [a_2 - x]/[a_2 - b] \\ x > a_2 \text{ or if } x < a_1 & 0 \end{cases} \quad (3.1)$$

Fuzzy set operations include union, intersection, complement and difference operations. In the universe U , A and B two fuzzy sets μ_a and μ_b are accepted as membership functions, respectively. In the case of the union of two fuzzy subsets, the highest degree of membership in the clusters to which the item belonging to each cluster belongs is taken [Milošević et al., 2021] (Figure 3.4). The standard combination is shown in Equation 3.2 and Equation 3.3.

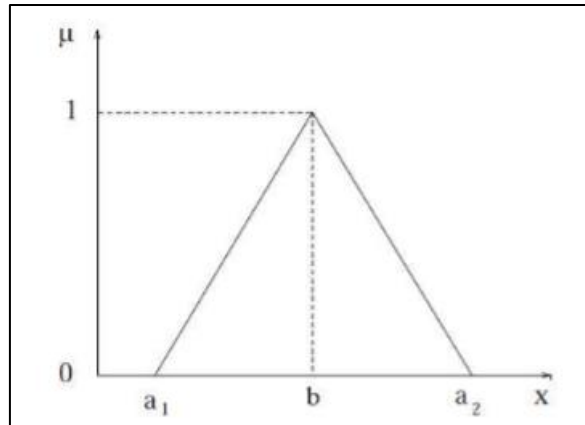


Figure 3.4: Triangle membership function.

$$U[\mu_A(x), \mu_B(x)] = \max[\mu_A(x), \mu_B(x)] \text{ or} \quad (3.2)$$

$$\mu_{A \cup B}(x) = \max[\mu_A(x), \mu_B(x)] \quad (3.3)$$

In the case of the union of two fuzzy subsets, the lowest degree of membership in the clusters to which the item belonging to each cluster belongs is taken. The standard combination is shown in Equation 3.4 and Equation 3.5.

$$I[\mu_A(x), \mu_B(x)] = \min[\mu_A(x), \mu_B(x)] \text{ or} \quad (3.4)$$

$$\mu_{A \cap B}(x) = \min[\mu_A(x), \mu_B(x)] \quad (3.5)$$

To find the complement of a fuzzy set, the membership degrees of the elements of this set must be subtracted from 1 shown in Equation 3.6 and Equation 3.7.

$$C(a) = 1 - a \text{ or} \quad (3.6)$$

$$\mu_{A^c}(x) = 1 - \mu_A(x) \quad (3.7)$$

Fuzzy inference systems are useful mathematical tools used to represent and interpret imprecise and non-numerical information. Since true and false results are represented with 0 and 1 in classic logic, fuzzy logic truth values vary between 0 and 1 on a fuzzy mathematical model [Cavallaro, 2015]. The term of fuzzy logic which was set by scientist Lotfi Zadeh dates back to 1965 [Zadeh, 2008].

The structure of fuzzy inference basically consists of three units. The fuzzy rules, the database containing the participation functions, and the reasoning mechanism applied to evaluate the results. In a fuzzy inference system, even if the input is clear or fuzzy, the output of the system is always a fuzzy set. After the fuzzy inference method, defuzzification is applied to convert the fuzzy units to crisp numbers [Gabriel et al., 2014].

There are different fuzzy methods such as the single input connected fuzzy inference method (SIC method), the simplified fuzzy inference method, the single input rule modules connected type fuzzy inference method (SIRMs method) and the product-sum-gravity method. Methods are used in many decision-making applications. Although simplified fuzzy inference is used to normalize fuzzy sets. It is recommended to use the product-sum-gravity method or the fuzzy singleton-type inference method in solving complex problems [Seki and Mizumoto, 2011]. The fuzzy

logic method is valuable resource that frequently used in decision making problems by integrating human reasoning schemes and automation systems.

3.1.4. Integration of AHP and Fuzzy Inference

Analytical hierarchy process which is one of the multi-criteria decision-making methods has been applied in many steps of decision making with its ease of use, flexibility and simple structure [R. W. Saaty, 1987]. Although its application is not complicated, AHP can be insufficient in solving some problems and has been integrated with other methods. The integration of AHP with many methods has been used to solve problems such as supplier evaluation and selection, business performance assessment and manufacturing process evaluation and selection [Hruška et al., 2014].

AHP can be integrated with fuzzy set theory, DEA, mathematical programming approaches like QFD, quantitative risk assessment (QRA), activity-based costing (ABC), Analytical Network Process (ANP), entropy, GA, GRA, K-means, rough sets theory (RST) and TOPSIS. Among all, its integration with fuzzy set theory allows decision makers to form interval judgments and reveal fuzziness and uncertainty [Ho and Ma, 2018b]. Crisp numbers are used to describe the pairwise comparison of criteria and alternatives in the AHP. However, the crisp values can be converted to fuzzy numbers with the concept of fuzzy set in order to examine the step of evaluating the problem properly. Where criteria cannot be quantified in AHP or are not certain, fuzzy number scales are appropriate to express uncertainty. In the concept of fuzzy AHP which emerges when fuzzy inference set theory and AHP are integrated matrices are formed according to fuzzy numbers [Abdullah and Zulkifli, 2015]. Fuzzy AHP is an efficient method that is applied when there is no data for criteria or when definite class limits cannot be determined for grouping due to uncertainty. Also, fuzzy-AHP is appropriate when the evaluation is affected by many factors due to the complexity of the situation. In fuzzy AHP, the rating scale depends on the linguistic terms for the weights of the decision criteria. Decisions can be any real number between 0 to 10 [Khashei-Siuki et al., 2020]. For example, while the fuzzy number 1 is represented as (1,1,1) in the triangular fuzzy scale, its linguistic language is equally important. On the other hand, the equivalent of 9 fuzzy numbers extremely indicates importance. For example, due to the lack of data on wastewater recovery technology, it is recommended to attribute fuzzy numbers for the installation cost criterion. As the

criteria increase in fuzzy AHP, the matrix size enlarges, and decision making may become complicated. For example, the higher the number of factors in the comparison matrices, the higher the comparison cases [Aydi et al., 2016]. While, a three-factor matrix requires 6 comparisons, a six-factor matrix requires 30 comparisons.

Fuzzy inference can be expressed with the set theory. According to fuzzy logic, the truth value of a set is a real number between (0,1). With fuzzy inference, it can be understood how much it depends on that cluster. In fuzzy logic, linguistic expressions are used, and the decision-making process is given by consulting the ideas of expert people. Rules and membership functions, fuzzification stage, inference block generation and defuzzification block are the four basic parts of the standard fuzzy inference system (FIS) [Jabłoński and Grychowski, 2018]. Fuzzy inference scheme and six steps of fuzzy AHP process is shown in Figure 3.5 and 3.6. Fuzzy inference scheme FIS is widely used in environmental sciences. Table 3.2 indicates the studies about Fuzzy AHP and Fuzzy Inference in various application areas.

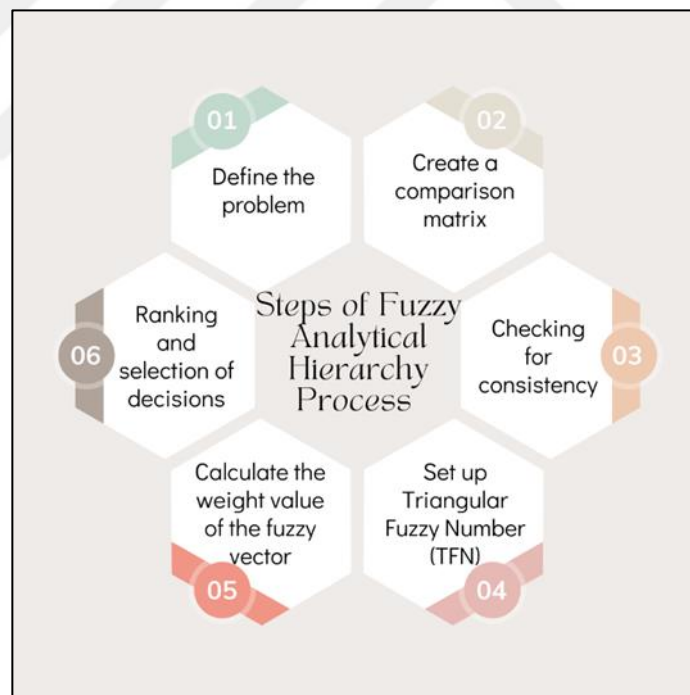


Figure 3.5: Six steps of F-AHP phase process.

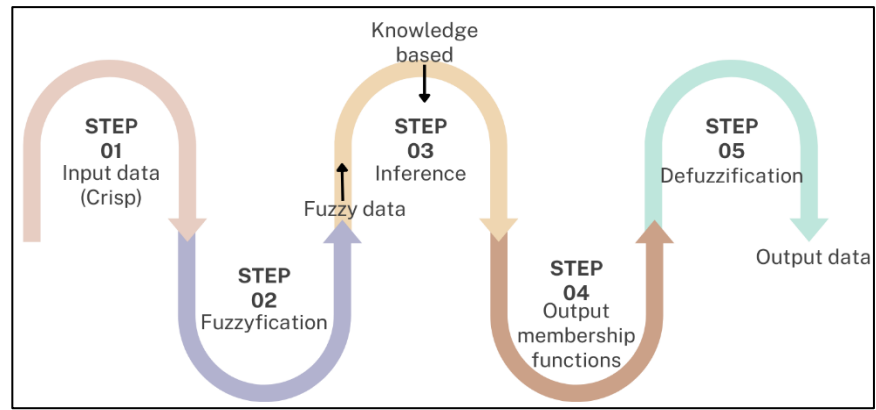


Figure 3.6: Fuzzy inference scheme.

Table 3.2: Application of Fuzzy AHP and Fuzzy inference in different fields.

Method	Subject	Reference
Fuzzy AHP	Landfill site selection, wastewater site selection, green supplier selection, drinking water harvesting	[Aydi et al., 2016], [Donevska et al., 2012], [Khashei-Siuki et al., 2020], [Torabzadeh Khorasani, 2018]
Fuzzy Inference	Indoor environmental quality, energy production from biomass, river water quality, life cycle assessment of renewable energy system, environmental impact assessment of mining area	[Cavallaro, 2015], [Duque et al., 2021], [Jabłoński and Grychowski, 2018], [G. Liu et al., 2012], [Valente et al., 2011]

3.2. Analytic Network Process

Analytic Network Process is one of the most complex decision-making techniques which was created by Thomas Saaty who is also developer of Analytic Hierarchy Process (AHP). ANP needs more information in the model when it is compared by AHP. ANP is a general form of AHP. ANP model is a nonlinear network and the relationship between elements are used in the model. So, dependencies between elements must be obtained to model ANP but there must be enough level of dependencies to implement ANP. Forming cognitive maps is useful as its outputs can be used as input for the dependencies of elements in ANP model [T. L. Saaty, 2004].

Unlike the hierarchical structure, in the analytical network process (ANP) there may be external dependencies between clusters and internal dependencies between the elements of the clusters, so pairwise comparisons should be made by considering these dependencies. As shown in Figure 3.7, the arrow directions show dependency and are from the component influencing the arrow direction to the affected component. In ANP, two comparisons are carried out by comparing all the criteria that arrows arrive at, according to the criteria from which the arrows come out.

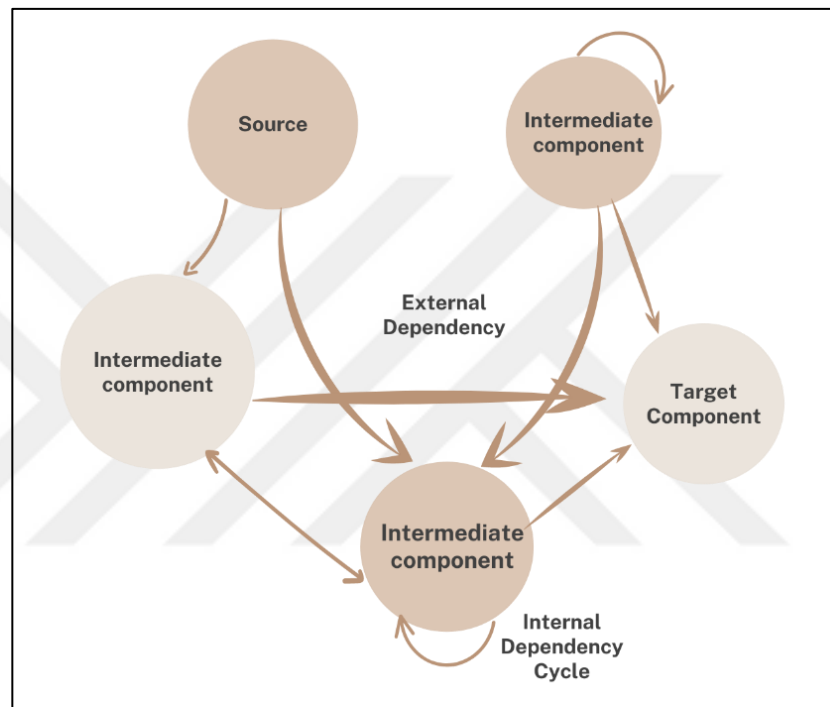


Figure 3.7: Feedback Network.

The analytical network process is a multi-purpose method for decision making in the social and public domain. This method has been developed to take into account all criteria and factors, to define the relationships between them and to make the best decision. ANP allows relationships and feedbacks between criteria [cluster] and sub-criteria (node). Hierarchical definitions are not sufficient when the relationships among the components in a problem are reciprocal rather than unidirectional. In this case, the levels disappear and finding the weights of the components requires the analysis of a more complex process. The Analytical Network Process expresses problems in the form of a layout by describing the relationships between components and their aspects. Thanks to this structure, indirect interactions and feedbacks between

components that are not directly associated are also taken into account [T. L. Saaty, 2006].

3.2.1. ANP Theory

The supermatrix approach is a parallel approach to Markov chains. Relative weights are set with the supermatrix form. Developing this form requires a series of steps for model calculations. First step is making two-way comparisons of controlled factors, second one is creating submatrices with relative weights, other one is adjusting the supermatrix with stochastic columns. Lastly, the weights of the matrix are taken until the weights are constant [T. L. Saaty, 2004].

Considering an n-dimensional matrix A, which obtained as a result of pairwise comparisons as described in AHP.

From equation

$$Aw = nw \quad (3.8)$$

$$(A - nl)w = 0 \quad (3.9)$$

Here n is the eigenvalue and w are the eigenvector. If we take the pth power of the Equation 3.8 It is obtained.

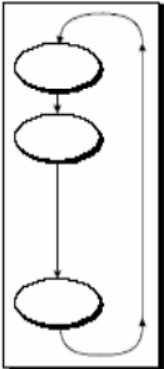
$$A^p w^p = \lambda_{max} w^p \quad (3.10)$$

ANP is based on a structure called supermatrix, which consists of submatrices. Figure 3.8 [T. L. Saaty, 2004] shows the supermatrix of the hierarchy structure.

$$\begin{array}{c}
 \begin{array}{c}
 C_1 \quad C_2 \quad \dots \quad C_N \\
 e_{11} e_{12} \dots e_{1n_1} \quad e_{21} e_{22} \dots e_{2n_2} \quad \dots \quad e_{N1} e_{N2} \dots e_{Nn_N}
 \end{array} \\
 W = \begin{bmatrix}
 e_{11} & & & \\
 e_{12} & W_{11} & W_{12} & \dots & W_{1N} \\
 \vdots & & & & \\
 e_{1n_1} & & & & \\
 e_{21} & W_{21} & W_{22} & \dots & W_{2N} \\
 e_{22} & & & & \\
 \vdots & & & & \\
 e_{2n_2} & & & & \\
 \vdots & & & & \\
 e_{N1} & & & & \\
 e_{N2} & W_{N1} & W_{N2} & \dots & W_{NN} \\
 \vdots & & & & \\
 e_{Nn_N} & & & &
 \end{bmatrix}
 \end{array}$$

Figure 3.8: Hierarchy structure of super matrix.

In Figure 3.9 [T. L. Saaty, 2004], the holarchy structure and the supermatrix of this structure can be seen.



$$\begin{array}{c}
 \begin{array}{c}
 C_1 \quad C_2 \quad \dots \quad C_{N-2} \quad C_{N-1} \quad C_N \\
 e_{11} \dots e_{1n_1} e_{21} \dots e_{2n_2} \quad \dots \quad e_{(N-2)1} \dots e_{(N-2)n_{N-2}} \quad e_{(N-1)1} \dots e_{(N-1)n_{N-1}} \quad e_{N1} \dots e_{Nn_N}
 \end{array} \\
 W = \begin{bmatrix}
 e_{11} & & & & & \\
 \vdots & & & & & \\
 e_{1n_1} & 0 & 0 & \dots & 0 & W_{1,n} \\
 e_{21} & W_{21} & 0 & \dots & 0 & 0 \\
 \vdots & & & & & \\
 e_{2n_2} & 0 & W_{32} & \dots & 0 & 0 \\
 \vdots & & & & & \\
 \vdots & & & & & \\
 e_{N1} & 0 & 0 & \dots & W_{n-1, n-2} & 0 \\
 \vdots & & & & & \\
 e_{Nn_N} & 0 & 0 & \dots & W_{n, n-1} & 0
 \end{bmatrix}
 \end{array}$$

Figure 3.9: The holarchy structure and its supermatrix.

The w_{ij} vectors here are the eigenvalue vectors of the matrices obtained as a result of pairwise comparisons. The resulting matrix is called the unweighted supermatrix. The matrix obtained by dividing each element of this matrix by the column sum is

called a weighted supermatrix. The weighted supermatrix is also stochastic. And by raising the stochastic supermatrix to quite large powers, the limit supermatrix $[\lim_{k \rightarrow \infty} W^k]$ is obtained. All columns of the limit supermatrix are the same and give the weight vector w . The components of the vector give the effect priority weight of each element (sub-criteria) [T. L. Saaty, 2004].

$$\lim_{k \rightarrow \infty} W^k = we^t \quad (3.11)$$

The purpose of raising a pairwise comparison matrix or a supermatrix to powers can be explained by graph theory. According to the theorem, the matrix V (Figure 3.10) [T. L. Saaty, 2003] is the density matrix of a directed graph. According to the theorem, the element of $V^k [i,j]$ is the total density of k -step walks from node i to node j , with the matrix V being the density matrix of a directed graph.

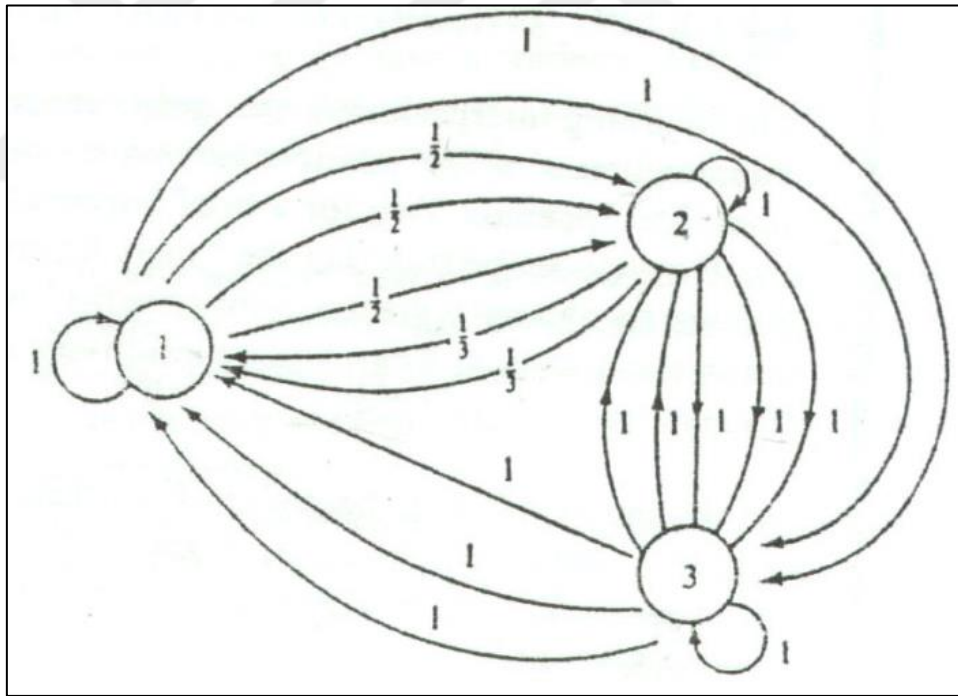


Figure 3.10: Graph structure of the V matrix.

$$V = \begin{bmatrix} 1 & 3/2 & 2 \\ 2/3 & 1 & 3 \\ 3 & 2 & 1 \end{bmatrix} \quad (3.12)$$

Given an example, the elements (node) of the matrix are considered to show the densities from element i to element j. These values are also i from element j are the one-step total densities to the element. The total intensity of the 2-step walks from node 1 to node 3 will be as follows.

$$3[[1/2*1] + [1/2*1] + [1/2*1]]: 1, x_{12}, 2, x_{23}, 3$$

$$2[1*1]: 1, x_{11}, 1, x_{13}, 3$$

$$2[1*1]: 1, x_{13}, 3, x_{33}, 3$$

Their sum will give 17/2. When the V matrix is squared;

$$V^2 = \begin{bmatrix} 8 & 7 & 17/2 \\ 31/3 & 8 & 22/3 \\ 22/3 & 17/2 & 13 \end{bmatrix} \quad (3.13)$$

It will be seen that the value of v_{13} is also 17/2. This example applies to other elements as well. i sub-criteria [node] can affect j sub-criteria (node) directly, or l can affect it indirectly through an intermediate sub-criterion. All l sub-criteria should be considered in indirect influence. The a_{ij} element of the matrix formed by squaring the weighted matrix gives the two-step total densities from i to j. Then, the weighted matrix is cubed to find the three-step total densities between i sub-criteria and m sub-criteria over j sub-criteria. As this process continues, an infinite array of density matrices with W_k [$k= 1,2,\dots,\infty$] is obtained. Since the weighted supermatrix is stochastic, this. It is shown that the limit of the array is present [T. L. Saaty, 2004].

3.2.2. Integration of ANP with TOPSIS

The TOPSIS method was first developed by Hwang and Yoon in 1981 to solve multi-criteria decision-making problems. The TOPSIS method is generally based on the principle that the chosen alternative is the closest to the positive ideal solution and the farthest from the negative ideal solution. The TOPSIS method can also be defined as a technique of ranking preferences by proximity to ideal solutions [Ömürbek et al., 2013].

Analytical Network Process and TOPSIS methods can be used together. The main areas where it is used and sample applications in these areas are given in Table 3.3 below.

Table 3.3: Application of ANP with TOPSIS in different fields.

Meth od	Subject	Reference
ANP with TOPSIS	Facility location selection	[Rathore and Sarmah, 2019]
	Supplier selection	[Supplier Selection and Order Allocation a Main Factor in Supply Chain, 2011]
	RandD Project Selection	[Li, Xuerui, Yu, Suihuai, and Chu, 2018]
	Land evaluation	[Supplier Selection and Order Allocation a Main Factor in Supply Chain, 2011] [Baykara, 2012]

The TOPSIS method is one of the multi-criteria decision-making methods and can be applied directly on the data without a qualitative conversion. By using the method, it is possible to rank the alternative options in line with certain criteria and by evaluating their distance from the ideal solution between the maximum and minimum values that the criteria can take. In the TOPSIS method, the alternative chosen by the decision maker is the closest to the ideal result and the farthest from the negative-ideal result. The TOPSIS method assumes that each criterion has a uniformly increasing or decreasing utility trend. Therefore, it is easy to identify ideal and negative-ideal solutions [Alpay, 2010]. Integration of ANP with TOPSIS method is indicated in Figure 3.11 [Guerrero-Liquet et al., 2018].

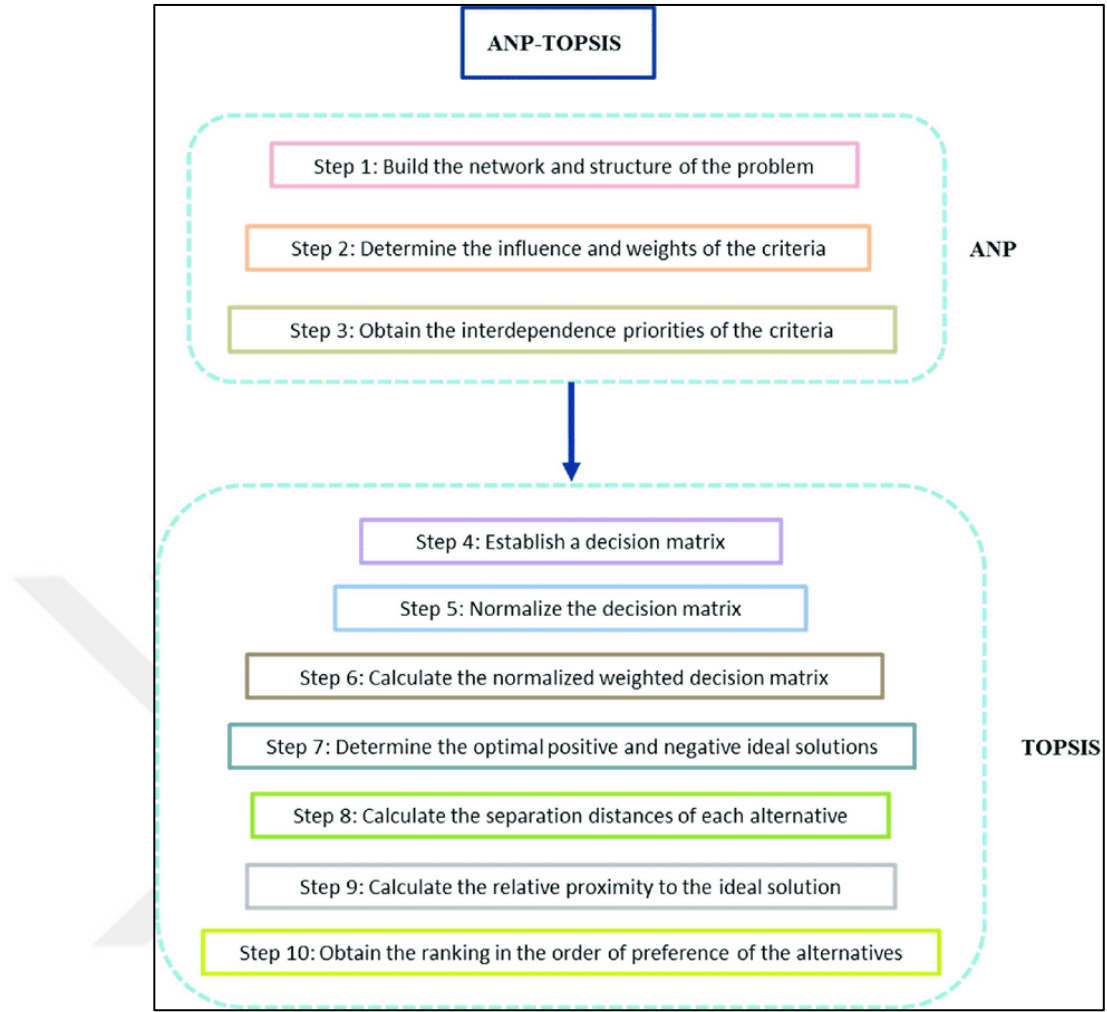


Figure 3.11: Implementation of ANP and TOPSIS method in steps.

3.3. Super Decisions

The Super Decisions program is a free program developed for the practical application of AHP and ANP, created by Thomas Saaty. The development and maintenance portion of the program is supported by the Creative Decisions Foundation. This institution was founded in 1996 by Saaty and his wife Rozann Whitaker Saaty. The foundation aims to support and educate decision makers [Web 3, 2023]. In this section, it will be given information about the introduction of a simple network structure to the program, how to create a step-by-step network model, how to create relationships, how to make pairwise comparisons and how to obtain results.

Firstly, when the Super Decisions program is opened, all clusters are defined one by one by selecting Design-Cluster-New. Cluster names are given as A..., B... and C..

because the program is in alphabetical order. When the cluster entry is finished, Cancel is pressed. Then the clusters are dragged and dropped to different places, making them all visible.

To enter the node [criterion] into the clusters, the right mouse button is pressed while on that cluster, and the create node in cluster is selected in the menu that comes up. The criteria [node] under that cluster are entered as A1, A2, A3, In order to make the nodes visible, the cluster is expanded by holding the lower-right corner and then the organized node is selected in the menu that comes up by pressing the right button on the cluster. Then, starting from A1, the relations are transferred to the software, for this, press the right button while on the node that represents the criterion. Node connections from is selected in the menu that comes up. In the window that appears, all the criteria marked in the column of the relevant criterion in the "relationship matrix" are selected one by one.

Lastly, it should be checked whether the model is suitable for the network. Computations-Limit Matrix-Text is selected from the menu. The matrix that appears will be the limit matrix, reflecting what would happen if all pairwise comparison responses were 1. The fact that the number in a row is the same throughout the entire row and this situation is valid in all rows indicates that the matrix converges, and the model is suitable for the network.

4. PROPOSED METHOD

In this thesis, the sustainability index approach for wastewater recovery technologies is explained in detail in Chapter 4. The proposed approach is based on AHP, and the calculation steps are combined with fuzzy logic. The AHP provides a systematic analysis of the various criteria for technology selection. Fuzzy logic calculations can reflect the uncertainties about the subject to the calculations by using score ranges. Moreover, it enables to solve complex problems by using expert opinions.

4.1. Resource Recovery Plan

The proposed approach starts with the resource recovery plan, where the necessary data are collected, continues with the scoring of the criteria for technology selection, and ends with the final factor index calculation via fuzzy inference (Figure 4.1).

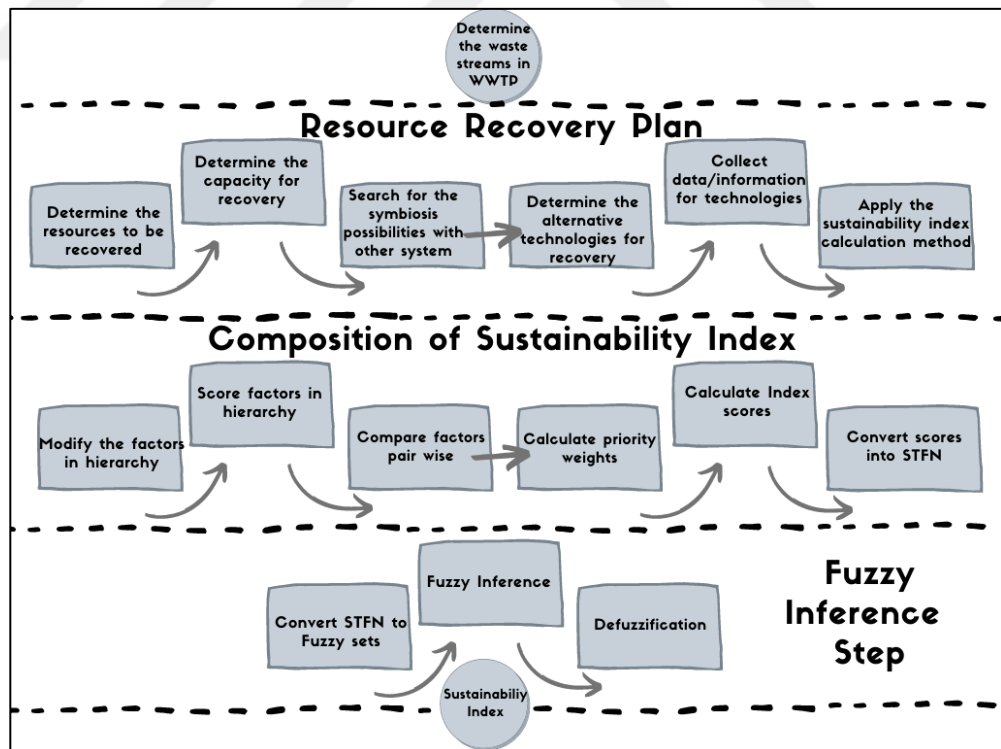


Figure 4.1: Proposed method for sustainability index for recovery technologies.

Since the subject of this thesis is wastewater recovery technologies, extensive research has been carried out in the literature on wastewater recovery. After the research, potential resource recovery streams, technologies and recovered products were determined and classified systematically. The sustainability index calculation is exemplified by integrating it into a region. The risk assessment study was evaluated across the region.

4.2. Composition of Sustainability Index

According to the principles of the Analytical Hierarchy Process, in the first stage, the factors necessary for the realization of the purpose to be analyzed should be determined and these factors should be placed in a certain logic hierarchy. At the first level in the hierarchy, analysis has purpose. After the first level, the criteria are diversified by descending to a lower level in line with the purpose. In this thesis, after the purpose of the thesis was clearly defined, the relevant factors were placed in a hierarchy in this logical framework.

4.3. Modify the factors in hierarchy

In this thesis, the sustainability method is presented for wastewater recovery plan. Decision makers can add or delete any criterion the method according to their own case studies.

The first step is to create the hierarchy. This step also be used in areas such as energy and waste management in circular cities. Sustainability can be divided into technical, economic, environmental, and social criteria (Figure 4.2).

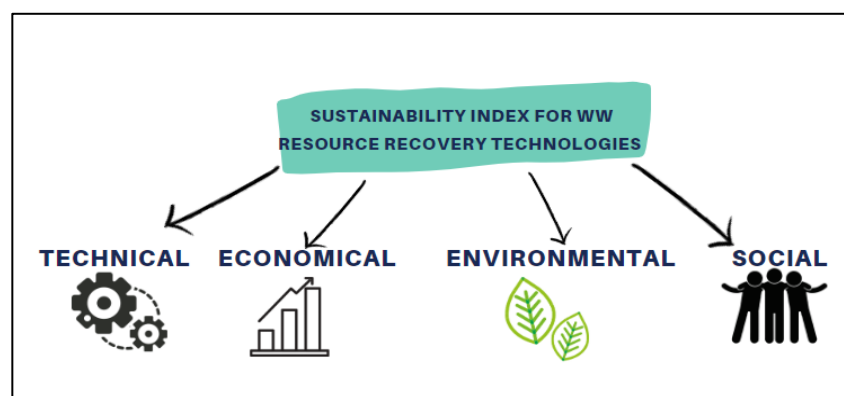


Figure 4.2: First level of the hierarchy for sustainability index.

The sustainability index is used to design more efficient, innovative and hybrid systems for circular cities. The different sustainability index values obtained in this study can be compared with sustainable decisions such as which resources can be recovered and which technologies are possible.

4.3.1. Technical

It is important to consider technical criteria in sustainability. Technical criteria can be examined under headings such as applicability, reliability, capacity of plant, system complexity, waste generation, time limitation, land requirement and quality of the recovered material (Figure 4.3).

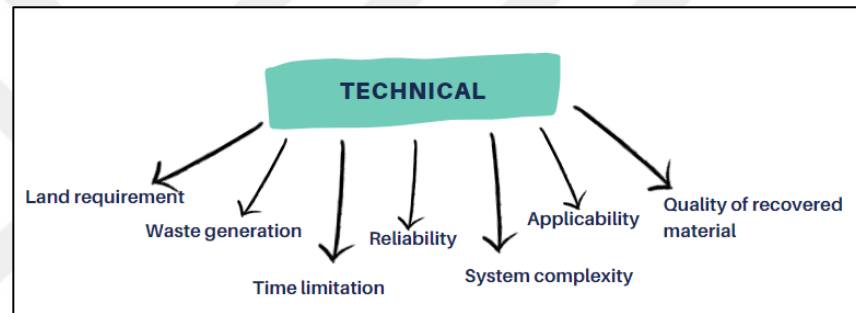


Figure 4.3: Technical criteria for sustainability index of wastewater recovery technology.

The land requirement for the application of resource recovery technology is one of the sustainability criteria as limited space is a problem for businesses or institutions [Kerstens et al., 2015]. The compactness of the system has recently been evaluated within the scope of innovative technology development studies [Chang et al., 2019]. Wastewater is an important factor in the selection of recovery processes as it must be considered as a continuous resource for recovery [ElMekawy et al., 2015]. An important element in the technical part is the capacity of the resource recovery plant. In this sense, the flow or amount of the source coming to the wastewater stream is very important. In particular, the production ranges and the production capacity of the technology are decisive criteria. Time has always been a critical criterion in every process. State-of-the-art development studies aim to perform the right operation as soon as possible [Chaterjee et al., 2019]. Reliability is an important criterion especially for domestic use of treated wastewater. Since converting pilot and laboratory scale

systems to real systems requires great effort, the system must be realistic to be developed. Reliability in water recycling systems is related to the dynamics of the system, the city's infrastructure system and its cost [Lodge et al., 2004]. The new system, which requires qualified people and complexity as well as its applicability, is decisive in the decision support system. The situation becomes more complicated as the parameter to be monitored in the system increases. First, it is very important that the chosen technology is applicable. This criterion guides decision makers to an appropriate alternative for their situation in resource recovery. The scaling range of recovery technology can be an indicator of applicability. Recovery technologies can be demonstrated in the literature if they have full-scale applications [Perera et al., 2019].

The quality of recovered materials is a critical criterion as it must meet customers' needs. The recovered products can be used for various types of industrial production where different quality requirements may be required [Alemayehu et al., 2020],[Ghosh Ray and Ghangrekar, 2015],[Lu et al., 2019],[Nenov et al., 2020],[Xie et al., 2016b]. Considering resource recovery options, recovered material is potential to be alternative for energy supply. Bioenergy production is developing rapidly through the utilization of algal biomass from various wastewater streams [Bhatia et al., 2021],[Chia et al., 2020]. Waste heat can be recovered to produce electricity [Bamigbetan et al., 2019],[Bolognesi et al., 2021].

4.3.2. Economic

In addition to operation, installation, maintenance and investment costs, natural input requirement, waste cost and revenue are also economically important factors (Figure 4.4).

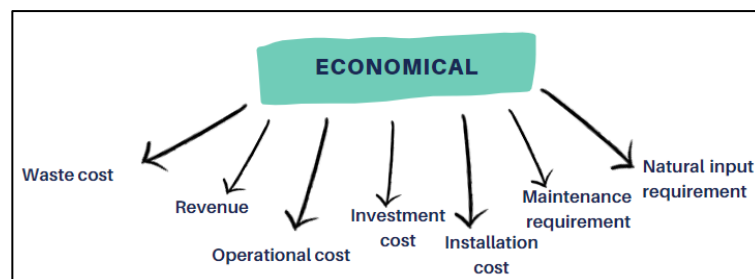


Figure 4.4: Economic criteria for sustainability index of wastewater recovery technology.

Operating and initial investment costs are bonded to each other. While innovative technology may seem inconvenient in the short term for applying the technologies, it can be beneficial when considered together with the operating cost such as ammonium stripping for nutrient recovery [Robles et al., 2020a]. State-art resource recovery technologies can procure low operating costs with advanced functions such as Hydrothermal Liquefaction applied to municipal wastewater sludge [Gu et al., 2019]. It is estimated that by eliminating 3.46 billion USD/year in total disposal liability, the operating cost of biosolids disposal is reduced by 1.43 Billion USD/year compared to current practice [Seiple et al., 2020].

In order to extend the life of the process materials and obtain more efficient results, the maintenance cost must be considered. Designing biogas and wastewater treatment systems with a sustainable approach reduces the maintenance cost [Tilmans et al., 2014]. Natural resources such as water and energy that are needed for production are considered as natural input requirements. It is a system in which sustainable and green energy use is preferred. The market value and unit price of the recovered product show its economic contribution to the system. For instance, the market value of ammonium sulfate recovered from wastewater is 230 euro per ton, while the market value of white phosphorus is 1900 euro and struvite are 480 euro per ton [Campos et al., 2019]. In terms of economic benefit, apart from energy recovery from anaerobic digesters, organic and mineral rich fertilizers and by-products can be recovered and exported [Campos et al., 2019],[Delvigne et al., 2015],[Mehta et al., 2015],[Patel et al., 2020a],[van der Hoek et al., 2018]. The factors that determine the waste cost are the amount of waste and its characterization. Wastes can be disposed of inside as well as outside the facility. In this case, transport cost should also be considered for the supply of the necessary chemicals and waste disposal. The use of the recovered wastewater sludge in the construction activities within the facility minimizes the transportation waste cost [Patel et al., 2020a].

The equipment to be used during the installation of the facility constitutes an important item of the installation cost. Data such as the number of reinforced concrete structures in the facility, the amount of valves and pipes affect the installation cost according to the complexity of the system. Considering modular systems such as membrane, adapting compact systems to the field will be more practical. Chemical usage takes place depending on the stability of the process and the amount of product

recovered. Some problems such as scaling and fouling [Ansari et al., 2017] may be encountered in processes that take place in the recovery of phosphorus from wastewater [Campos et al., 2019].

4.3.3. Environmental

The environmental elements used in the thesis are taken from the sub-criteria used in the Life Cycle Assessment (LCA) studies which are widely used in circularity assessments. There are many LCA studies [Ding et al., 2021],[Hao et al., 2019a],[Lam et al., 2020] investigating the contribution of the products obtained from wastewater to the soil application and beneficial use of sustainability. Environmental criteria can be examined under the following headings: air, water and soil pollution, ecological risk, environmental impact, thermal pollution, and aquifer preservation (Figure 4.5).

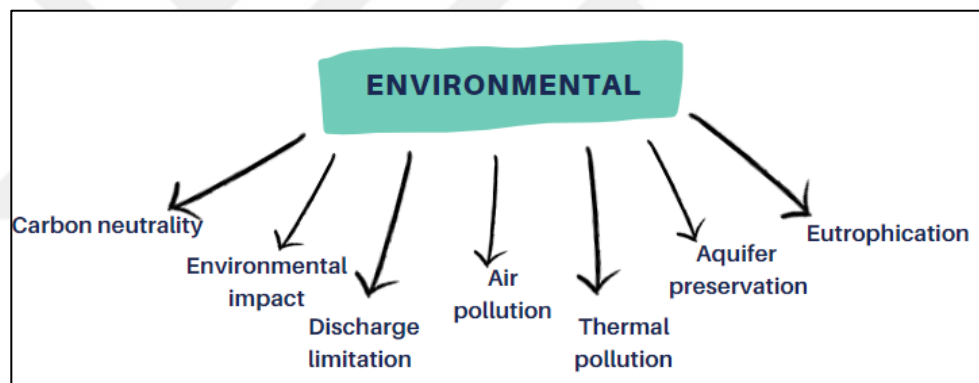


Figure 4.5. Environmental criteria for sustainability index of wastewater recovery technology.

Although there are no discharge limitation sub-criteria in LCA, it provides information about the risks of technology that may pose a threat to the environment and water resources. Likewise, the water supply criterion is not a qualification used in LCA studies. It is a criterion used to determine and evaluate the useful water use depending on the water consumption of the technology. Although studies have been carried out to protect water resources within the scope of LCA studies, there are no criteria for aquifer pollution. Special efforts should be made to protect aquifers, like other water sources.

Air pollution may occur due to carbon dioxide, sulfur dioxide, hydrochloric acid and particulate matter emissions in waste-to-energy plants such as incineration,

gasification and pyrolysis [Shareefdeen and Mishu, 2021]. Although maximum efficiency is aimed during recovery, toxic pollutants such as heavy metals, organic micro-pollutants and pathogens must be removed with high efficiency, considering ecological risks [Egle et al., 2016]. Eutrophication, which negatively affects the fate of the ecosystem, is a problem that must be prevented. The fact that the waste heat generated as a result of the energy recovery processes in the wastewater treatment plants is not balanced before the discharge causes the threat of thermal pollution [Hao et al., 2019b]. In the environmental pollution criterion, in addition to water and air pollution, the possible impact of recovery technology on soil and groundwater is examined. In addition, concepts such as energy balancing and carbon neutrality are presented for sustainable product recovery from the wastewater stream [Barry et al., 2019]. Some wastewater treatment plants today are required to comply with required discharge standards and are able to recover a resource while adhering to a reduced carbon footprint [Delvigne et al., 2015]. As a result of the fuel and electrical energy used during the recovery of energy, food, water and valuable materials, greenhouse gas emissions may increase depending on the size of the facility [Diaz-Elsayed et al., 2019b].

4.3.4. Social

Social aspects are accepted as basic criteria for sustainability. Social criteria such as social benefit, the creation of direct and indirect jobs, the increase in health and well-being, and even the aesthetic evaluation of the situation are the criteria that allow the selection of technology in a human-centered manner (Figure 4.6).

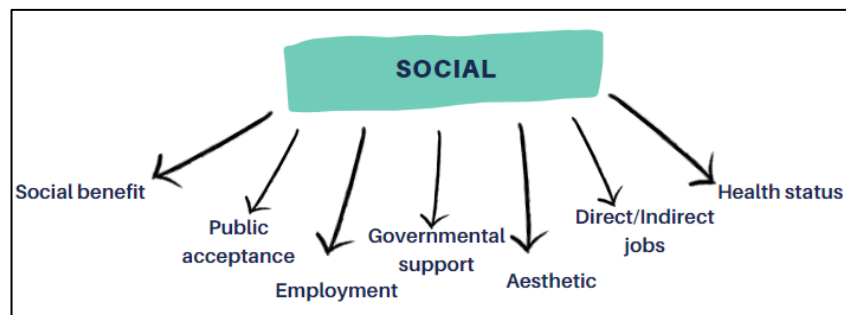


Figure 4.6: Social criteria for sustainability index of wastewater recovery technology.

Social aspects are often overlooked or weakly revealed in the literature. It is socially important to reintroduce waste into society as a product through certain processes. The collection of used oil wastes for recovery is seen as the responsibility of the state for the benefit of society. Recovery technologies affect the general condition of cities, and it takes time for the public to accept these technologies and use the recovered products. For instance, waste-to-energy plants are large-scale projects and rely on generating energy from solid waste. Social acceptability is a matter of debate. To increase the social acceptability of recovery technologies, electrical energy and heat generated in WTE systems can be distributed to residential areas by local industry and the community [Chong et al., 2016]. Also, incineration to generate energy for municipal solid waste is promoted by the government in many countries. Investors who are experienced in financing in the private sector have started to play a role in this sector [Hrabec et al., 2020]. In order to improve the quality of life of the people, social support should be provided in addition to environmental measures and incentives. In addition to government, social organizations also have a stake in waste and wastewater management and resource recovery in circular cities [Šomplák et al., 2019].

The aesthetic appearance of the facilities to be established is important for the society. Parameters such as the size or shape of the reactors are the criteria taken into account when designing. However, the smaller reactor designed while maintaining an aesthetically pleasing appearance increases the need for sludge collection and processing [Kamali et al., 2019]. The cultural and educational contribution of recovery technology should not be ignored in the transformation of wastewater into valuable products in systems where circularity provides social benefits. The factors of education and culture cannot be denied in the adaptation of future generations to their social awareness and cultural accumulation. In addition to the social and economic benefits of recovery technologies, they have a great impact on public health. City plans and improvement infrastructure systems need to be designed in a way that causes the least harm to the public. Waste-to-energy recovery investment provides new business opportunities for the green industry. Direct or indirect job opportunities depend on facility capacity, process complexity, and level of automation in the waste management process [Sweeney and Kabouris, 2020]. In another study, it was found

that the increase in job opportunities and employment, which is defined as a social indicator, contributes to social benefit [Tonini et al., 2020].

4.4. Score factors in hierarchy

The scoring step is done to measure the contribution of each criterion to sustainability. FI is determined by the lowest level risk factors in the hierarchy. Scoring is done by taking expert opinions. Although studies on wastewater recovery technologies are accelerating, fuzzy scale has been preferred in order to tolerate uncertainty due to the lack of literature on this subject. The expert group can assign scores in clear, fuzzy or linguistic terms transferred to a standardized trapezoidal fuzzy number (STFN). Table 4.1 shows five language variants for expressing FI. Points are awarded from “Very Low” to “Very High” according to their degree of contribution to sustainability.

Table 4.1: Scales of scores to be given to the sub-factors in the hierarchy and explanations of Factor Index (FI) and its components.

Definition of FI	Explanation	FI Fuzzy Number
very low (VL)	exactly no contribution to sustainability index	(0.0,0.0,2.5)
low (L)	no contribution to sustainability index	(0.0,2.5,5.0)
medium (M)	no critical contribution to sustainability index	(2.5,5.0,7.5)
high (H)	significant contribution to sustainability index	(5.0,7.5,10.0)
very high (VH)	very high contribution to sustainability index	(7.5,10.0,10.0)
Definition of SI	Explanation	SI Fuzzy Number
low (L)	not sustainable	(0.0,0.0,1.0,3.0)
medium (M)	not sustainable unless measures are taken	(1.0,3.0,4.0,6.0)
high (H)	sustainable	(4.0,6.0,7.0,9.0)
very high (VH)	very supportive in terms of sustainability	(7.0,9.0,10.0,10.0)

4.5. Compare factors pairwise

After scoring the factors according to each technology, all factors at the same level in the hierarchy are compared according to their importance for the sustainability index. In the matrix, each row is compared with the columns of a matrix. Factors are compared in pairs according to their importance using the (1-9) scale as described in Section 3.1.2. Odd numbers between 1 and 9 on the Chang's scale represent significant increase, while even numbers 2 through 8 indicate median comparisons. All hierarchy levels scored according to their importance levels by creating binary matrices. All evaluations are converted to trapezoidal fuzzy numbers to ensure the standard and clarified to calculate weight scores. Comparison matrices are shown with clarified numbers rather than the trapezoidal fuzzy numbers.

Shown in the Figure 4.7 a_{ij} is the pure score representing the numerical value obtained as a result of the comparison of F_i and F_j .

$$a_{ij} = 1, a_{ji} = \frac{1}{a_{ij}} \quad (4.1)$$

$$A = \begin{matrix} & \begin{matrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{matrix} & \begin{pmatrix} F_1 & F_2 & \dots & F_n \\ 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \dots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{pmatrix} \end{matrix}$$

Figure 4.7: Comparison matrix example.

4.6. Calculate priority weights

Fuzzy Analytical Hierarchy Process (F-AHP) mainly consists of six steps. First step is determination of the problem, after using known data comparison matrixes are developed. To indicate pairwise comparisons below equations are used. Where n

indicates the number of criteria, w_i is the weight of the i criterion, and a_{ij} represents the ratio of the weight of the i criterion and j .

$$w_i = \frac{i}{n} \sum_{j=1}^n \frac{a_{ij}}{\sum_{k=1}^n a_{kj}} \quad i, j = 1, 2, \dots, n \quad (4.2)$$

$$a_{ij} = \frac{w_i}{w_j}, \quad i, j = 1, 2, \dots, n \quad (4.3)$$

In Equation 4.2 w_i represents the priority weight of i th factor in its own level. Also, a_{ij} is the defuzzied comparison score of i th factor. w_i' , modified priority weight, shows the priority weight of i in the whole hierarchy.

$$w_i' = w_i \times \prod_{i=1}^t w^{(i)} \text{ section} \quad (4.4)$$

The arithmetic mean method given in Equation 4.3 is used to calculate the priority weights of the factors in the comparison matrix. a_{ij} is a fuzzy form of score given for the comparison of F_i and F_j factors at the same level as n factors. If the total STFNI is shown as $a_{ij} = [a_{lij}, a_{mij}, a_{nij}, a_{uij}]$, the net value of a_{ij} can be calculated using Equation 4.4.

Where W_i is the weight of F_i at its own level, the w given in Equation X represents the weight of F_i in the hierarchy. $w[i]_{\text{section}}$ indicates the priority weight of i .

4.7. Calculate index score

FI is obtained in regard to Equation 4.5 below, by multiplying the score of the factors, P_i , with the n represents the number of bottom level of hierarchy.

$$FI = \sum_{i=1}^n P_i^* \times w_i' \quad i = 1, 2, \dots, n \quad (4.5)$$

4.8. Convert scores into STFNN

Since the scores for the FI measure and pairwise comparisons are in different formats, it is necessary to convert them to a common form before calculations. The standard trapezoidal fuzzy numbers [Zeng et al.,2007] are also used. The trapezoidal membership function can be expressed as $A = [a_l, a_m, a_n, a_u]$. The fuzzy numbers are converted into STFNN as $a_l = a_m$ and $a_n = a_u$. Factor index scale is shown in Figure 4.8.

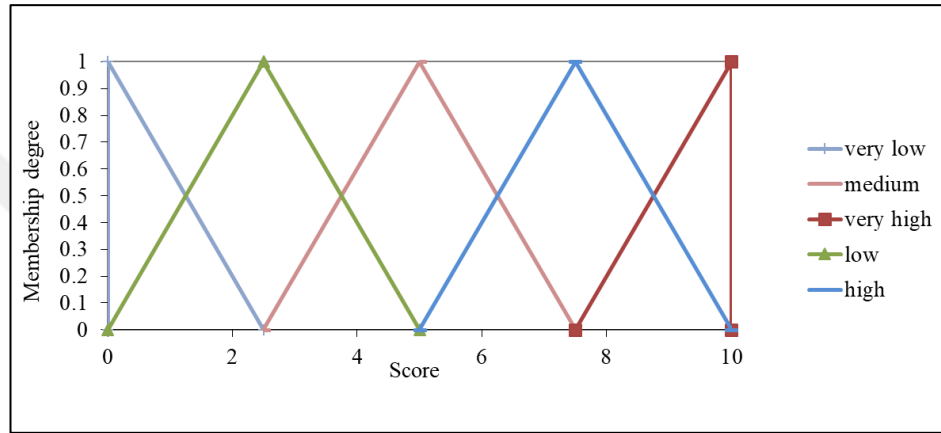


Figure 4.8: Factor index scale.

4.9. Fuzzy Inference Step

Fuzzy inference is applied as it is described in [Topuz et al., 2011]. The difference is that this study includes 4 main criteria that will be combined to create an SI. FI for technologic, economic, environmental, and social aspects are transformed to fuzzy sets. For the purpose, FI is plotted for each dimension according to the scale given in Table 4.1. The intersection points give the fuzzy sets containing the class and membership degree for the FI. Then the SI is found by combining the technological, economic, environmental, and social aspects using the fuzzy SI scale in Figure 4.9. Fuzzy inference is done by following Equation 4.6.

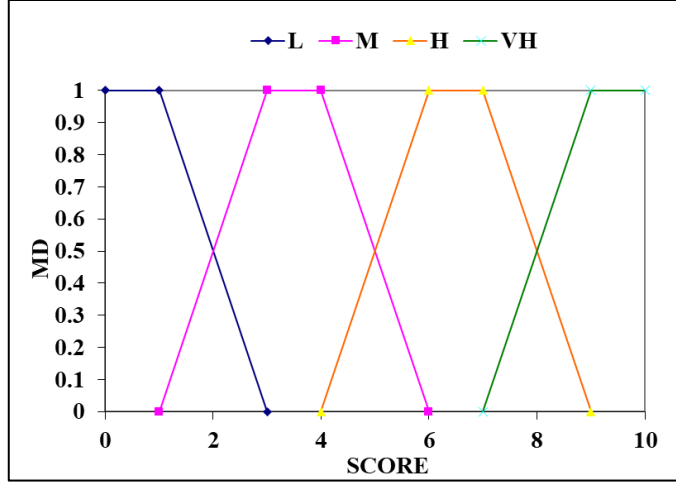


Figure 4.9: Factor index scale.

$$FI = \sum_{i=1}^n P_i^* x w_i' \quad (4.6)$$

Lastly, defuzzification is carried out by following Equation 4.7.

$$SI = \frac{\sum_{i=1}^q Y_i \mu_{SI} \times [y_i]}{(\sum_{i=1}^q \mu_{SI} \times [y_i])} \quad i = 1, 2, \dots, q \quad (4.7)$$

4.10. Proposed method with ANP

ANP method has common steps with the AHP method. The recommended method specific to ANP is shown in Figure 4.10. In the ANP method, the resource recovery plan and composition of sustainability index part are made within the AHP method. The integration of ANP with TOPSIS includes the creation of cognitive mapping, the creation of super and limit matrices as a result of comparing the attributes pairwise. Finally, the integration of ANP with TOPSIS includes vector normalization and generation of positive and negative ideal solutions. Therefore, ANP with TOPSIS is given as an alternative to AHP with Fuzzy Inference. Compared to the fuzzy AHP method, this method is thought to be less complicated because it takes into account crisp numbers, and it is considered to be very useful because of the pairwise comparison of the criteria between clusters.

Multi-Criteria Decision Making (MCDM) is very useful in the selection of recovery technologies. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), one of the multi-criteria decision-making techniques, is used alone or in combination with other current methods in technology selection as the closest ranking preference technique to the ideal solution. In this part of the thesis, the ANP method with TOPSIS will be proposed and the steps will guide the decision makers in choosing the resource recovery technology.

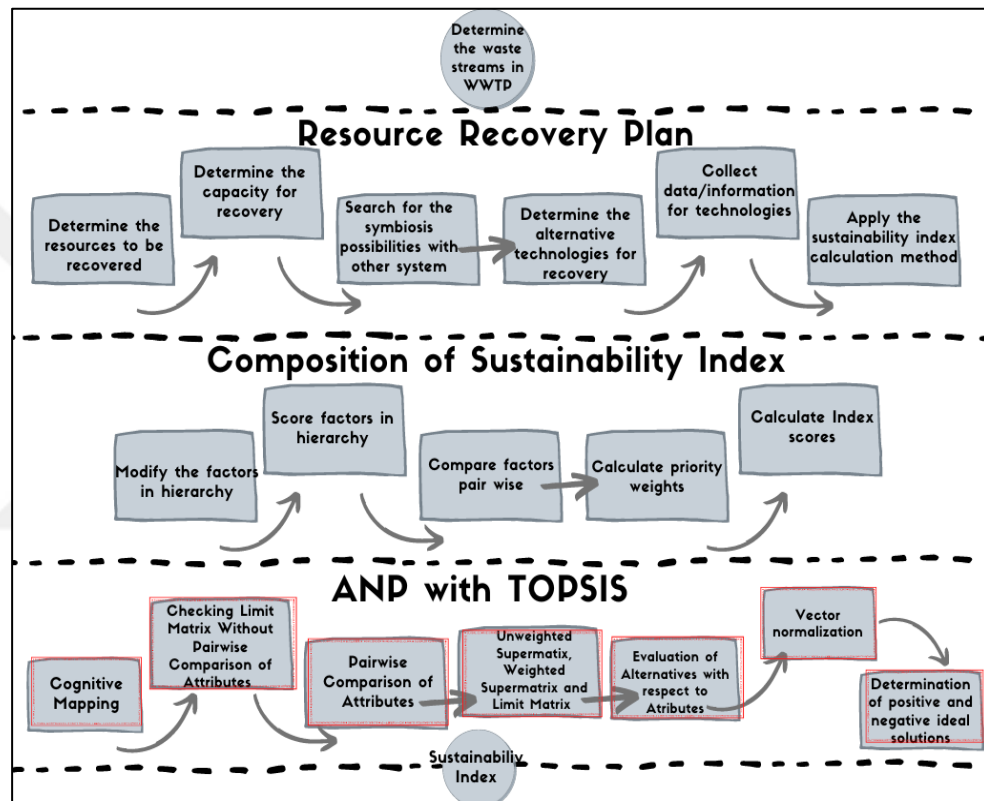


Figure 4.10. Proposed ANP method.

4.11. Cognitive Mapping

Cognitive Mapping, developed by Edward C. Tolmen in 1948, is a very useful tool for visually displaying thoughts about a problem through mapping. It aims to make the problem easier to understand by simplifying the complexity of complicated problems [Thinusblanc, 1984].

Cognitive mapping is the task of mapping a person's thinking about a problem or issue. A cognitive map is the representation of thinking about a problem that follows from the process of mapping. Cognition can be used to refer to the mental models, or belief systems, that people use to perceive, contextualize, simplify, and make sense of otherwise complex problems [Thinusblanc, 1984].

A cognitive map is an image of cognitive processes and an attempt to utilize expert opinion and cognition about ill-structured social relationships ["A System for Organizational Learning Using Cognitive Maps," 1992]. Cognitive maps are cause-effect networks, with nodes representing concepts articulated by individuals, and directional linkages capturing causal dependencies [Thinusblanc, 1984].

One of the practical aims of cognitive mapping is to attain an appropriate and powerful link between the qualitative aspects of a problem definition and the role of quantitative analysis [Thinusblanc, 1984]. In cognitive mapping, there may be a positive or negative relationship between attributes, or there may be no relationship. For the application of the ANP method, whether positive or negative is taken into account, it is only important whether there is a relationship between the qualities.

If there is a positive relationship between attributes, a plus sign is placed from affecting to affected. If there is a negative relationship between the attributes, an arrow is drawn from the affecting to the affected and a minus sign is put. As a result, if the affecting attribute increases, the affected attribute decreases. In cognitive maps, centrality is important. Centrality is the sum of the total number of arrows coming into the variable and arrows coming out of the variable.

An example of signed digraph is given in Figure 4.11 where A, B, C and D are concept variables. It can be said that B negatively affects A and C. So, if there is an increase happen in B, it will create decrease in A and C. Moreover, A and D positively affect C. So, if there is an increase happen in A or D, it will also create an increase C. It may be said that C affects nothing but affected by all given variables. Here C is the head as it has no outgoing arrows and B, and D are tails since they have no incoming arrows. Centrality of A can be easily calculated as sum of out degree (1) and in degree (1) which results in 2. C is the most central one as its centrality is 3.

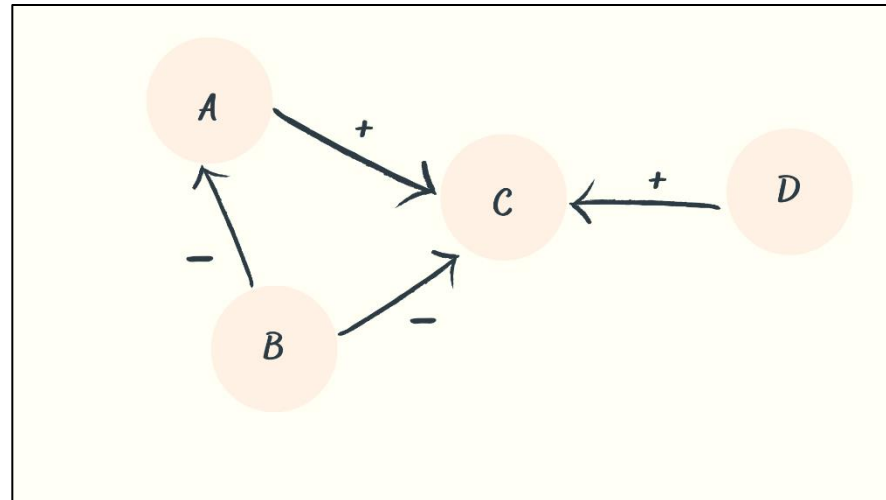


Figure 4.11: Example of signed diagram.

Cognitive maps expressed in figures can also be represented by matrices. The matrix format is very useful in solving complex problems. Attributes are placed in rows and columns. First the row is read, then the column. If the attribute in the row positively affects the attribute in the column, their intersection is assigned a plus sign. If the opposite is the case, a negative sign is put. If the variable in the row has no effect on the variable in the column, nothing or zero is assigned to their intersection. Example matrix representation is given in Table 4.2.

Table 4.2: Relationships by Matrix Representation.

	A	B	C	D-
A	0	0	+	0
B	-	0	-	0
C	0	0	0	0
D	0	0	+	0

C row has zero which means it is a head which affects nothing. B and D columns have all zeros which means they are tails which are affected by nothing in the model.

In Analytic Network Process (ANP) there is no need to consider if the relationship is positive or negative. The knowledge of the relationship between the attributes and the sign of the relationship is sufficient for cognitive maps. The relationships obtained from the cognitive map are enough as input for the ANP.

4.12. Checking Limit Matrix Without Pairwise Comparison of Attributes

In the proposed method, Analytical Network Process (ANP) is used to determine the weight of each attribute to be used in the evaluation of alternatives. In the ANP method, the weights of the features are based on the relationships between the features and the decision makers' preference among the features obtained by pairwise comparisons. As a result, the dependencies between the features must be at a sufficient level for the ANP method to be applied.

The important point in ANP is to create sufficient dependencies between the attributes. If the dependencies are not sufficient, the ANP method cannot be applied, so it should be checked whether the subject to be decided is suitable for the use of ANP.

There are many steps to determine whether ANP is suitable for case studies. As a first step, it is assumed that the feature preferences are the same within the same cluster when performing the feature comparison. As a result, a first-order unweighted super matrix is created. Next, the unweighted super matrix is calculated using Manhattan distance normalization to find the weighted super matrix. Lastly, the square matrix of the weighted super matrix is taken to find the limit matrix.

4.13. Pairwise Comparison of Attributes

Since the scores in AHP are given with fuzzy numbers, the average of the binary numbers assigned for the features is taken for the pairwise comparison of the features in the ANP.

Pairwise comparisons are performed in the Super Decisions program, the program automatically assigns the appropriate number for empty cells. The Super Decisions Software automatically assigns the eigenvector of the matrices. The weights of the features are represented by eigenvectors. All eigenvectors in the matrix are created using the Super Decisions Software, with the eigenvectors an unweighted super matrix.

4.14. Unweighted Supermatrix, Weighted Supermatrix and Limit Matrix

As a result of combining the eigenvector results resulting from the pairwise comparisons, an unweighted super matrix is formed. On the other hand, for the weighted super matrix, Manhattan distance normalization is used. With Super Decisions Software it is possible to calculate both limit and super matrices. To obtain the limit matrix, the weighted super matrix is squared up to the point where convergence occurs.

4.15. Evaluation of Alternatives with respect to Attributes

The next step after determining the weights of the attributes is the evaluation of the wastewater recovery alternatives according to the attributes. Using the numbers in Table 4.3 from 1 to 10, the alternatives were evaluated according to their contribution to sustainability. While alternatives are compared according to their qualities, they are scored by evaluating the benefit quality. For example, an alternative gets a high score if it is positive for one attribute. Thus, the attribute weights and performance values of the alternatives are found. The next step is to analyze the problem and rank wastewater recovery technologies accordingly.

Table 4.3: Scale for evaluation of alternatives with respect to attributes.

Number	Scale
1	exactly no contribution to sustainability index
2	no contribution to sustainability index
3	no critical contribution to sustainability index
4	moderate contribution to sustainability index
5	significant contribution to sustainability index
6	very high contribution to sustainability index
7	not sustainable
8	not sustainable unless measures are taken
9	sustainable
10	very supportive in terms of sustainability

4.16. Integration of ANP with TOPSIS

In order to rank and evaluate sustainable technologies as alternatives, the data obtained in the ANP are ranked with the TOPSIS method. First of all, like in the method for AHP and ANP the alternatives and selection criteria are determined. Then, the decision criteria of the decision makers and the evaluation of the alternatives according to the decision criteria with linguistic variables and the determination of the importance weights of the criteria. In the fourth step, the decision matrix and the normalized decision matrix are created. After this step, a weighted normalized decision matrix is created. According to the obtained data, positive and negative ideal solutions are determined and their distances from ideal solutions are calculated. In the last step, the closeness coefficients are calculated, and the alternatives are ranked.

4.16.1. Vector normalization

The first step of the TOPSIS method is vector normalization. First, all attributes are assumed to be utility attributes. In the next step, the weighted normalized ratings are calculated with multiple attribute weights with normalized performance values as shown in Equation 4.8.

$$v_i = v_j \times r_{ij} \quad ij = 1, 2, \dots, n \quad (4.8)$$

4.16.2. Determination of positive and negative ideal solutions

In this step of the TOPSIS method, positive ideal and negative ideal solutions are found. a^* is used for the positive ideal and the maximum of the sustainability feature is selected. For the negative ideal, a^- is used and the minimum of the sustainability feature is selected. Then, the deviations of each alternative from the positive and negative ideal solution are measured separately with the formulas given below.

$$S_i^* = \left[\sum_{j=1}^n [a_{ij} - a_i^*]^2 \right]^{0.5} \quad ij = 1, 2, \dots, n \quad (4.9)$$

$$S_i^- = \left[\sum_{j=1}^n [a_{ij} - a_i^-]^2 \right]^{0.5} \quad ij = 1, 2, \dots, n \quad (4.10)$$

In the next step, the similarities with the positive ideal solution are calculated with the following formula.

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-} \quad i = 1, 2, \dots, n \quad (4.11)$$

Finally, the alternatives are ranked according to their similarity. The alternative with the highest similarity result is selected as the best alternative.

5. CASE STUDY FOR WASTEWATER RESOURCE RECOVERY TECHNOLOGIES

This study aims to propose an approach to select the most applicable wastewater recovery technology based on the recovered resource by calculating the sustainability indices. The proposed approach was applied to a case study involving three alternative technologies for nutrient recovery from industrial wastewater.

5.1. Resource Recovery Plan

A resource recovery plan is needed before taking action on technology adoption as shown in Figure 4.1. The first step is to identify the waste streams in the WWTP. For this case study, only wastewater stream is selected for nutrient recovery. Literature search for three selected technology is shown in Table 5.1. The second step is to identify the resources to be recovered. Nitrogen will be recovered from wastewater stream.

Table 5.1: Literature search for selected three technology.

	CRITERIA	AMMONIA STRIPPING+PRECIPITATION	MEMBRANE BASED TECHNOLOGIES	PRECIPITATION
TECHNICAL	Applicability	easy installation	complete nutrient recovery	industry scale applications [Lorick et al., 2020]
	Quality of recovered material	soluble, available for plants [Alemayehu et al., 2020]	further treatment [Xie et al., 2016b]	suitable fertilizer
	System complexity	many parameters to control [Cao et al., 2019]	automation	continuous monitoring [Nenov et al., 2020]
	Waste generation	waste generation less	salts on digestate [Chen et al., 2020]	low pollutant [Egle et al., 2015]
	Capacity of the plant	no industrial application	no industrial application	100-500 kg/d struvite [Ahmed et al., 2015]
ECONOMIC	Time limitation	direct recovery is possible	separation is rapid	sludge pumping
	Reliability	not suitable for cold climates, pH adjustment [Sengupta et al., 2015]	membrane fouling, scaling [Ansari et al., 2017]	competitive ion effect [Alemayehu et al., 2020]
	Revenue	230€/ton [Campos et al., 2019]	1900€/ton [Robles et al., 2020a]	480€/ton [Campos et al., 2019]
	Maintenance requirement	daily, weekly [Campos et al., 2019]	yearly [Ansari et al., 2017]	daily, weekly [Ahmed et al., 2015]
	Carbon neutrality	heat requirement, emission [Kjerstadius et al., 2017a]	low chemical use	heat, chemicals [Kjerstadius et al., 2017a]
ENVIRONMENTAL	Environmental impact	threat for water bodies	small footprint [Diaz-Elsayed et al., 2019b]	environmental profit [Magri et al., 2020]
	Discharge limitation	98% N removal efficiency [Robles et al., 2020a]	accumulation of salts [Mehta et al., 2015]	90% removal [Nenov et al., 2020]
	Ecological risk	chemicals reagents for regeneration [Alemayehu et al., 2020]	safe for environment [Amann et al., 2018]	chemical threat
SOCIAL	Thermal pollution	heat consumption	no heat requirement	heat consumption
	Governmental support	universities and nongovernmental organization support	carbon emission policies	eco labeling
	Direct/Indirect jobs	qualified workers need high	qualified worker needs less	qualified workers need high
	Health status	air pollution	green technology	greenhouse gas emission

The third step is to look for other sources of wastewater streams that have the same resource recovery potential and are technically viable to combine the streams for effluent recovery. For this case study, symbiosis was not considered. Information on alternative technologies should then be collected. After conducting a thorough review of the available literature, it is evident from Table 5.1 that air stripping, membrane filtration, and precipitation technologies have emerged as the prominent methods for wastewater recovery. These methods have demonstrated significant efficacy in removing contaminants from wastewater and recovering valuable resources, thereby proving their potential as sustainable solutions for wastewater treatment.

Sustainability has been chosen as an indicator for strategy performance as it is the most widely accepted and reliable assessment for environmental issues recently [Bui et al., 2019]. As the circular economy and resource recovery come to the fore as a result of sustainable development goals, sustainability is used as a collective feasibility function that includes technical, economic, environmental and social issues. The sustainability index can help authorities choose the most appropriate strategy.

5.2. Composition of Sustainability Index

First, a hierarchy, in Section 4, is developed that includes various criteria for making sustainability assessments. According to the contribution of the criteria in the hierarchy to sustainability, the criteria are scored by the experts according to the scale of scores Table 4.1. Then, the criteria are compared based on their importance for sustainability according to scale of scores. The scores and priority weights of the criteria, which are then clarified by fuzzy inference, form the SI.

5.3. Modify the factors in hierarchy

Since the technology selection approach for nutrient recovery from wastewater proposed in this thesis is based on AHP, one of the most important steps of the approach is to determine and systematically organize the criteria that contribute to sustainability. The hierarchy created by the results of the literature review carried out in detail is explained in detail in Section 4.3. The proposed approach should be reviewed before being used, and criteria irrelevant to the situation being evaluated should be eliminated before implementation. For example, groundwater pollution was excluded from the criteria because the concept of aquifer discharge is not common.

5.4. Score factors in hierarchy

The proposed approach in this thesis is based on AHP, but fuzzy numbers and fuzzy inference engine approach are used for calculation steps. In the scoring based on the contribution of the criteria to sustainability, fuzzy numbers are used instead of classical numbers to reflect the situations where the contribution of the criteria to the risk is uncertain. In addition, it ensures that criteria for which there is no clear data set are scored with linguistic variables by expert opinion. Those who will use the proposed approach can be flexible in changing the scoring scale for their situation. The scale in Table 4.1 recommended in section 4.4. was used.

While applying the sustainability index using the approach suggested in Chapter 4.2, separate evaluations were made for technical, economic, environmental, and social criteria, as in the proposed approach. With the help of detailed information on technologies in Section 5.1, the criteria in the hierarchy are scored using the scale in Table 4.1, based on their contribution to sustainability.

5.4.1. Evaluation of Alternatives with respect to technical criteria

The three selected technologies were evaluated with the sub-criteria under technical, economic, social, and environmental aspects. First, three technologies are scored for each technical criterion.

The applicability of air stripping and membrane-based technologies for nutrient recovery are shown in moderate efficiency while using precipitation methods has been found to be highly efficient [Perera et al., 2019]. Therefore, the precipitation technology has been given high score [7-8] based on the scale in Table 4.1 for applicability criterion (Table 5.2). Due to the fact that nutrient recovery efficiency of the membrane technologies varies in the studies (Table 5.1), the score of applicability for membrane technology is given with a wider range (Table 5.3) to reflect the uncertainty about for nutrient recovery. Similar approach was used for the scoring of other criteria. Nutrient recovered with membrane technology cannot be directly used by plants and requires treatment [Xie et al., 2016a] and low-moderate score (4-5) were given for recovered material quality of membrane technology (Table 5.3). On the other hand, nutrients obtained by ammonia stripping and precipitation in dissolved form and can be used directly by plants [Alemayehu et al., 2020],[Nenov et al., 2020],[Xie et al., 2016a]. Literature searches for ammonia stripping technology indicates that the

most important technical criteria are the quality of the recovered material and its alternative for energy supply [Alemayehu et al., 2020]. Therefore, high scores were assigned for these technologies (Table 5.2) in terms of recovered material quality as shown in Table 5.1. In ammonia stripping and precipitation technologies, there are many parameters that need to be controlled such as pH, temperature, magnesium content, suspended substance content (Table 5.1) [Cao et al., 2019], Xie et al., 2016a] therefore, their scores were in low ranges (Table 5.2 and Table 5.4.). Membrane technology, on the other hand, can be easily managed and intervened with the automation system, and they are not considered as complex. Therefore, the score for membrane technology is much higher (8-9) due its lower system complexity (Table 5.3). In terms of time limitation direct nutrient recovery is possible with the ammonia stripping process and membrane separates the concentrate from the water quickly (Table 5.1). In the precipitation method, the process time may be prolonged due to the possibility of clogging of the pipes [ElMekawy et al., 2015], Patel et al., 2020b]. Thus, the score of time limitation were high for ammonia stripping and membrane technology and low for precipitation technology (Table 5.2 and Table 5.3). All scores are show in Table 5.2, Table 5.3 and Table 5.4 for air stripping, membrane, and precipitation, respectively.

Table 5.2: Technical criteria for air stripping technology

Factor	Sub Factor	Score		STFN			
				A	B	C	D
Technical	Applicability	4	6	4	4	6	6
	Quality of recovered material	7	8	7	7	8	8
	Land requirement	3	4	3	3	4	4
	System complexity	2	3	2	2	3	3
	Alternative for energy supply	7	9	7	7	9	9
	Waste generation	2	3	2	2	3	3
	Capacity of the plant	2	6	2	2	6	6
	Time limitation	6	8	6	6	8	8
	Reliability	3	4	3	3	4	4

Table 5.3: Technical criteria for membrane technology.

Factor	Sub Factor	Score		STFN			
				A	B	C	D
Technical	Applicability	3	7	3	3	7	7
	Quality of recovered material	4	5	4	4	5	5
	Land requirement	7	8	7	7	8	8
	System complexity	8	9	8	8	9	9
	Alternative for energy supply	1	2	1	1	2	2
	Waste generation	4	5	4	4	5	5
	Capacity of the plant	2	6	2	2	6	6
	Time limitation	5	7	5	5	7	7
	Reliability	5	8	5	5	8	8

Table 5.4: Technical criteria for precipitation technology.

Factor	Sub Factor	Score		STFN			
				A	B	C	D
Technical	Applicability	7	8	7	7	8	8
	Quality of recovered material	7	9	7	7	9	9
	Land requirement	3	5	3	3	5	5
	System complexity	3	4	3	3	4	4
	Alternative for energy supply	1	2	1	1	2	2
	Waste generation	6	8	6	6	8	8
	Capacity of the plant	8	9	8	8	9	9
	Time limitation	3	5	3	3	5	5
	Reliability	5	6	5	5	6	6

5.4.2. Evaluation of Alternatives with respect to economic criteria

In terms of economic criteria, while the consumption of natural resources for the ventilation system and energy cost of the technology was expected to be high for air stripping, the uncertainty regarding natural input requirement enabled it to score between 2 and 4 (Table 5.5).

Scoring of the economic criteria was made by using the available information in Table 5.1. Phosphorus obtained by membrane technology have a market value of 1900 euro per ton, ammonium sulphate gained by air stripping is 230 euro per ton, and struvite recovered by precipitation is 480 euro per ton [Campos et al., 2019]. Membrane technology which has a high market value, high score (7-9) was awarded in terms of revenue. In terms of waste costs, it is expected that the chemical and waste transportation costs for membrane technology can be minimal. Since the chemical consumption of ammonium stripping and precipitation technology is high, the sludge

production and the cost of chemical transportation and waste disposal can be costly [Siciliano et al., 2020]. Hence, the score of waste cost is medium-high for membrane technology (Table 5.6) and low for the other technologies because of high sludge production. Operational cost varies according to parameters such as flowrate, capacity of the plant, energy, and resource consumption. The operation of the ammonium stripping process under alkaline conditions requires constant use of chemicals leading to high operational cost [Alemayehu et al., 2020], [Robles et al., 2020b]. It has been proven that 9 kWh of energy consumption is needed for 1 kg of nutrient recovered. At the same time, this energy consumption can be reduced with jet loop aero cyclone reactors [Campos et al., 2019], [Guštin and Marinšek-Logar, 2011], [Perera et al., 2019], [Sengupta et al., 2015]. Like stripping, precipitation technology requires the continuous use of chemicals for the precipitation process. It has been asserted that the operational cost of struvite recovery with industrial scale precipitation technology is 2900 Euros per ton of nutrient produced [Campos et al., 2019]. In membrane technology, chemical washing is performed in certain periods to prevent clogging and fouling. Accordingly, membrane technology has been given a higher score (Table 5.6) and other technologies received low scores when considering the inverse relation between the resource consumption and sustainability. The necessity for natural resources depends on the water consumption and energy use of the processes. As it is explained for waste cost, membrane technology is considered to require fewer natural resources compared to the other two technologies (Table 5.5) and has a higher score (Table 5.6). All scores are shown in Table 5.5, Table 5.6 and Table 5.7 for air stripping, membrane, and precipitation, respectively.

Table 5.5: Economic criteria for air stripping technology.

Factor	Sub Factor	Score		STFN			
				A	B	C	D
Economic	Waste cost	2	3	2	2	3	3
	Revenue	6	7	6	6	7	7
	Operational cost	3	4	3	3	4	4
	Investment cost	5	6	5	5	6	6
	Installation cost	2	3	2	2	3	3
	Maintenance requirement	2	3	2	2	3	3
	Natural input requirement	2	4	2	2	4	4

Table 5.6:Economic criteria for membrane technology.

Factor	Sub Factor	Score		STFN			
				A	B	C	D
Economic	Waste cost	5	6	5	5	6	6
	Revenue	7	9	7	7	9	9
	Operational cost	6	7	6	6	7	7
	Investment cost	4	6	4	4	6	6
	Installation cost	7	8	7	7	8	8
	Maintenance requirement	6	7	6	6	7	7
	Natural input requirement	2	6	2	2	6	6

Table 5.7: Economic criteria for precipitation criteria.

Factor	Sub Factor	Score		STFN			
				A	B	C	D
Economic	Waste cost	3	4	3	3	4	4
	Revenue	4	6	4	4	6	6
	Operational cost	3	4	3	3	4	4
	Investment cost	4	5	4	4	5	5
	Installation cost	2	3	2	2	3	3
	Maintenance requirement	3	5	3	3	5	5
	Natural input requirement	3	6	3	3	6	6

5.4.3. Evaluation of Alternatives with respect to environmental criteria

In terms of environmental criteria, the use of less chemicals and heat makes membrane technology more sustainable and scores high in terms of carbon neutrality (Table 5.9). In a study, the annual carbon dioxide emission for ammonia stripping and precipitation is found to be 18 kg / eq. capita. [Kjerstadius et al., 2017b]; therefore, they received lower scores (Table 5.8). Ammonia stripping and struvite precipitation technologies require intense chemical use and heat for the process (Table 5.1), they must be well managed from an environmental point of view. Therefore, score of environmental impact is high for air stripping and precipitation (Table 5.8 and Table 5.10) and low for the membrane (Table 5.9). While examining the criteria of discharge limitation, the possibilities of technologies to treat wastewater and pollutant content of wastewater were taken into consideration. It has been observed that ammonia stripping can treat about 98 percent nitrogen, and it serve a purpose of odor removal [Robles et al., 2020a]. In struvite precipitation, this efficiency is approximately between 80 and 90 percent [Nenov et al., 2020]. The scores for discharge limitations are similar (Table

5.10) due to the close treatment efficiencies. Air pollution can be associated with energy consumption. The more energy is consumed, the higher the greenhouse gas emission in the process [Theragowda et al., 2019]. The scores of air pollution were given similar to GHG emissions with the assumption that there is no additional air pollution source in the system. The technology that requires heat treatment creates the possibility of thermal pollution during discharge. Membrane technology does not involve a heat treatment process. Therefore, the score of thermal pollution is very low for membrane (Table 5.8) while the scores were very high for the other technologies (Table 5.8 and Table 5.10). All scores are show in Table 5.8, Table 5.9 and Table 5.10 for air stripping, membrane, and precipitation, respectively.

Table 5.8: Environmental criteria for air stripping technology.

Factor	Sub Factor	Score		STFN			
				A	B	C	D
Environmental	Carbon neutrality	2	3	2	2	3	3
	Greenhouse gas emission	2	3	2	2	3	3
	Environmental impact	3	5	3	3	5	5
	Discharge limitation	3	5	3	3	5	5
	Air pollution	2	4	2	2	4	4
	Water supply	2	6	2	2	6	6
	Green energy	6	7	6	6	7	7
	Eutrophication	7	8	7	7	8	8
	Ecological risk	4	6	4	4	6	6
	Thermal pollution	1	4	1	1	4	4
	Pollution of water	2	5	2	2	5	5
	Aquifer preservation	6	8	6	6	8	8

Table 5.9: Environmental criteria for membrane technology.

Factor	Sub Factor	Score		STFN			
				A	B	C	D
Environmental	Carbon neutrality	6	8	6	6	8	8
	Greenhouse gas emission	4	6	4	4	6	6
	Environmental impact	7	8	7	7	8	8
	Discharge limitation	4	5	4	4	5	5
	Air pollution	2	5	2	2	5	5
	Water supply	2	6	2	2	6	6
	Green energy	1	2	1	1	2	2
	Eutrophication	3	5	3	3	5	5
	Ecological risk	5	7	5	5	7	7
	Thermal pollution	7	8	7	7	8	8
	Pollution of water	4	6	4	4	6	6
	Aquifer preservation	6	8	6	6	8	8

Table 5.10: Environmental criteria for precipitation technology.

Factor	Sub Factor	Score	STFN				
			A	B	C	D	
Environmental	Carbon neutrality	2	3	2	2	3	3
	Greenhouse gas emission	3	4	3	3	4	4
	Environmental impact	3	5	3	3	5	5
	Discharge limitation	5	6	5	5	6	6
	Air pollution	3	4	3	3	4	4
	Water supply	2	6	2	2	6	6
	Green energy	1	2	1	1	2	2
	Eutrophication	3	4	3	3	4	4
	Ecological risk	3	6	3	3	6	6
	Thermal pollution	1	4	1	1	4	4
	Pollution of water	4	5	4	4	5	5
	Aquifer preservation	5	6	5	5	6	6

5.4.4. Evaluation of Alternatives with respect to social criteria

Three technologies have been analyzed in terms of social criteria based on the information in Table 5.1. Social benefit is considered equally with assuming that there is no additional social benefit except nutrient recovery. Table 5.11 indicates the direct job criterion has high impact on sustainability. The product recovered should support circularity regarding sanitation, water and food safety and public health. When considering public health issue, reliability of the technology is accepted as the indicator for public health protection and membrane technology scored higher than others (Table 5.12). More work and action are needed in terms of education and culture. Studies on this subject have been found insufficient. Although the aesthetic criterion seems insignificant, the design of recovery technologies and the compactness of the facility accelerate public acceptance. Cooperative work of the state, universities, private sector, and non-governmental organizations is essential while developing recovered technologies. Tax reductions and eco-labeling can be an option to encourage recovered products. In addition, it is possible to obtain energy by combining air stripping technology with the bio refinery concept, but this is not possible for membrane and precipitation technology. Therefore, the alternative for energy supply and the green energy criterion have been ignored for these technologies. Unfortunately, the information for the social factors is very limited in the literature and the relevant studies are highly encouraged with the collaboration of environmental and

social scientists. All scores are show in Table 5.11, Table 5.12 and Table 5.13 for air stripping, membrane, and precipitation, respectively.

Table 5.11: Social criteria for air stripping technology.

Factor	Sub Factor	Score	STFN				
			A	B	C	D	
Social	Social Benefit	4	7	4	4	7	7
	Employment	6	8	6	6	8	8
	Governmental support	3	5	3	3	5	5
	Aesthetic	1	3	1	1	3	3
	Direct/Indirect jobs	6	8	6	6	8	8
	Health status	2	3	2	2	3	3
	Education/cultural	1	2	1	1	2	2

Table 5.12: Social criteria for membrane technology.

Factor	Sub Factor	Score	STFN				
			A	B	C	D	
Social	Social Benefit	4	7	4	4	7	7
	Employment	6	8	6	6	8	8
	Governmental support	3	5	3	3	5	5
	Aesthetic	1	3	1	1	3	3
	Direct/Indirect jobs	4	5	6	6	8	8
	Health status	2	4	2	2	3	3
	Education/cultural	1	2	1	1	2	2

Table 5.13: Social criteria for precipitation technology.

Factor	Sub Factor	Score	STFN				
			A	B	C	D	
Social	Social Benefit	4	7	4	4	7	7
	Employment	6	8	6	6	8	8
	Governmental support	7	8	7	7	8	8
	Aesthetic	2	3	2	2	3	3
	Direct/Indirect jobs	4	5	4	4	5	5
	Health status	2	4	2	2	4	4
	Education/cultural	2	5	2	2	5	5

5.5. Compare factors pairwise and priority weights

Factors were compared in pairs according to their importance using the (1-9) scale as described in Chapter 3.1.2. All hierarchy levels described in Chapter 4.3 were

scored according to their importance levels by creating binary matrices among themselves.

All evaluations are converted to trapezoidal fuzzy numbers to ensure the standard and clarified to calculate net weight scores. For the first comparison example, after these conversion operations are shown in detail, the corresponding clarified numbers are shown.

5.5.1. Comparison matrixes for technical criteria

To evaluate wastewater recovery technologies, 4 main criteria were previously classified as technical, economic, environmental, and social. All these main criteria are divided into sub-criteria, evaluated in terms of recovery technologies, and importance scores are given.

While making the evaluation, the determination of the priority order of the criteria was also made within the scope of the thesis. With the ANP method, the criteria were listed, and their priorities were determined. Also, using the TOPSIS method, technologies are listed according to the priority order of the criteria (Section 6).

We can divide the technical criteria as applicability, quality of recovered material land requirement, system complexity, alternative for energy supply, waste generation, capacity of the plant, time limitation and reliability. In this way, after scoring, the fuzzy score is clarified using Equation 4.2. Fuzzy scores are shown in Table 5.14.

When sub-criteria for technical issues are compared, applicability is evaluated as the most critical. Once the technology could be applied, reliability is the second most important criterion. On the other hand, it is understood that land requirement, time limitation and system capacity have less impact on sustainability of other sub-criteria.

Table 5.14: Comparison matrix of technical criteria.

	Applicability		Quality of recovered material		Land requirement		System complexity		Alternative for energy supply		Waste generation		Capacity of the plant		Time limitation		Reliability	
	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN
Applicability	(1,1)	(1,1,1,1)	(5,6)	(5,5,6,6)	(8,9)	(8,8,9,9)	(4,5)	(4,4,5,5)	(2,3)	(2,2,3,3)	(7,8)	(7,7,8,8)	(1,2)	(1,1,2,2)	(1,2)	(1,1,2,2)	(4,6)	(4,4,6,6)
Quality of recovered material	(1/5, 1/7)	(1/5,1/5,1/6,1/6)	(1,1)	(1,1,1,1)	(7,8)	(7,7,8,8)	(4,6)	(4,4,6,6)	(1,2)	(1,1,2,2)	(6,7)	(6,6,7,7)	(1,2)	(1,1,2,2)	(1,2)	(1,1,2,2)	(1/5,1/6)	(1/5,1/5,1/6,1/6)
Land requirement	(1/8, 1/9)	(1/8,1/8,1/9,1/9)	(1/7,1/8)	(1/7,1/7,1/8,1/8)	(1,1)	(1,1,1,1)	(1/7, 1/8)	(1/7,1/7,1/8,1/8)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(3,4)	(3,3,4,4)	(2,3)	(2,2,3,3)	(1/8,1/9)	(1/8,1/8,1/9,1/9)
System complexity	(1/4, 1/5)	(1/4,1/4,1/5,1/5)	(1/4,1/6)	(1/4,1/4,1/6,1/6)	(7,8)	(7,7,8,8)	(1,1)	(1,1,1,1)	(2,3)	(2,2,3,3)	(7,8)	(7,7,8,8)	(4,5)	(4,4,5,5)	(2,3)	(2,2,3,3)	(1/6,1/7)	(1/6,1/6,1/7,1/7)
Alternative for energy supply	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(1,1/2)	(1,1,1/2,1/2)	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(1,1)	(1,1,1,1)	(1,2)	(1,1,2,2)	(3,5)	(3,3,5,5)	(3,4)	(3,3,4,4)	(1/8,1/9)	(1/8,1/8,1/9,1/9)
Waste generation	(1/7, 1/8)	(1/7,1/7,1/8,1/8)	(1/6,1/7)	(1/6,1/6,1/7,1/7)	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(1/7, 1/8)	(1/7,1/7,1/8,1/8)	(1,1/2)	(1,1,1/2,1/2)	(1,1)	(1,1,1,1)	(7,8)	(7,7,8,8)	(2,3)	(2,2,3,3)	(1,2)	(1,1,2,2)
Capacity of the plant	(1,1/2)	(1,1,1/2,1/2)	(1,1/2)	(1,1,1/2,1/2)	(1/3, 1/4)	(1/3,1/3,1/4,1/4)	(1/4, 1/5)	(1/4,1/4,1/5,1/5)	(1/3, 1/5)	(1/3,1/3,1/5,1/5)	(1/7,1/8)	(1/7,1/7,1/8,1/8)	(1,1)	(1,1,1,1)	(4,5)	(4,4,5,5)	(1/5,1/6)	(1/5,1/5,1/6,1/6)
Time limitation	(1,1/2)	(1,1,1/2,1/2)	(1,1/2)	(1,1,1/2,1/2)	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(1/3, 1/4)	(1/3,1/3,1/4,1/4)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/4,1/5)	(1/4,1/4,1/5,1/5)	(1,1)	(1,1,1,1)	(1,2)	(1,1,2,2)
Reliability	(1/4, 1/6)	(1/4,1/4,1/6,1/6)	(5,6)	(5,5,6,6)	(8,9)	(8,8,9,9)	(6,7)	(6,6,7,7)	(8,9)	(8,8,9,9)	(1,1/2)	(1,1,1/2,1/2)	(5,6)	(5,5,6,6)	(1,1/2)	(1,1,1/2,1/2)	(1,1)	(1,1,1,1)

Table 5.14 depicts the matrix against which technical factors are compared for the air stripping process. For example, since applicability is much more important than land requirement, the score (first row, third column in Table 5.14) was given as (8–9). After that, STF numbers (Table 5.14) were defuzzified into crisp numbers (by using Equation 5.1) and crisp numbers are shown in Table 5.15. To calculate the priority weights for applicability vs land requirement Equation 5.2 is used.

$$A = a_{13} = \frac{8 + 2x(8 + 9) + 9}{6} = 8.5 \quad (5.1)$$

$$w_{applicability} = \frac{\frac{1}{3.8} + \frac{5.5}{14.7} + \frac{8.5}{34.6} + \frac{4.5}{18.3} + \frac{2.5}{19.8} + \frac{7.5}{27.8} + \frac{1.5}{29.2} + \frac{1.5}{20.2} + \frac{5}{9.7}}{9} = 0.24 \quad (5.2)$$

Table 5.15: Comparison matrix with crisp numbers for the technical criteria.

	Appl icabi lity	Quality of recovered material	Land require ment	System comple xity	Alternative for energy supply	Waste genera tion	Capacit y of the plant	Time limita tion	Reli abil ity
Applicability	1	5.5	8.5	4.5	2.5	7.5	1.5	1.5	5
Quality of recovered material	0.18	1	7.5	5	1.5	6.5	1.5	1.5	0.18
Land requiremen t	0.12	0.13	1	0.13	2.5	2.5	3.5	2.5	0.12
System complexity	0.23	0.21	7.5	1	2.5	7.5	4.5	2.5	0.15
Alternative for energy supply	0.42	0.75	0.42	0.42	1	1.5	4	3.5	0.12
Waste generation	0.13	0.15	0.42	0.13	0.75	1	7.5	2.5	1.50
Capacity of the plant	0.75	0.75	0.29	0.23	0.27	0.13	1	4.5	0.18
Time limitation	0.75	0.75	0.50	0.42	0.29	0.42	0.23	1	1.50
Reliability	0.21	5.50	8.50	6.50	8.50	0.75	5.5	0.75	1

Matrix comparisons were made based on criteria independent of technologies and the weighted average (w) of each criterion was found. Then, considering the contribution to sustainability, the factor indexes of the application were calculated by

multiplying the scores given to the criterion. The technical criteria factor index calculation for the three selected technologies is shown in Table 5.16.



Table 5.16: Technical criteria of three selected technology: fuzzy scores and priority numbers of the factors at the hierarchy level (w').

Air Stripping Technology												Membrane Technology					Precipitation Technology								
Factor	Sub Factor	Score		STFN				w'	A* w'	B* w'	C* w'	D* w'	w'	A* w'	B* w'	C* w'	D* w'	w'	A* w'	B* w'	C* w'	D* w'			
				A	B	C	D																		
Technical	Applicability	4	6	4	4	6	6	0.2 4	0.9 8	0.98	1.46	1.46	0.2 4	0.7 3	0.73	1.71	1.71	0.2 4	1.7 1	1.71	1.95	1.95			
	Quality of recovered material	7	8	7	7	8	8	0.1 2	0.8 4	0.84	0.96	0.96	0.1 2	0.4 8	0.48	0.60	0.60	0.1 2	0.8 4	0.84	1.08	1.08			
	Land requirement	3	4	3	3	4	4	0.0 6	0.1 9	0.19	0.26	0.26	0.0 6	0.4 5	0.45	0.52	0.52	0.0 6	0.1 9	0.19	0.32	0.32			
	System complexity	2	3	2	2	3	3	0.1 2	0.2 4	0.24	0.36	0.36	0.1 2	0.9 5	0.95	1.07	1.07	0.1 2	0.3 6	0.36	0.48	0.48			
	Alternative for energy supply	7	9	7	7	9	9	0.0 7	0.4 9	0.49	0.64	0.64	0.0 7	0.0 7	0.07	0.14	0.14	0.0 7	0.0 7	0.07	0.14	0.14			
	Waste generation	2	3	2	2	3	3	0.0 8	0.1 5	0.15	0.23	0.23	0.0 8	0.3 0	0.30	0.38	0.38	0.0 8	0.4 6	0.46	0.61	0.61			
	Capacity of the plant	2	6	2	2	6	6	0.0 6	0.1 3	0.13	0.38	0.38	0.0 6	0.1 3	0.13	0.38	0.38	0.0 6	0.5 0	0.50	0.57	0.57			
	Time limitation	6	8	6	6	8	8	0.0 6	0.3 5	0.35	0.47	0.47	0.0 6	0.2 9	0.29	0.41	0.41	0.0 6	0.1 8	0.18	0.29	0.29			
	Reliability	3	4	3	3	4	4	0.1 8	0.5 5	0.55	0.73	0.73	0.1 8	0.9 2	0.92	1.47	1.47	0.1 8	0.9 2	0.92	1.10	1.10			
Index Score										3.93	3.93	5.49	5.4 9			4.33	4.33	6.68	6.6 8			5.23	5.23	6.55	6.5 5

5.5.2. Comparison matrixes for economic criteria

In comparing economic criteria, in many studies [Ahmed et al., 2015], [Campos et al., 2019], [Lu et al., 2019], [Magrí et al., 2020] it has been observed that the revenue has a high effect on sustainability. For example, as seen in Table 5.17, when the revenue and installation cost are compared, 8 and 9 points (8.5) are given. It means, revenue criterion has a considerable impact on sustainability compared to the construction cost.



Table 5.17: Comparison matrix of economic criteria.

	Waste cost		Revenue		Operational cost		Investment cost		Installation cost		Maintenance requirement		Natural input requirement	
	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN
Waste cost	(1,1)	(1,1,1,1)	(1/8, 1/9)	(1/8,1/8,1/9,1/9)	(2,3)	(2,2,3,3)	(7,8)	(7,7,8,8)	(6,7)	(6,6,7,7)	(5,7)	(5,5,7,7)	(2,3)	(2,2,3,3)
Revenue	(8,9)	(8,8,9,9)	(1,1)	(1,1,1,1)	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(8,9)	(8,8,9,9)	(8,9)	(8,8,9,9)	(4,5)	(4,4,5,5)	(3,4)	(3,3,4,4)
Operational cost	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(1,2)	(1,1,2,2)	(1,1)	(1,1,1,1)	(8,9)	(8,8,9,9)	(7,8)	(7,7,8,8)	(6,7)	(6,6,7,7)	(7,8)	(7,7,8,8)
Investment cost	(1/7, 1/8)	(1/7,1/7,1/8,1/8)	(1/8, 1/9)	(1/8,1/8,1/9,1/9)	(1/8, 1/9)	(1/8,1/8,1/9,1/9)	(1,1)	(1,1,1,1)	(5,7)	(5,5,7,7)	(1/5, 1/7)	(1/5,1/5,1/7,1/7)	(1/3, 1/4)	(1/3,1/3,1/4,1/4)
Installation cost	(1/6, 1/7)	(1/6,1/6,1/7,1/7)	(1/8, 1/9)	(1/8,1/8,1/9,1/9)	(1/7, 1/8)	(1/7,1/7,1/8,1/8)	(1/5, 1/7)	(1/5,1/5,1/7,1/7)	(1,1)	(1,1,1,1)	(2,3)	(2,2,3,3)	(1,2)	(1,1,2,2)
Maintenance requirement	(1/5, 1/7)	(1/5,1/5,1/7,1/7)	(1/4, 1/5)	(1/4,1/4,1/5,1/5)	(1/6, 1/7)	(1/6,1/6,1/7,1/7)	(5,7)	(5,5,7,7)	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(1,1)	(1,1,1,1)	(4,5)	(4,4,5,5)
Natural input requirement	(1/2, 1/3)	(1/2,1/2,1/3,1/3)	(1/3, 1/4)	(1/3,1/3,1/4,1/4)	(1/7, 1/8)	(1/7,1/7,1/8,1/8)	(3,7)	(3,3,7,7)	(1,1/2)	(1,1,1/2,1/2)	(1/4, 1/5)	(1/4,1/4,1/5,1/5)	(1,1)	(1,1,1,1)

Matrix comparisons were made based on criteria independent of technologies and the weighted average (w) of each criterion was found. The calculations for priority weights are not shown in here, they are calculated like section 5.5.1. Then, considering the contribution to sustainability, the factor indexes of the application were calculated by multiplying the scores given to the criterion. The economic criteria factor index calculation for the three selected technologies is shown in Table 5.18.



Table 5.18: Economical criteria of three selected technology: fuzzy scores and priority numbers of the factors at the hierarchy level (w').

Air Stripping Technology												Membrane Technology					Precipitation Technology										
Factor	Sub Factor	Score		STFN				w'	A* w'	B* w'	C* w'	D* w'	w'	A* w'	B* w'	C* w'	D* w'	w'	A* w'	B* w'	C* w'	D* w'					
				A	B	C	D																				
Economic	Waste cost	2	3	2	2	3	3	0.22	0.43	0.43	0.65	0.65	0.22	1.08	1.08	1.30	1.30	0.22	0.65	0.65	0.86	0.86					
	Revenue	6	7	6	6	7	7	0.30	1.77	1.77	2.07	2.07	0.30	2.07	2.07	2.66	2.66	0.30	1.18	1.18	1.77	1.77					
	Operational cost	3	4	3	3	4	4	0.27	0.80	0.80	1.06	1.06	0.27	1.59	1.59	1.86	1.86	0.27	0.80	0.80	1.06	1.06					
	Investment cost	5	6	5	5	6	6	0.05	0.23	0.23	0.27	0.27	0.05	0.18	0.18	0.27	0.27	0.05	0.18	0.18	0.23	0.23					
	Installation cost	2	3	2	2	3	3	0.04	0.09	0.09	0.13	0.13	0.04	0.31	0.31	0.35	0.35	0.04	0.09	0.09	0.13	0.13					
	Maintenance requirement	2	3	2	2	3	3	0.08	0.16	0.16	0.24	0.24	0.08	0.48	0.48	0.56	0.56	0.08	0.24	0.24	0.40	0.40					
	Natural input requirement	2	4	2	2	4	4	0.05	0.11	0.11	0.21	0.21	0.05	0.11	0.11	0.32	0.32	0.05	0.16	0.16	0.32	0.32					
	Index Score								3.58	3.58	4.64	4.64					5.82	5.82	7.32	7.32					3.30	3.30	4.78

5.5.3. Comparison matrixes for environmental criteria

We can divide the environmental criteria as carbon neutrality, greenhouse gas emission, environmental impact, discharge limitation, air pollution, water supply, green energy, eutrophication, ecological risk, thermal pollution, pollution of water aquifer preservation.

When the status of environmental criteria under life cycle analysis studies [Miller-Robbie et al., 2013], [Morelli et al., 2018], [Orner et al., 2021] is examined, it is more important for the system to be carbon neutral in terms of sustainability. While air, water and soil pollution are almost the same, the aquifer preservation has lowest impact on the sustainability (Table 5.19).

Table 5.19: Comparison matrix of environmental criteria.

	Carbon neutrality		Greenhouse gas emission		Environmental impact		Discharge limitation		Air pollution		Water supply		Green energy		Eutrophication		Ecological risk		Thermal pollution		Pollution of water		Aquifer preservation	
	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN
Carbon neutrality	(1,1)	(1,1,1,1)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(1,2)	(1,1,2,2)	(1,2)	(1,1,2,2)	(2,3)	(2,2,3,3)	(1,1/2)	(1,1,1/2,1/2)	(2,3)	(2,2,3,3)
Greenhouse gas emission	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1,1)	(1,1,1,1)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(1,2)	(1,1,2,2)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(1/2,2)	(1/2,1/2,2)	(2,3)	(2,2,3,3)
Environmental impact	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1,1)	(1,1,1,1)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(1,2)	(1,1,2,2)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(1/2,2)	(1/2,1/2,2)	(6,8)	(6,6,8,8)
Discharge limitation	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1,1)	(1,1,1,1)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(1,2)	(1,1,2,2)	(2,3)	(2,2,3,3)	(2,3)	(2,2,3,3)	(1/2,2)	(1/2,1/2,2)	(7,8)	(7,7,8,8)
Air pollution	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1,1)	(1,1,1,1)	(7,8)	(7,7,8,8)	(8,9)	(8,8,9,9)	(1,2)	(1,1,2,2)	(4,5)	(4,4,5,5)	(8,9)	(8,8,9,9)	(1/2,2)	(1/2,1/2,2)	(8,9)	(8,8,9,9)
Water supply	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/7,1/8)	(1/7,1/7,1/8,1/8)	(1,1)	(1,1,1,1)	(1,2)	(1,1,2,2)	(1,2)	(1,1,2,2)	(1,2)	(1,1,2,2)	(1,2)	(1,1,2,2)	(1/2,2)	(1/2,1/2,2)	(7,8)	(7,7,8,8)
Green energy	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/8,1/9)	(1/7,1/7,1/8,1/9)	(1,1/2)	(1,1,1/2,1/2)	(1,1)	(1,1,1,1)	(1,2)	(1,1,2,2)	(1,2)	(1,1,2,2)	(1,2)	(1,1,2,2)	(1/2,2)	(1/2,1/2,2)	(4,5)	(4,4,5,5)
Eutrophication	(1,1/2)	(1,1,1/2,1/2)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1,1/2)	(1,1,1/2,1/2)	(1,1/2)	(1,1,1/2,1/2)	(1,1/2)	(1,1,1/2,1/2)	(1,1/2)	(1,1,1/2,1/2)	(1,1/2)	(1,1,1/2,1/2)	(1,1)	(1,1,1,1)	(3,4)	(3,3,4,4)	(2,3)	(2,2,3,3)	(1/2,2)	(1/2,1/2,2)	(5,6)	(5,5,6,6)
Ecological risk	(1,1/2)	(1,1,1/2,1/2)	(1,1/2)	(1,1,1/2,1/2)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/4,1/5)	(1/4,1/4,1/5,1/5)	(1,1/2)	(1,1,1/2,1/2)	(1,1/2)	(1,1,1/2,1/2)	(1/3,1/4)	(1/3,1/3,1/4,1/4)	(1,1)	(1,1,1,1)	(7,8)	(7,7,8,8)	(1/2,2)	(1/2,1/2,2)	(8,9)	(8,8,9,9)
Thermal pollution	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/8,1/9)	(1/8,1/8,1/9,1/9)	(1,1/2)	(1,1,1/2,1/2)	(1,1/2)	(1,1,1/2,1/2)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/7,1/8)	(1/7,1/7,1/8,1/8)	(1,1)	(1,1,1,1)	(1,2)	(1,1,2,2)	(5,7)	(5,5,7,7)
Pollution of water	(1,2)	(1,1,2,2)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,2)	(1/2,1/2,2)	(1/2,2)	(1/2,1/2,2)	(1/2,2)	(1/2,1/2,2)	(1/2,2)	(1/2,1/2,2)	(1/2,2)	(1/2,1/2,2)	(1/2,2)	(1/2,1/2,2)	(1/2,2)	(1/2,1/2,2)	(1,1/2)	(1,1,1/2,1/2)	(1,1)	(1,1,1,1)	(4,5)	(4,4,5,5)
Aquifer preservation	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/2,1/3)	(1/2,1/2,1/3,1/3)	(1/6,1/8)	(1/6,1/6,1/8,1/8)	(1/7,1/8)	(1/7,1/7,1/8,1/8)	(1/8,1/9)	(1/8,1/8,1/9,1/9)	(1/7,1/8)	(1/7,1/7,1/8,1/8)	(1/4,1/5)	(1/4,1/4,1/5,1/5)	(1/5,1/6)	(1/5,1/5,1/6,1/6)	(1/8,1/9)	(1/8,1/8,1/9,1/9)	(1/5,1/6)	(1/5,1/5,1/6,1/6)	(1,1/5)	(1,1,1/5,1/5)	(1,1)	(1,1,1,1)

Matrix comparisons were made on the basis of criteria independent of technologies and the weighted average (w) of each criterion was found. The calculations for priority weights are not shown in here, they are calculated like section 5.5.1. Then, considering the contribution to sustainability, the factor indexes of the application were calculated by multiplying the scores given to the criterion. The environmental criteria factor index calculation for the three selected technologies is shown in Table 5.20.



Table 5.20: Environmental criteria of three selected technology: fuzzy scores and priority numbers of the factors at the hierarchy level (w').

Air Stripping Technology												Membrane Technology					Precipitation Technology					
Factor	Sub Factor	Score		STFN				w'	A* w'	B* w'	C* w'	D* w'	w'	A* w'	B* w'	C* w'	D* w'	w'	A* w'	B* w'	C* w'	D* w'
				A	B	C	D															
Environmental	Carbon neutrality	2	3	2	2	3	3	0.13	0.27	0.27	0.40	0.40	0.13	0.81	0.81	1.08	1.08	0.13	0.27	0.27	0.40	0.40
	Greenhouse gas emission	2	3	2	2	3	3	0.12	0.24	0.24	0.36	0.36	0.12	0.48	0.48	0.72	0.72	0.12	0.36	0.36	0.48	0.48
	Environmental impact	3	5	3	3	5	5	0.11	0.32	0.32	0.54	0.54	0.11	0.75	0.75	0.86	0.86	0.11	0.32	0.32	0.54	0.54
	Discharge limitation	3	5	3	3	5	5	0.09	0.28	0.28	0.47	0.47	0.09	0.37	0.37	0.47	0.47	0.09	0.47	0.47	0.56	0.56
	Air pollution	2	4	2	2	4	4	0.14	0.28	0.28	0.57	0.57	0.14	0.28	0.28	0.71	0.71	0.14	0.43	0.43	0.57	0.57
	Water supply	2	6	2	2	6	6	0.06	0.12	0.12	0.36	0.36	0.06	0.12	0.12	0.36	0.36	0.06	0.12	0.12	0.36	0.36
	Green energy	6	7	6	6	7	7	0.05	0.32	0.32	0.38	0.38	0.05	0.05	0.05	0.11	0.11	0.05	0.05	0.05	0.11	0.11
	Eutrophication	7	8	7	7	8	8	0.07	0.51	0.51	0.59	0.59	0.07	0.22	0.22	0.37	0.37	0.07	0.22	0.22	0.29	0.29
	Ecological risk	4	6	4	4	6	6	0.07	0.29	0.29	0.43	0.43	0.07	0.36	0.36	0.50	0.50	0.07	0.21	0.21	0.43	0.43
	Thermal pollution	1	4	1	1	4	4	0.04	0.04	0.04	0.17	0.17	0.04	0.30	0.30	0.35	0.35	0.04	0.04	0.04	0.17	0.17
	Pollution of water	2	5	2	2	5	5	0.08	0.16	0.16	0.41	0.41	0.08	0.33	0.33	0.49	0.49	0.08	0.33	0.33	0.41	0.41
	Aquifer preservation	6	8	6	6	8	8	0.02	0.12	0.12	0.16	0.16	0.02	0.12	0.12	0.16	0.16	0.02	0.10	0.10	0.12	0.12
Index Score								2.96	2.96	4.82	4.82	4.19	4.19	6.16	6.16	2.92	2.92	4.44	4.44			

5.5.4. Comparison matrix for social criteria

There are very few studies in which innovative technologies are evaluated socially. Sustainable strategies can be developed by evaluating the results that can be determined because of social analysis and survey studies. In social perspective, the social benefit of recovered technology has a high percentage for sustainability, while the educational and cultural contribution and aesthetic features of recovered technology are the least considered criteria in sustainability (Table 5.21).

Table 5.21: Comparison matrix of social criteria.

	Social Benefit		Public acceptance		Governmental support		Aesthetic		Direct/Indirect jobs		Health status		Educational/cultural	
	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN	Score	STFN
Social Benefit	(1, 1)	(1,1,1, 1)	(4, 6)	(4,4,6, 6)	(5, 6)	(5,5,6, 6)	(8, 9)	(8,8,9, 9)	(3, 4)	(3,3,4, 4)	(2, 3)	(2,2,3, 3)	(7, 9)	(7, 7,9, 9)
Public acceptance	(1/4, 1/6)	(1/4,1/6, 1/6)	(1, 1)	(1,1,1, 1)	(3, 4)	(3,3,4, 4)	(7, 8)	(7,7,8, 8)	(8, 9)	(8,8,9, 9)	(4, 5)	(4,4,5, 5)	(8, 9)	(8, 8,9, 9)
Governmental support	(1/5, 1/6)	(1/5,1/6, 1/6)	(1/3, 1/4)	(1/3,1/4, 1/4)	(1, 1)	(1,1,1, 1)	(7, 8)	(7,7,8, 8)	(4, 5)	(4,4,5, 5)	(4, 5)	(4,4,5, 5)	(6, 8)	(6, 6,8, 8)
Aesthetic	(1/8, 1/9)	(1/8,1/9, 1/9)	(1/7, 1/8)	(1/7,1/8, 1/8)	(1/7, 1/8)	(1/7,1/8, 1/8)	(1, 1)	(1,1,1, 1)	(1, 2)	(1,1,2, 2)	(1, 2)	(1,1,2, 2)	(2, 3)	(2, 2,3, 3)
Direct/Indirect jobs	(1/3, 1/4)	(1/3,1/4, 1/4)	(1/8, 1/9)	(1/8,1/9, 1/9)	(1/4, 1/5)	(1/4,1/5, 1/5)	(1, 1/2)	(1,1,1/2, 1/2)	(1, 1)	(1,1,1, 1)	(4, 5)	(4,4,5, 5)	(5, 7)	(5, 5,7, 7)
Health status	(1/2, 1/3)	(1/2,1/3, 1/3)	(1/4, 1/5)	(1/4,1/5, 1/5)	(1/4, 1/5)	(1/4,1/5, 1/5)	(1, 1/2)	(1,1,1/2, 1/2)	(1/4, 1/5)	(1/4,1/5, 1/5)	(1, 1)	(1,1,1, 1)	(3, 7)	(3, 3,7, 7)
Educational/cultural	(1/7, 1/9)	(1/7,1/9, 1/9)	(1/8, 1/9)	(1/8,1/9, 1/9)	(1/6, 1/8)	(1/6,1/8, 1/8)	(1/2, 1/3)	(1/2,1/3, 1/3)	(1/5, 1/7)	(1/5,1/7, 1/7)	(1/3, 1/7)	(1/3,1/7, 1/7)	(1, 1)	(1, 1,1, 1)

Matrix comparisons were made based on criteria independent of technologies and the weighted average (w) of each criterion was found. The calculations for priority weights are not shown in here, they are calculated like section 5.5.1. Then, considering the contribution to sustainability, the factor indexes of the application were calculated by multiplying the scores given to the criterion. The social criteria factor index calculation for the three selected technologies is shown in Table 5.22.

Table 5.22: Social criteria of three selected technology: fuzzy scores and priority numbers of the factors at the hierarchy level (w').

Air Stripping Technology												Membrane Technology					Precipitation Technology					
Factor	Sub Factor	Score		STFN				w'	A* w'	B* w'	C* w'	D* w'	w'	A* w'	B* w'	C* w'	D* w'	w'	A* w'	B* w'	C* w'	D* w'
				A	B	C	D															
Social	Social Benefit	4	7	4	4	7	7	0.33	1.43	1.43	2.51	2.51	0.33	1.43	1.43	2.51	2.51	0.33	1.43	1.43	2.51	2.51
	Employment	6	8	6	6	8	8	0.24	1.50	1.50	2.00	2.00	0.24	1.50	1.50	2.00	2.00	0.24	1.50	1.50	2.00	2.00
	Governmental support	3	5	3	3	5	5	0.18	0.49	0.49	0.82	0.82	0.18	0.49	0.49	0.82	0.82	0.18	1.15	1.15	1.32	1.32
	Aesthetic	1	3	1	1	3	3	0.06	0.05	0.05	0.15	0.15	0.06	0.05	0.05	0.15	0.15	0.06	0.10	0.10	0.15	0.15
	Direct/Indirect jobs	6	8	6	6	8	8	0.10	0.55	0.55	0.73	0.73	0.10	0.37	0.37	0.46	0.46	0.10	0.37	0.37	0.46	0.46
	Health status	2	3	2	2	3	3	0.07	0.13	0.13	0.20	0.20	0.07	0.13	0.13	0.26	0.26	0.07	0.13	0.13	0.26	0.26
	Education/cultural	1	2	1	1	2	2	0.02	0.02	0.02	0.04	0.04	0.02	0.02	0.02	0.04	0.04	0.02	0.04	0.04	0.11	0.11
	Index Score								4.18	4.18	6.45	6.45		3.99	3.99	6.24	6.24		4.72	4.72	6.80	6.80

5.6. Convert scores into STF_N

The priority weights of the technical, economic, environmental, and social criteria evaluated for air stripping technology were plotted, and then the regions on the score lines where they were located and at which point, they cut were found.

5.6.1. Factor index and membership degree for air stripping

After scoring the factors in the hierarchy and calculation of priority weights, Factor Index (FI) is calculated by using Equation 4.5 in Section 4.6. For example, factor index of technical factors for ammonia stripping technology is calculated with the data in Table 5.16 by using Equation 4.

$$FI = 4 \times 0.24 + 7 \times 0.12 + 3 \times 0.06 + 2 \times 0.11 + 7 \times 0.07 + 2 \times 0.07 + 2 \times 0.06 + 6 \times 0.06 + 3 \times 0.20 \quad (5.6)$$

$$FI = 3.93$$

For air stripping technology intersection points of technical criteria are low (0.45), medium (0.8) and high (0.2). For economic criteria low (0.55) and medium (0.8). For environmental criteria is between low (0.8) and medium (0.95). Social criteria constitute high range which is low (0.35), medium (0.7) and high (0.6) shown in Figure 5.1.

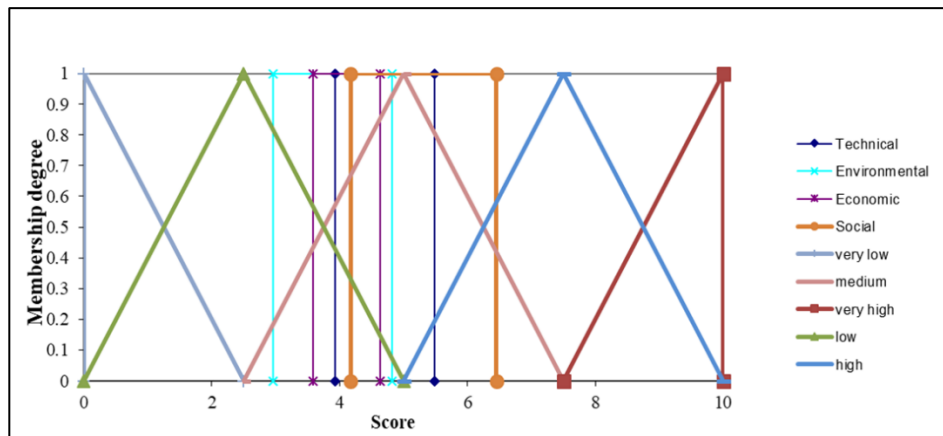


Figure 5.1: Determination of classes and membership degrees of Factor Index for air stripping technology.

5.6.2. Factor index and membership degree for membrane technology

For membrane technology intersection points of technical criteria are low (0.3), medium (0.75) and high (0.65). For economic criteria medium (0.7) and high (0.95). For environmental criteria is between low (0.35), medium (0.7) and high (0.45). Social criteria constitute high range which is low (0.4), medium (0.6) and high (0.5) shown in Figure 5.2.

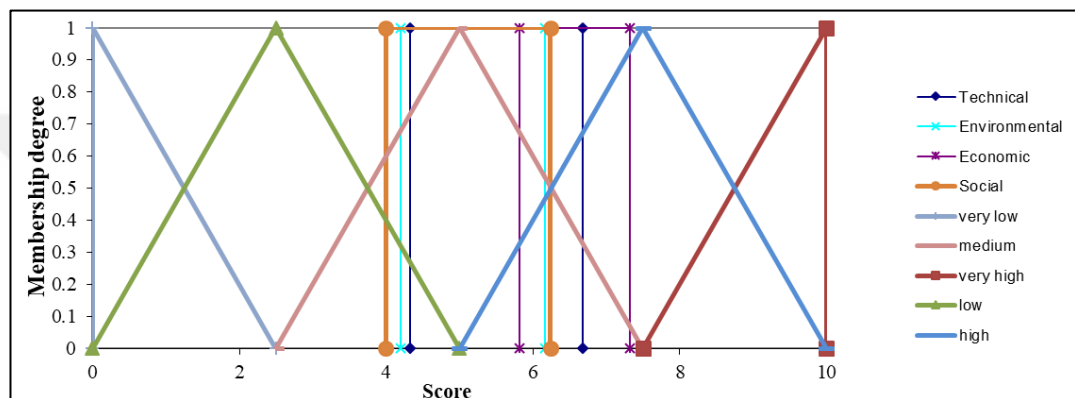


Figure 5.2: Determination of classes and membership degrees of Factor Index for membrane technology.

5.6.3. Factor index and membership degree for precipitation technology

For precipitation technology intersection points of technical criteria are medium (0.95) and high (0.65). For economic criteria low (0.7) and medium (0.9). For environmental criteria is between low (0.85) and medium (0.8). Social criteria constitute high range which is low (0.15), medium (0.9) and high (0.75) shown in Figure 5.3.

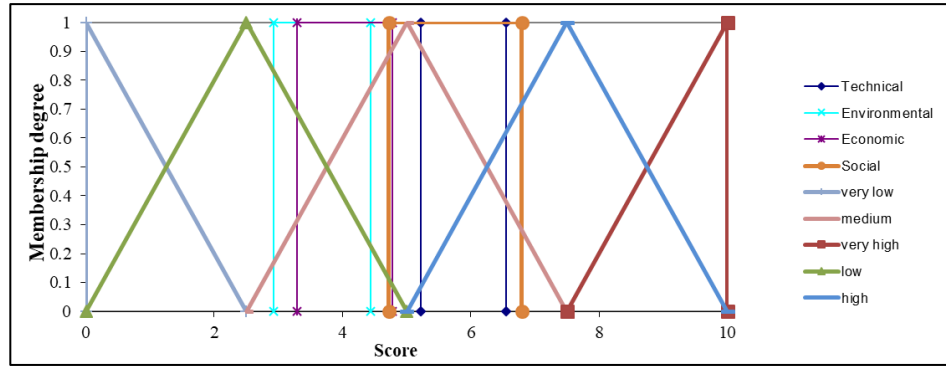


Figure 5.3: Determination of classes and membership degrees of Factor Index for precipitation technology.

For all three technologies membership degree is found high (1).

5.7. Fuzzy Inference Step

5.7.1. Sustainability index for air stripping technology

After calculating the Factor Index of the main factors for the sustainability index necessary evaluations were made and it was predicted how sustainable the technology would be. For example, if all four of the technical, economic, environmental, and social criteria fall within their low range, then the sustainability is low. However, if all four criteria are in the high field, the sustainability of technology becomes high. After Table 5.23 was created, the sustainability index of air stripping technology was investigated. In this case, the areas of importance created according to the criteria used in sustainability index and the points where the graph cuts are critical.

Table 5.23: Membership degrees of stripping technology in terms of technical, economic, environmental, and social aspects.

Technical	Economical	Environmental	Social		
			Low(0.35)	Medium (0.7)	High (0.6)
Low(0.45)	Low (0.55)	Low (0.8)	Low(0.35)	Low(0.45)	Medium(0.45)
		Medium (0.95)	Low(0.35)	Medium(0.45)	Medium(0.45)
	Medium (0.8)	Low (0.8)	Low(0.35)	Medium(0.45)	Medium(0.45)
		Medium (0.95)	Medium(0.35)	Medium(0.45)	Medium(0.45)
Medium(0.8)	Low (0.55)	Low (0.8)	Low(0.35)	Medium(0.55)	Medium(0.55)
		Medium (0.95)	Medium(0.35)	Medium(0.55)	Medium(0.55)
	Medium (0.8)	Low (0.8)	Medium(0.35)	Medium(0.7)	Medium(0.6)
		Medium (0.95)	Medium(0.35)	Medium(0.7)	Medium(0.6)
High(0.2)	Low (0.55)	Low (0.8)	Medium(0.2)	Medium(0.2)	Medium(0.2)
		Medium (0.95)	Medium(0.2)	Medium(0.2)	Medium(0.2)
	Medium (0.8)	Low (0.8)	Medium(0.2)	Medium(0.2)	Medium(0.2)
		Medium (0.95)	Medium(0.2)	Medium(0.2)	Medium(0.2)

To find the sustainability index, FI scores in STFNN form are converted into fuzzy sets, so fuzzy inference can be applied. Overall, the combined values are summarized in the Table 5.23 for air stripping. According to Table 5.23 low (0.45), medium (0.7)

values are integrated with scale scores, then according to Equation 4.6 SI for air stripping is calculated as 2.83.

$$SI_{air\ stripping} = \frac{0.45 \times 1 + 0.7 \times 4}{0.45 + 0.7} = 2.83 \quad (5.7)$$

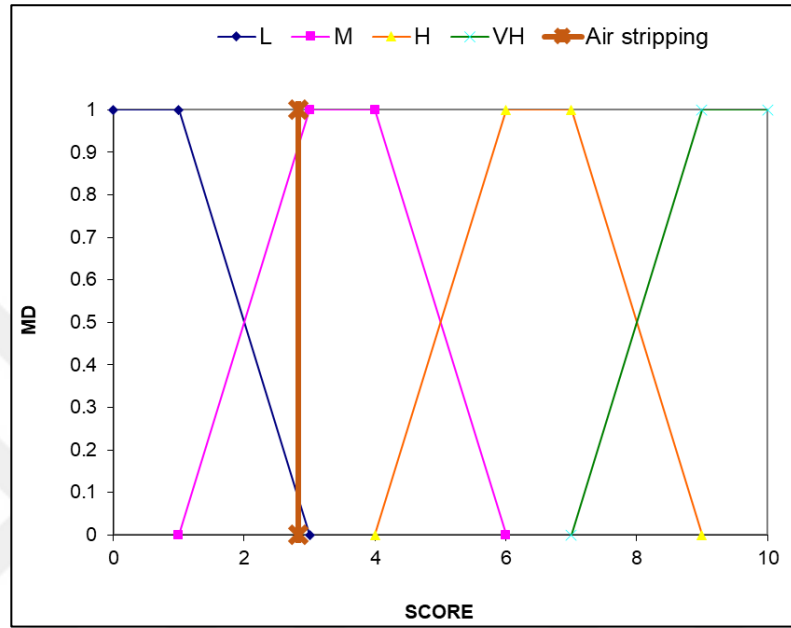


Figure 5.4: Sustainability index of air stripping technology.

The value transferred to Table 5.24 and calculated by multiplying the maximum scale limit is shown on the chart containing low, medium, high, very high (Figure 5.4).

Table 5.24: Calculation of sustainability index intervals found as a result of the evaluation for air stripping technology.

	Max value	Scale constant
Low	0.45	1
Medium	0.7	4

5.7.2. Sustainability index for membrane technology

After Table 5.25 was created, the sustainability index of membrane technology was investigated. In this case, the areas of importance created according to the criteria used in sustainability index and the points where the graph cuts are critical.

Table 5.25: Membership degrees of membrane technology in terms of technical, economic, environmental, and social aspects.

			Social		
Technical	Economical	Environmental	Low(0.4)	Medium(0.6)	High (0.5)
Low(0.3)	Medium (0.7)	Low (0.35)	Low(0.3)	Low(0.3)	Medium(0.3)
		Medium (0.7)	Low(0.3)	Medium(0.3)	Medium(0.3)
		High (0.45)	Medium(0.3)	Medium(0.3)	Medium(0.3)
	High (0.95)	Low (0.35)	Low(0.3)	Medium(0.3)	Medium(0.3)
		Medium (0.7)	Medium(0.3)	Medium(0.3)	Medium(0.3)
		High (0.45)	Medium(0.3)	Medium(0.3)	High(0.3)
Medium(0.75)	Medium (0.7)	Low (0.35)	Low(0.35)	Medium(0.35)	Medium(0.35)
		Medium (0.7)	Medium(0.4)	Medium(0.6)	Medium(0.5)
		High (0.45)	Medium(0.4)	Medium(0.45)	Medium(0.45)
	High (0.95)	Low (0.35)	Medium(0.35)	Medium(0.35)	Medium(0.35)
		Medium (0.7)	Medium(0.4)	Medium(0.6)	Medium(0.5)
		High (0.45)	Medium(0.4)	Medium(0.45)	High(0.45)
High(0.65)	Medium (0.7)	Low (0.35)	Medium(0.35)	Medium(0.35)	Medium(0.35)
		Medium (0.7)	Medium(0.4)	Medium(0.6)	Medium(0.5)
		High (0.45)	Medium(0.4)	Medium(0.45)	High(0.45)
	High (0.95)	Low (0.35)	Medium(0.35)	Medium(0.35)	High(0.35)
		Medium (0.7)	Medium(0.4)	Medium(0.6)	High(0.5)
		High (0.45)	High(0.4)	High(0.45)	High(0.45)

Overall, the combined values are summarized in the Table 5.25 for membrane technology. According to Table 5.25 low (0.35), medium (0.6) and high (0.5) values are integrated with scale scores, then according to Equation 4.6. SI for membrane is calculated as 4.31.

$$SI_{membrane} = \frac{0.35 \times 1 + 0.6 \times 4 + 0.5 \times 7}{0.35 + 0.6 + 0.5} = 4.31 \quad (5.8)$$

The value transferred to Table 5.26 and calculated by multiplying the maximum scale limit is shown on the chart containing low, medium, high, and very high (Figure 5.5).

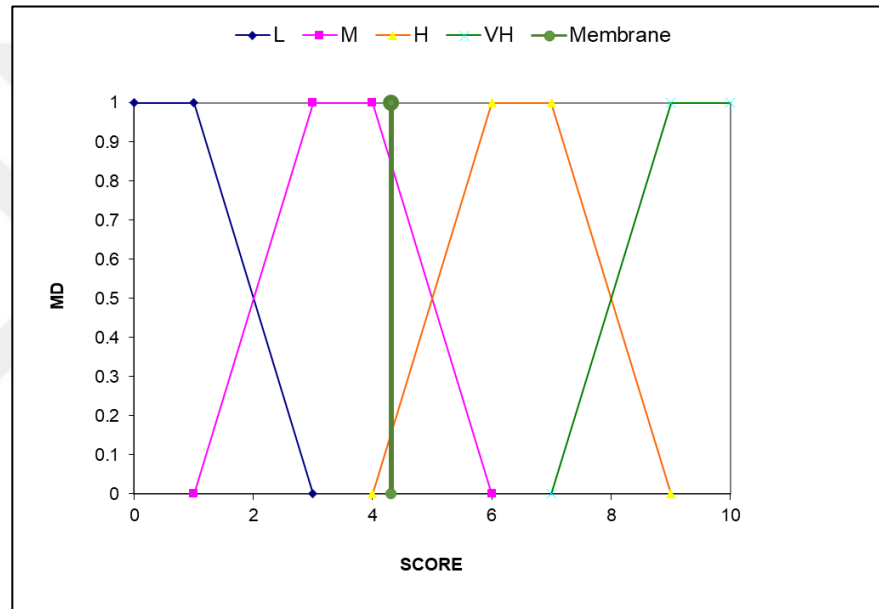


Figure 5.5: Sustainability index of membrane technology.

Table 5.26: Calculation of the sustainability index intervals found as a result of the evaluation for membrane technology.

	Max value	Scale score
Low	0.35	1
Medium	0.6	4
High	0.5	7

5.7.3. Sustainability index for precipitation technology

After Table 5.27 was created, the sustainability index of precipitation technology was investigated. In this case, the areas of importance created according to the criteria used in sustainability index and the points where the graph cuts are critical.

Table 5.27: Membership degrees of precipitation technology in terms of technical, economic, environmental, and social aspects.

			Social		
Technical	Economical	Environmental	Low(0.15)	Medium(0.9)	High (0.75)
Medium(0.95)	Low (0.7)	Low (0.85)	Low(0.15)	Low(0.7)	Medium(0.7)
		Medium (0.8)	Low(0.15)	Medium(0.7)	Medium(0.7)
	Medium (0.9)	Low (0.85)	Low(0.15)	Medium(0.85)	Medium(0.75)
		Medium (0.8)	Medium(0.15)	Medium(0.8)	Medium(0.75)
High(0.65)	Low (0.7)	Low (0.85)	Medium(0.15)	Medium(0.65)	Medium(0.65)
		Medium (0.8)	Medium(0.15)	Medium(0.65)	Medium(0.65)
	Medium (0.9)	Low (0.85)	Medium(0.15)	Medium(0.65)	Medium(0.65)
		Medium (0.8)	Medium(0.15)	Medium(0.65)	Medium(0.65)

Overall, the combined values are summarized in the Table 5.27 for precipitation technology. According to Table 5.27 low (0.7) and medium (0.85) values are

integrated with scale scores, then according to Equation 4.6 SI for membrane is calculated as 2.65.

$$SI_{precipitation} = \frac{0.7 \times 1 + 0.85 \times 4}{0.7 + 0.85} = 2.65 \quad (5.9)$$

The value transferred to Table 5.28 and calculated by multiplying the maximum scale limit is shown on the chart containing low, medium, high, and very high (Figure 5.6).

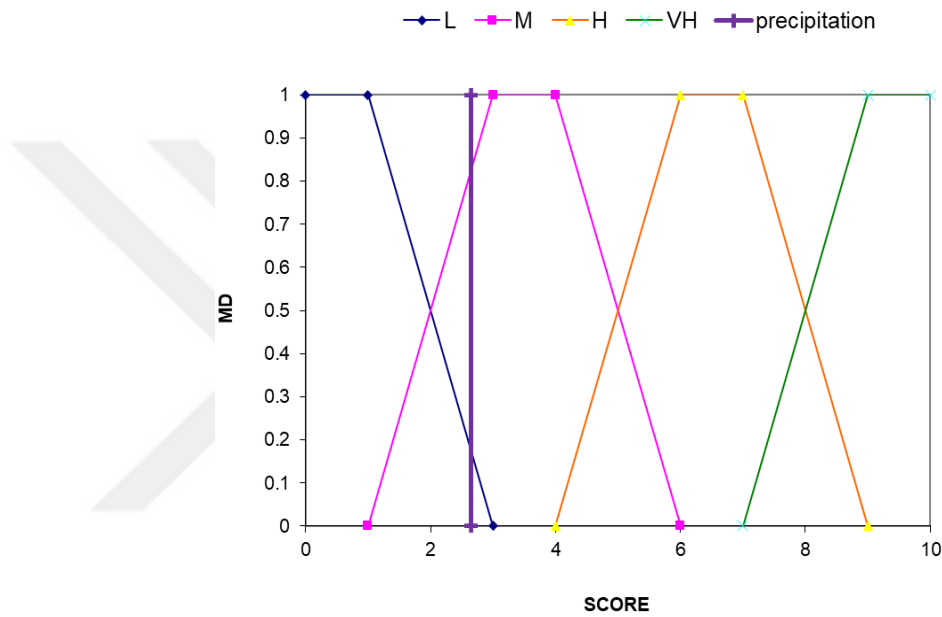


Figure 5.6: Sustainability index of precipitation technology.

Table 5.28: Calculation of the sustainability index intervals found as a result of the evaluation for precipitation technology.

	Max value	Scale score
Low	0.7	1
Medium	0.85	4

5.8. ANP method with TOPSIS

5.8.1. Cognitive Mapping

For three alternative technologies targeted to be selected for nitrogen recovery from wastewater, the relationship between 32 related criteria was investigated with cognitive mapping.

An empty 32x32 matrix with attributes in both rows and columns is created and filled as a cognitive map by experts, regardless of the sign of the relationship between all these 32 attributes. All relationships between each attribute can be seen in the matrix given in Table 5.29.

For example, it is seen that the attribute of applicability among technical attributes is related to reliability, complexity of the system, time limitation and waste generation within its own cluster. Since the applicability attribute reveals the technical possibility of the recovery technology, this qualification has no relation with the economic and social criteria. System complexity, among the technical attributes, affects the initial installation, repair and maintenance costs, while at the same time it affects the direct/indirect jobs from the social cluster as it symbolizes the presence of new technology. Among the economic attributes, the initial investment cost is related to the land requirement, applicability, reliability, and whether the recovery technology will be an alternative for energy supply. Operation cost attribute, on the other hand, is related to the greenhouse emission among the environmental attributes, while it is related to the transport cost and waste cost, which are considered as the items of the operational cost from the same cluster.

Although recovery technologies are a part of sustainability, they are not considered innocent technologies for the environment totally. Of the environmental attributes, environmental pollution is associated with the health status attribute among many technical and social attributes. The thermal pollution criterion can only be related in cases where the technology is suitable for energy recovery where the waste hot water potential of the process is present. Therefore, the thermal pollution attribute is related to the alternative for energy supply attribute among the attributes.

The social benefit attribute is related to the capacity of the plant and the revenue attribute, since the wastewater recovery technology requires governmental support, the

governmental support attribute, and the technical possibilities of the technology contribute to the social benefit. In addition, while providing social benefits, the emission of greenhouse gases related to public health and environmental pollution are directly related to social benefit attribute. The aesthetic attribute was the weakest attribute among the social attributes and its relationship with other attributes. Providing employment is shaped in line with human needs, depending on the characteristics of new technologies. Therefore, the employment attribute can be correlated with the applicability and realism of the system. Since recovery technologies are an important breakthrough for society, social attributes are the most closely linked to other attributes (Table 5.29).



Table 5.29: Cognitive map in matrix representation.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7	
A1	0	0	0	*	0	0	*	0	0	*	*	*	0	*	*	*	*	0	*	0	*	*	*	*	*	0	*	*	*	0	*	*	
A2	0	0	0	0	0	*	*	0	0	0	*	*	*	*	*	0	0	0	0	0	*	*	0	0	0	0	*	*	*	0	*	*	
A3	0	0	0	0	0	0	0	0	0	0	0	*	*	*	*	*	0	0	0	0	*	*	0	*	0	0	*	0	0	0	0	*	
A4	*	0	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A5	0	0	0	0	0	*	0	0	0	0	0	0	0	*	*	0	0	0	0	0	0	*	0	0	0	0	0	0	0	*	0	*	
A6	0	*	0	0	*	0	*	0	0	0	*	*	0	*	*	0	0	0	0	0	*	*	0	0	0	0	*	*	*	0	*	*	
A7	*	*	*	0	*	*	0	0	*	*	*	*	*	*	0	0	0	0	0	0	*	*	0	0	0	0	*	0	*	0	*	0	
A8	0	*	0	0	0	*	0	0	0	0	0	0	0	*	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A9	*	0	*	0	*	0	0	0	0	0	0	0	*	*	0	*	0	0	0	0	*	*	0	*	*	0	0	0	0	0	*	0	0
B1	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B2	*	*	0	0	0	*	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	0	0	0	
B3	*	*	*	0	0	*	*	0	0	0	0	0	0	*	0	0	0	*	0	0	*	0	0	0	0	0	0	0	0	0	*	*	0
B4	0	*	0	0	0	0	*	0	*	0	0	0	0	0	*	*	0	0	0	*	*	0	0	0	0	0	0	0	0	0	0	*	0
B5	*	*	*	0	*	*	*	*	*	0	0	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B6	*	*	*	0	*	*	0	*	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	*	*	*	
B7	*	0	*	0	0	0	0	0	*	0	0	0	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	0	0	0	0	*	*	0	0	0	0	0	*	0	*	
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	0	0	0	0	0	*	*	0	0	0	0	*	0	0	0	
C3	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	*	0	0	0	0	0	0	0	0	0	*	0	0
C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	*	0	*	*	0	0	0	0	0	0	0	0
C5	*	*	*	0	0	*	*	0	*	0	0	0	0	0	0	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0	*	0	0
C6	*	*	*	0	*	*	*	0	*	0	0	0	0	0	0	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0	*	0	0
C7	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0	0	0	0	*	0	0
C8	*	0	*	0	0	0	0	0	*	0	0	0	0	0	0	0	*	0	0	*	0	0	0	0	0	0	0	0	0	*	0	*	0
C9	*	0	0	0	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0	*	0	0	0	0	0	0	0	0	0	0	*	0	0
D1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	0	*
D2	*	*	*	0	0	*	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	0	0	0	0	0	*	0	0	*	*	
D3	*	*	0	0	0	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	*
D4	*	*	0	0	*	*	0	0	0	0	*	0	0	0	*	0	0	*	0	0	0	0	*	0	*	0	0	0	0	0	0	0	*
D5	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	0	*	0	*	*	*	0	*	0	0	0	0	0	0	*	0
D6	*	*	0	0	*	*	*	0	0	0	0	*	*	0	*	0	0	0	0	0	0	0	0	*	*	*	*	*	0	*	0	0	0
D7	*	0	*	0	*	*	0	0	0	0	0	0	0	0	*	0	*	0	0	0	0	0	0	0	0	0	*	*	*	0	0	0	0

5.8.2. Checking Limit Matrix Without Pairwise Comparison of Attributes

As explained in Chapter 3.3, the steps to create a hierarchy in the Super Decisions program are explained. A cognitive map was created by transferring 32 attributes to the program. Also, the dependencies between clusters, attribute under clusters, and attribute obtained from the cognitive map are entered into the Super Decisions software to have a suitable ANP model of the case study. Unweighted super matrix, weighted super matrix and limit matrix are shown in Tables 5.30, 5.31, 5.32.

While the relations obtained from the cognitive map are transferred to numerical values, firstly, unweighted supermatrix is created by assuming equal preferences of the attributes described in Chapter 4.13. To find the weighted super matrix, Manhattan distance normalization of the unweighted super matrix is calculated. Then, to find the limit matrix, the weighted supermatrix square matrix is taken 5 times until convergence occurs. At the end of the calculation, the limit matrix is reached. When the limit matrix is examined, all the numbers in the same row are found to be the same, it shows that the dependency between the attributes is sufficient and the ANP method can be used safely.

For example, when the A1 column is taken into account among the technical qualifications, the integer number 1 is divided by 2 and equal values are assigned to the qualifications since it is related to 2 criteria from the qualifications A1 to A9. Likewise, since the C5 criterion has 6 relations, equal relations are expressed with 0.167 (Figure 5.7) .

At the tables below unweighted supermatrix, weighted supermatrix and limit matrix without comparison of attributes are shown.

From the limit matrix calculation, it can be concluded that at the same row of limit matrix all the numbers are found to be same which shows that convergence happened. For example, for A3 row 0.02845 can be seen for the entire row. So ANP can be used as an appropriate method for this case study.

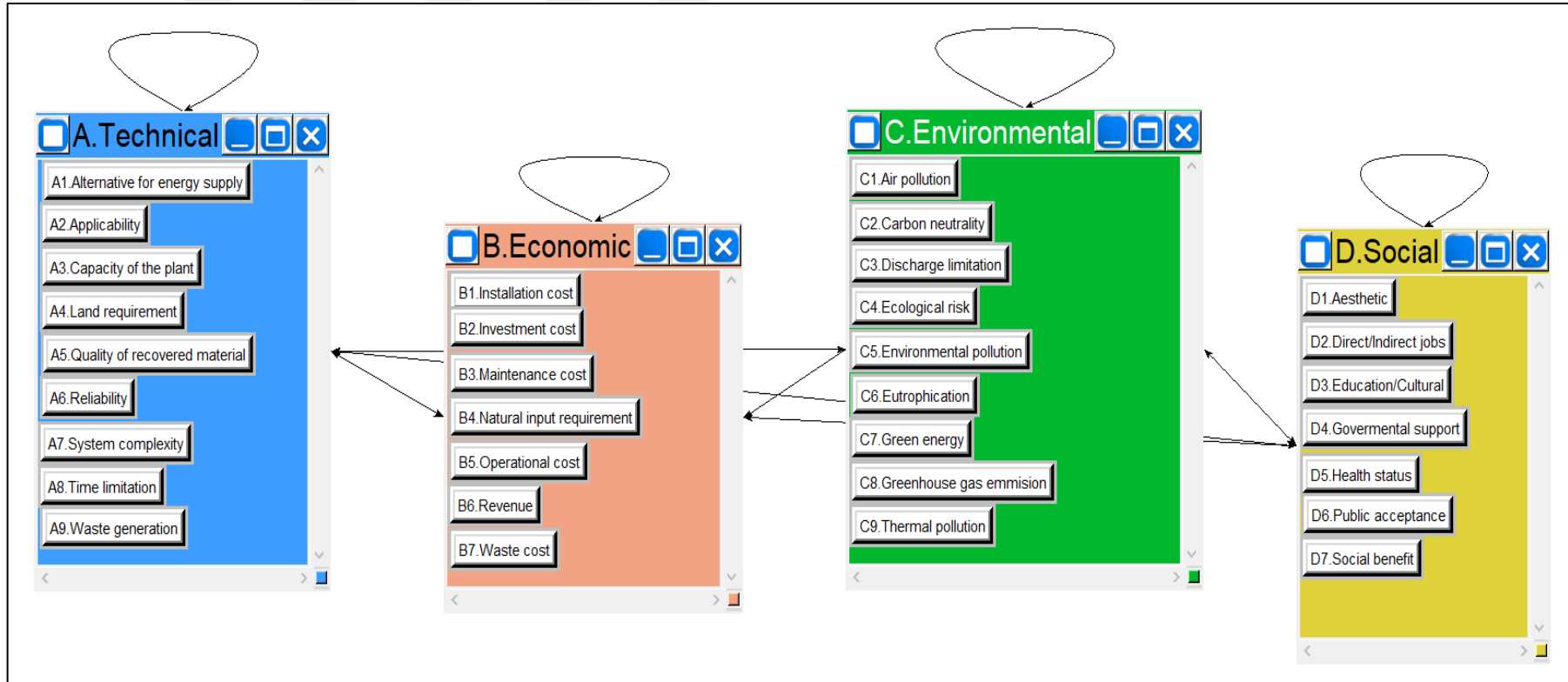


Figure 5.7: ANP model of study structured on Super Decisions Software.

Table 5.30: Unweighted Super Matrix Without Pairwise Comparison of Attributes.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7
A	0.0	0.0	0.0	1.0	0.0	0.0	0.3	0.0	0.0	0.5	0.2	0.2	0.0	0.1	0.1	0.3	1.0	0.0	1.0	0.0	0.1	0.1	1.0	0.3	0.5	0.0	0.2	0.3	0.2	0.0	0.2	0.2
1	00	00	00	00	00	00	33	00	00	00	50	00	00	25	67	33	00	00	00	00	67	43	00	33	00	00	00	33	00	00	00	00
A	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.0	0.0	0.0	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.2	0.3	0.2	0.0	0.2	0.2
2	00	00	00	00	00	50	33	00	00	00	50	00	50	25	67	00	00	00	00	00	67	43	00	00	00	00	00	33	00	00	00	00
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.1	0.1	0.3	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.2
3	00	00	00	00	00	00	00	00	00	00	00	00	50	25	67	33	00	00	00	00	67	43	00	33	00	00	00	00	00	00	00	00
A	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	33	00	33	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
A	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.2	0.2
5	00	00	00	00	00	50	00	00	00	00	00	00	00	25	67	00	00	00	00	00	00	43	00	00	00	00	00	00	00	00	00	00
A	0.0	0.3	0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.2	0.2	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.2	0.3	0.2	0.0	0.2	0.2
6	00	33	00	00	33	00	33	00	00	00	50	00	00	25	67	00	00	00	00	00	67	43	00	00	00	00	00	33	00	00	00	00
A	0.3	0.3	0.3	0.0	0.3	0.2	0.0	0.0	1.0	0.5	0.2	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.2	0.0	0.2	0.0	0.2	0.0
7	33	33	33	00	33	50	00	00	00	00	50	00	50	25	00	00	00	00	00	00	67	43	00	00	00	00	00	00	00	00	00	00
A	0.0	0.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	00	33	00	00	00	50	00	00	00	00	00	00	00	25	67	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
A	0.3	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.5	0.0	0.0	0.0	0.0	1.0	0.0	0.0
9	33	00	33	00	33	00	00	00	00	00	00	00	50	25	00	33	00	00	00	00	67	43	00	33	00	00	00	00	00	00	00	00
B	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	67	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
B	0.1	0.2	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
2	67	00	00	00	00	50	50	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
B	0.1	0.2	0.2	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	1.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.0
3	67	00	50	00	00	50	50	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00
B	0.0	0.2	0.0	0.0	0.0	0.0	0.2	0.0	0.3	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
4	00	00	00	00	00	00	50	00	33	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00
B	0.1	0.2	0.2	0.0	0.5	0.2	0.2	0.5	0.3	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	67	00	50	00	00	50	50	00	33	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
B	0.1	0.2	0.2	0.0	0.5	0.2	0.0	0.5	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.3	1.0
6	67	00	50	00	00	50	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00
B	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	67	00	50	00	00	00	00	00	33	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00

Table 5.30: continue.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7
C	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.2	0.0	1.0
1	43	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00	00	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0
2	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00	00	00	33	00	00	00	00	33	00	00	00
C	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
3	43	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	50	00	00	00	00	00	00	00	00	00	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	0.0	0.3	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00	00	00	00	00
C	0.1	0.5	0.3	0.0	0.0	0.5	0.5	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	
5	43	00	33	00	00	00	00	00	50	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
C	0.1	0.5	0.3	0.0	1.0	0.5	0.5	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
6	43	00	33	00	00	00	00	00	50	00	00	00	00	00	00	00	00	00	00	50	00	00	00	00	00	00	00	00	00	00	00	00
C	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
7	43	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
C	0.1	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.5	0.0
8	43	00	33	00	00	00	00	00	50	00	00	00	00	00	00	00	33	00	00	50	00	00	00	00	00	00	00	00	33	00	00	00
C	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.5	0.0
9	43	00	00	00	00	00	00	00	50	00	00	00	00	00	00	00	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33	00	00	00
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	
1	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	50	00
D	0.1	0.2	0.5	0.0	0.0	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.2	0.3
2	67	50	00	00	00	00	33	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	50	33
D	0.1	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3
3	67	50	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	50	33
D	0.1	0.2	0.0	0.0	0.3	0.2	0.3	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.3	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
4	67	50	00	00	33	00	33	00	00	00	00	00	00	00	33	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33
D	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	1.0	0.0	1.0	1.0	0.5	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.2	0.0
5	67	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	50	00
D	0.1	0.2	0.0	0.0	0.3	0.2	0.3	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	1.0	0.5	0.3	0.0	1.0	0.0	0.0
6	67	50	00	00	33	00	33	00	00	00	00	00	00	00	33	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00
D	0.1	0.0	0.5	0.0	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3	1.0	0.0	0.0	0.0
7	67	00	00	00	33	00	00	00	00	00	00	00	00	00	33	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00

Table 5.31: Weighted Super Matrix Without Pairwise Comparison of Attributes.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7	
A1	0	0	0	1	0	0	0.083	0	0	0.05	0.125	0.067	0	0.063	0.056	0.167	0.333	0	0.025	0	0.042	0.048	0.333	0.111	0.167	0	0.01	0.167	0.05	0	0.05	0.05	
A2	0	0	0	0	0	0.063	0.083	0	0	0	0.125	0.067	0.083	0.063	0.056	0	0	0	0	0	0.042	0.048	0	0	0	0	0.01	0.167	0.05	0	0.05	0.05	
A3	0	0	0	0	0	0	0	0	0	0	0	0.067	0.083	0.063	0.056	0.167	0	0	0	0	0.042	0.048	0	0.111	0	0	0.01	0	0	0	0	0.05	
A4	0.083	0	0.083	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A5	0	0	0	0	0	0.063	0	0	0	0	0	0	0	0.063	0.056	0	0	0	0	0	0	0.048	0	0	0	0	0	0	0.05	0	0.05	0.05	
A6	0	0.083	0	0	0.083	0	0.083	0	0	0	0.125	0.067	0	0.063	0.056	0	0	0	0	0	0.042	0.048	0	0	0	0	0.01	0.167	0.05	0	0.05	0.05	
A7	0.083	0.083	0.083	0	0.083	0.063	0	0	0.333	0.05	0.125	0.067	0.083	0.063	0	0	0	0	0	0	0.042	0.048	0	0	0	0	0.01	0	0.05	0	0.05	0.05	
A8	0	0.083	0	0	0	0.063	0	0	0	0	0	0	0	0.063	0.056	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A9	0.083	0	0.083	0	0.083	0	0	0	0	0	0	0	0.083	0.063	0	0.167	0	0	0	0	0.042	0.048	0	0.111	0.167	0	0	0	0	0.25	0	0	
B1	0.042	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B2	0.042	0.05	0	0	0	0.063	0.063	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.125	0	0	0	
B3	0.042	0.05	0.063	0	0	0.063	0.063	0	0	0	0	0	0	0.5	0	0	0	0.333	0.25	0	0.125	0	0	0	0	0	0	0	0	0.125	0.083	0	
B4	0	0.05	0	0	0	0	0.063	0	0.111	0	0	0	0	0	0.333	0.5	0	0	0	0	0.125	0	0	0	0	0	0	0	0	0	0.083	0	
B5	0.042	0.05	0.063	0	0.125	0.063	0.063	0.05	0.111	0	0	0.333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B6	0.042	0.05	0.063	0	0.125	0.063	0	0.05	0	0	0	0	0.167	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.125	0.125	0.083	0.05	
B7	0.042	0	0.063	0	0	0	0	0	0.111	0	0	0	0.167	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.31: Continue.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
1	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	67	00	00	00	00	00	67	11	00	00	00	00	67	00	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	63	50	00	00	00	00	00	00	00	00	50	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	50	50	00	11	33	00	00	00	00	00	00	00	00
C	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	25	83	00	00	25	25	00	50	00	00	00	00	00	00	00	00	00	33	00	00	00	00	00	00	00	00	00	00	50	00	00	00
C	0.1	0.0	0.0	1.0	0.1	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	25	83	00	00	25	25	00	50	00	00	00	00	00	00	00	00	00	00	63	00	00	00	00	00	00	00	00	00	50	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	67	00	00	00	00	00	00	00	00	00	00	00	00	50	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0
7	00	83	00	00	00	00	00	50	00	00	00	00	00	00	00	67	00	00	63	00	00	00	00	00	00	00	00	67	00	25	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0
8	00	00	00	00	00	00	00	50	00	00	00	00	00	00	00	00	00	00	63	00	00	00	00	00	00	00	00	67	00	25	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	63	00	00	00
D	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
1	63	25	00	00	50	83	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	67	00	00	00	00	67	00	00	63	83	00
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	63	00	00	00	50	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	63	83	00
D	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	63	00	00	33	50	83	00	00	00	00	00	00	00	67	00	00	33	00	00	00	00	00	67	00	00	00	00	00	00	00	83	00
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.3	0.0	0.5	0.2	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	50	00	33	00	00	50	67	00	67	00	00	00	00	63	00	00	00
D	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.3	0.5	0.1	0.0	0.2	0.0	0.0	0.0
5	63	00	00	33	50	83	00	00	00	00	00	33	00	67	00	00	00	00	00	00	00	00	67	33	00	67	00	50	00	00	00	00
D	0.0	0.1	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.1	0.5	0.0	0.0	0.0	0.0
6	00	25	00	33	50	00	00	00	00	00	00	00	00	67	00	50	00	00	00	00	00	00	00	00	00	00	67	00	00	00	00	00
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00

Table 5.32: Limit Matrix Without Pa

[illegible]

Table 5.32: Continue.

[illegible]

5.8.3. Pairwise Comparison of Alternatives

As explained in Chapter 4.3 of the thesis, fuzzy scores used for scoring in the AHP method were used to compare the related attributes. However, since the fuzzy numbers are assigned in pairs, the values were determined by taking the average of the binary scores for the ANP method. Attributes affecting the same attribute in the same cluster are compared with pairwise comparisons on a scale of 1 to 9.

As a result of the comparisons, eigenvectors showing the weights of the criteria in the cluster according to a certain attribute were found. After having all the required eigenvectors, Super Decisions Software automatically combines these eigenvectors and creates an unweighted super matrix. Since the weights of the clusters were assumed to be equal in this study, cluster comparison was not made in this case study. Only criteria under clusters are compared.

As shown in Figure 5.8 matrix comparisons can be made directly with the Super Decisions Software. Blue scores represent the superiority of the attribute in that row over that column, while the numbers in red indicate the opposite of integers. The blue bar boxes on the right side of the figure represent the eigenvectors of the attributes.

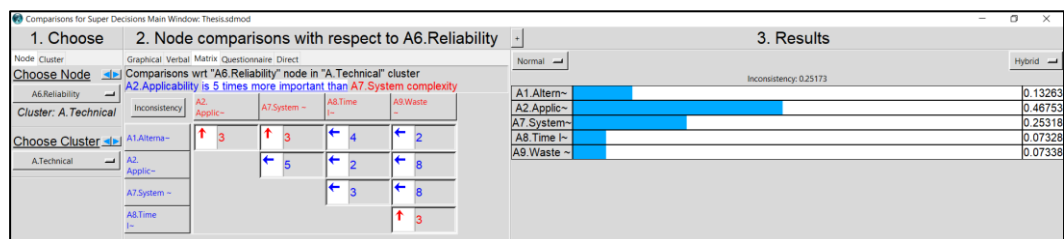


Figure 5.8: Super Decisions Software Attribute Comparisons.

5.8.4. Unweighted Supermatrix, Weighted Supermatrix and Limit Matrix

Matric generation with graphical and text is shown in Figure 5.9 and Figure 5.10. After pairwise comparisons are made, the Super Decisions software automatically generates the below unweighted supermatrix (Table 5.33), weighted supermatrix (Table 5.34) and limit matrix (Table 5.35) with comparison of attributes.

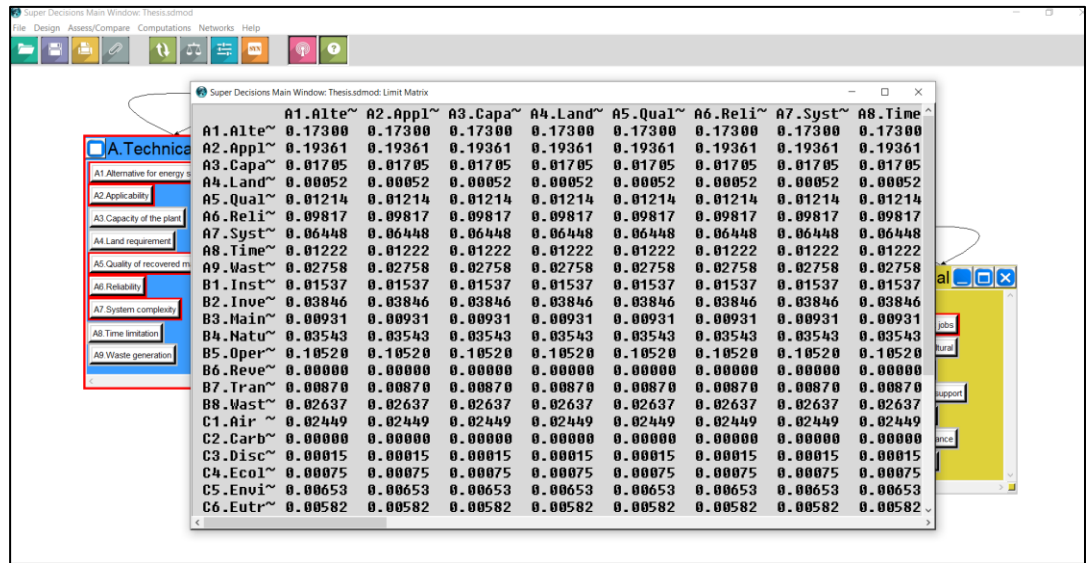


Figure 5.9: Matric generation with text in Super Decisions Software.

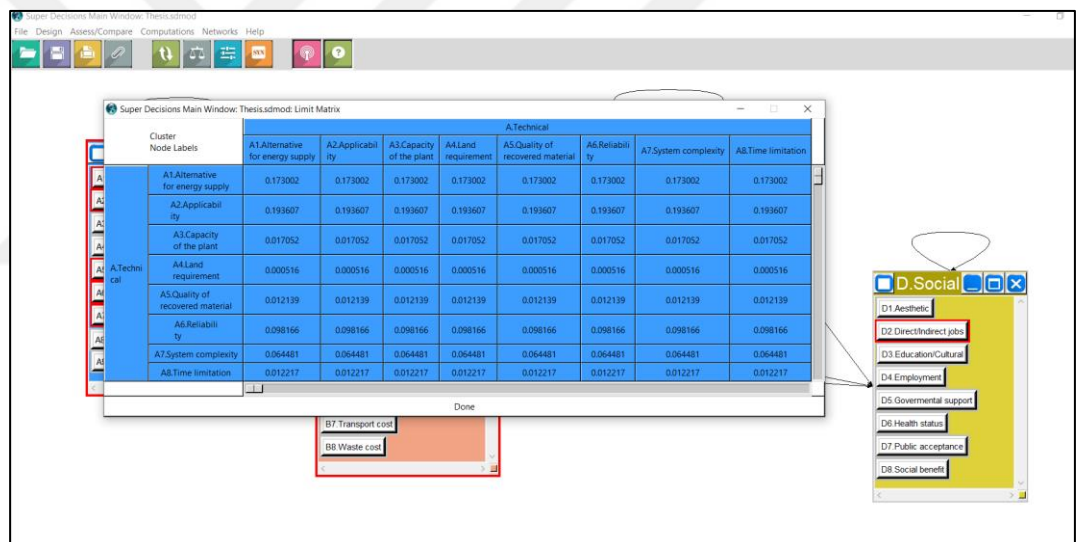


Figure 5.10: Matric generation with graphic in Super Decisions Software.

Table 5.33: Unweighted Super Matrix with Pairwise Comparison of Attributes.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7
A	0.0	0.0	0.0	1.0	0.0	0.0	0.1	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.1	0.2	1.0	0.0	1.0	0.0	0.0	0.0	1.0	0.3	0.5	0.0	0.1	0.1	0.2	0.0	0.1	0.1
1	00	00	00	00	00	00	69	00	00	50	24	81	00	69	67	50	00	00	00	00	94	76	00	11	00	00	12	69	13	00	59	41
A	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.0	0.0	0.3	0.4	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.0	0.0	0.0	0.0	0.3	0.4	0.2	0.0	0.3	0.3
2	00	00	00	00	00	69	43	00	00	00	89	13	55	50	67	00	00	00	00	00	11	36	00	00	00	00	46	43	94	00	60	30
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
3	00	00	00	00	00	00	00	00	00	00	00	00	86	41	65	67	50	00	00	00	00	44	00	00	96	00	00	08	00	00	00	41
A	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	43	00	96	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
A	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1
5	00	00	00	00	00	40	00	00	00	00	00	00	00	45	67	00	00	00	00	00	00	26	00	00	00	00	00	00	41	00	90	41
A	0.0	0.5	0.0	0.0	0.4	0.0	0.3	0.0	0.0	0.0	0.2	0.2	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.2	0.3	0.2	0.0	0.2	0.2
6	00	70	00	00	93	00	87	00	00	00	99	80	00	03	67	00	00	00	00	00	64	06	00	00	00	00	28	87	13	00	11	48
A	0.8	0.3	0.4	0.0	0.3	0.1	0.0	0.0	1.0	0.7	0.1	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.1	0.0
7	57	33	93	00	11	80	00	00	00	50	88	40	63	34	00	00	00	00	00	00	04	49	00	00	00	00	06	00	40	00	80	00
A	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	00	97	00	00	00	10	00	00	00	00	00	00	00	52	67	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
A	0.0	0.0	0.3	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.4	0.5	0.0	0.0	0.0	0.0	1.0	0.0	0.0
9	00	00	11	00	96	00	00	00	00	00	00	00	41	82	00	00	00	00	00	00	83	07	00	93	00	00	00	00	00	00	00	00
B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	23	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
B	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
2	87	67	00	00	00	94	69	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	50	00	00	00
B	0.1	0.1	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	1.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.0
3	02	12	74	00	00	34	61	00	00	00	00	00	00	00	00	00	00	00	00	00	67	00	00	00	00	00	00	00	00	33	11	00
B	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	1.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
4	00	67	00	00	00	00	19	00	49	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00	00	00	00	00	00	96	00
B	0.2	0.3	0.2	0.0	0.3	0.3	0.4	0.3	0.4	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	84	11	94	00	33	58	51	33	74	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
B	0.3	0.4	0.4	0.0	0.6	0.4	0.0	0.6	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.6	0.4	1.0
6	48	43	39	00	67	14	00	67	00	00	00	00	67	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	50	67	93	00
B	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	55	00	92	00	00	00	00	00	76	00	00	00	33	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00

Table 5.33: Continue.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7
C	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.0	0.0	0.0	0.0	0.3	0.0	1.0
1	89	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	67	93	00	00	00	00	00	27	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0
2	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	11	00	00	00	00	33	00	00	00
C	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
3	45	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	76	67	00	00	00	00	00	00	63	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.0	0.0	0.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	96	00	00	00	00	00	00	00	00
C	0.2	0.6	0.2	0.0	0.0	0.6	0.6	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
5	43	67	49	00	00	67	67	00	05	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	47	00	00	00
C	0.1	0.3	0.1	0.0	1.0	0.3	0.3	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
6	09	33	57	00	00	33	33	00	99	00	00	00	00	00	00	00	00	00	00	45	00	00	00	00	00	00	00	00	39	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
7	80	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	23	00	00	00
C	0.1	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.7	0.0
8	58	00	94	00	00	00	00	00	07	00	00	00	00	00	00	00	00	00	00	98	00	00	00	00	00	00	00	00	28	00	50	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0
9	76	00	00	00	00	00	00	00	89	00	00	00	00	00	00	00	00	00	00	81	00	00	00	00	00	00	00	00	40	00	50	00
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
1	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	20	00	00
D	0.2	0.3	0.2	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
2	14	21	00	00	00	20	49	00	00	00	00	00	00	00	00	00	00	00	00	00	00	67	00	00	00	00	00	00	00	65	11	00
D	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0
3	04	94	00	00	00	74	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	35	96	00
D	0.1	0.1	0.0	0.0	0.1	0.1	0.3	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.4	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
4	75	83	00	00	96	60	76	00	00	00	00	00	00	00	62	00	00	00	00	00	00	00	33	00	00	00	00	00	00	00	00	93
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	1.0	0.0	1.0	1.0	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.2	0.0	0.0
5	91	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00	33	00	33	00	00	00	00	00	81	00	00
D	0.1	0.4	0.0	0.0	0.3	0.2	0.4	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6	1.0	0.3	0.3	0.0	1.0	0.0	0.0	0.0
6	66	02	00	00	11	95	74	00	00	00	00	00	00	00	77	00	00	00	00	00	00	00	67	67	00	33	33	00	00	00	00	00
D	0.2	0.0	0.8	0.0	0.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6	1.0	0.0	0.0	0.0
7	51	00	00	00	93	50	00	00	00	00	00	00	00	00	62	00	67	00	00	00	00	00	00	00	00	00	67	67	00	00	00	00

Table 5.34: Weighted Super Matrix with Pairwise Comparison of Attributes.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7
A	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	00	00	00	00	00	00	42	00	00	50	62	27	00	34	56	25	33	00	50	00	24	25	33	04	67	00	56	85	53	00	40	35
A	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.0	
2	00	00	00	00	00	17	11	00	00	00	94	38	52	25	56	00	00	00	00	00	78	79	00	00	00	00	73	22	73	00	90	83
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	00	00	00	00	00	00	00	00	00	00	00	29	47	33	56	25	00	00	00	00	36	33	00	65	00	00	54	00	00	00	00	35
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	36	00	49	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	00	00	00	00	00	60	00	00	00	00	00	00	00	73	56	00	00	00	00	00	00	42	00	00	00	00	00	00	35	00	22	35
A	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	
6	00	42	00	00	23	00	97	00	00	00	50	93	00	01	56	00	00	00	00	00	66	69	00	00	00	00	14	94	53	00	53	62
A	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
7	14	83	23	00	78	45	00	00	33	50	94	47	88	67	00	00	00	00	00	00	26	50	00	00	00	00	03	00	35	00	45	00
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	00	24	00	00	00	28	00	00	00	00	00	00	00	26	56	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
9	00	00	78	00	49	00	00	00	00	00	00	47	41	00	50	00	00	00	00	00	21	36	00	64	67	00	00	00	00	50	00	00
B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	06	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	22	17	00	00	00	24	42	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	63	00	00	00
B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.3	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	25	28	18	00	00	33	65	00	00	00	00	00	00	00	00	00	00	33	50	00	67	00	00	00	00	00	00	00	83	78	00	00
B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.5	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	00	17	00	00	00	00	30	00	50	00	00	00	00	00	33	00	00	00	00	00	83	00	00	00	00	00	00	00	00	49	00	00
B	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	71	78	74	00	83	89	13	33	58	00	00	33	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
B	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	
6	87	11	10	00	67	03	00	67	00	00	00	22	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	88	67	23	50	00
B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	39	00	48	00	00	00	00	00	25	00	00	00	11	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00

Table 5.34: Continue.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
1	47	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00	22	64	00	00	00	00	00	82	00	50
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	33	00	00	00	00	00	11	04	00	00	00	00	83	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	36	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	88	67	00	00	00	00	00	00	00	41	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	83	33	00	65	33	00	00	00	00	00	00	00
C	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	61	67	62	00	00	67	67	00	02	00	00	00	00	00	00	00	00	00	50	00	00	00	00	00	00	00	00	00	62	00	00	00
C	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	27	83	39	00	50	83	83	00	66	00	00	00	00	00	00	00	00	00	00	23	00	00	00	00	00	00	00	00	35	00	00	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	20	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	67	00	00	00	00	00	00	00	00	00	00	00	31	00	00	00
C	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0
8	40	00	48	00	00	00	00	00	36	00	00	00	00	00	00	00	33	00	00	49	00	00	00	00	00	00	00	00	32	00	88	00
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	19	00	00	00	00	00	00	00	30	00	00	00	00	00	00	00	00	00	00	40	00	00	00	00	00	00	00	00	35	00	63	00
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	30	00	00
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	53	80	50	00	00	30	37	00	00	00	00	00	00	00	00	00	00	00	00	00	00	22	00	00	00	00	00	00	00	91	78	00
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	26	23	00	00	00	18	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	59	49	00
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
4	44	46	00	00	49	40	94	00	00	00	00	00	00	54	00	00	33	00	00	00	00	00	11	00	00	00	00	00	00	00	00	23
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.2	0.3	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	23	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	11	00	50	00	50	33	11	00	11	00	00	00	00	70	00	00
D	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	1.0	0.1	0.1	0.0	0.2	0.0	0.0	
6	42	00	00	00	78	74	19	00	00	00	00	33	33	00	26	00	00	00	00	00	00	00	22	22	00	67	67	00	50	00	00	
D	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.2	0.0	0.0	0.0
7	63	00	00	00	23	88	00	00	00	00	00	00	00	54	00	22	00	00	00	00	00	00	00	00	00	00	33	33	50	00	00	00

Table 5.35: Limit Matrix with Pair

[illegible]

[illegible]

The preliminary weights of the attributes obtained from the limit matrix have been transferred to the graph, and the ranking of the attributes according to their priority scores can be seen in Figure 5.11. While public acceptance is of highest importance (0.0863), installation cost is of lowest (0.0003) importance among all attributes.

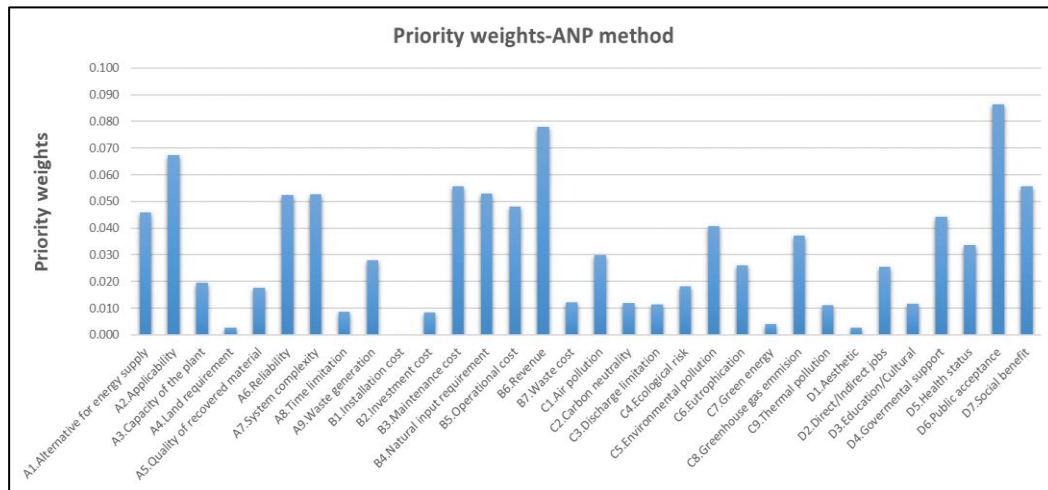


Figure 5.11: Weights of the attributes.

5.8.5. Evaluation of Alternatives with respect to Attributes

The next step after determining the weights of the attributes is the evaluation of the alternatives, which are wastewater recovery technologies, according to the attributes. In the study, there are 3 alternatives as air stripping, membrane, and precipitation. Each wastewater recovery technology is evaluated in terms of 32 different attributes.

The 1 to 10 scale described in Chapter 3.1.2 was used for the assessment. In the evaluation, it is assumed that all features are utility attributes, and the evaluation is made with this assumption. If an alternative is suitable for one attribute, it receives the numbers, while some alternatives are not suitable for some other attributes, it receives low numbers.

Each technology has been evaluated for sustainability for each attribute (Table 5.36). Thus, the feature weights and performance values of the alternatives are found. The next step is to analyze the problem and get the answer of which wastewater treatment technology is better.

For example, air stripping technology has been evaluated for its contribution to sustainability from A1 to D7 for all relevant attributes.

Table 5.36: Alternative Evaluation with respect to Attributes.

	A 1	A 2	A 3	A 4	A 5	A 6	A 7	A 8	A 9	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	D 1	D 2	D 3	D 4	D 5	D 6	D 7
Weights	0.0460	0.0674	0.0196	0.0026	0.0175	0.0524	0.0528	0.0087	0.0281	0.0003	0.0084	0.0557	0.0529	0.0480	0.0779	0.0121	0.0298	0.0119	0.0114	0.0182	0.0406	0.0261	0.0039	0.0372	0.0112	0.0026	0.0255	0.0115	0.0442	0.0338	0.0863	0.0555
Air strip	8	5	4	3.5	7.5	3.5	2.5	7	2.5	2.5	5.5	2.5	3	3.5	6.5	2.5	3	2.5	4	5	4	7.5	6.5	2.5	2.5	2	7	1.5	4	2.5	2.5	5.5
Membrane	1.5	5	4	7.5	4.5	6.5	8.5	6	4.5	7.5	5	6.5	4	6.5	8	5.5	3.5	7	4.5	6	7.5	4	1.5	5	7.5	2	4.5	1.5	4	3	3	5.5
Precipitation	1.5	7.5	8.5	4	8	5.5	3.5	4	7	2.5	4.5	4	4.5	3.5	5	3.5	3.5	2.5	5.5	4.5	4	3.5	1.5	3.5	2.5	2.5	4.5	3.5	7.5	3	3	5.5

5.8.6. Vector normalization

First, vector normalization is applied, and all features are considered as utility features in this step. Then, weighted normalized ratings are calculated by multiplying the feature weights with the normalized performance values, as shown in Equation 4.7 in the previous section. Example calculation for air stripping technology is shown in below. Calculations for all technologies shown in Table 5.37. The second step of vector normalization involves dividing the performance values by the square sum of the columns (Table 5.38). The second step of vector normalization involves dividing the performance values by the square sum of columns (Table 5.39).

$$v_{air\ stripping,A1} = 8 \times 0.046 = 0.367 \quad (5.10)$$

$$v_{membrane,A1} = 1.5 \times 0.046 = 0.068 \quad (5.11)$$

$$v_{adsorption,A1} = 1.5 \times 0.046 = 0.068 \quad (5.12)$$

Then, square of performance values and taking square,

$$v_{air\ stripping,A1}^2 = (0.367)^2 = 0.135 \quad (5.13)$$

$$v_{membrane,A1}^2 = (0.068)^2 = 0.004 \quad (5.14)$$

$$v_{precipitation,A1}^2 = (0.068)^2 = 0.004 \quad (5.15)$$

After, sum of columns is taken,

$$v_{sum,A1} = 0.135 + 0.004 + 0.004 = 0.144 \quad (5.16)$$

$$\sqrt{v_{sum,A1}} = \sqrt{0.144} = 0.380 \quad (5.17)$$

Finally, performance values are divided by square sum of columns,

$$v_{air\ stripping,A1} = \frac{0.367}{0.380} = 0.966 \quad (5.18)$$

Table 5.37: Decision matrix.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	D1	D2	D3	D4	D5	D6	D7	
Weights	0.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	
	46	06	01	00	01	05	05	00	02	00	00	05	05	04	07	01	02	01	01	01	04	02	00	03	01	00	02	01	04	03	08	05	
	0	74	96	26	75	24	28	87	81	03	84	57	29	80	79	21	98	19	14	82	06	61	39	72	12	26	55	15	42	38	63	55	
Air stripping	0.3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	
	67	33	07	00	13	18	13	06	07	00	04	13	15	16	50	03	08	02	04	09	16	19	02	09	02	00	17	01	17	08	21	30	
	92	70	83	91	12	35	19	07	01	06	59	93	85	78	65	03	93	98	56	11	23	54	56	30	79	51	82	72	66	44	57	54	
Membrane	0.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	
	68	33	07	01	07	34	44	05	12	00	04	36	21	31	62	06	10	08	05	10	30	10	00	18	08	00	11	01	17	10	25	30	
	98	70	83	95	87	09	86	20	62	2	17	21	14	17	33	66	42	35	13	93	44	42	59	61	39	51	45	72	66	13	89	54	
Precipitation	5	5	4	1	5	1	7	3	8	8	7	2	5	9	8	8	7	9	8	4	2	3	8	6	7	9	2	6	1	5			
	0.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	
	68	50	16	0.	13	28	18	03	19	00	0.	22	23	16	38	04	10	02	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	
	98	55	64	01	99	84	47	46	64	06	03	28	78	78	96	24	42	98	06	08	16	09	00	13	02	00	11	04	33	10	25	30	
	5	8	6	04	9	6	5	9	3	7	76	8	5	6	2	3	8	5	28	4	4	1	2	9	9	6	7	5	6	6	1	5	

Table 5.38: First step of vector normalization (square the performance values and get the squared sum of the columns).

	A 1	A 2	A 3	A 4	A 5	A 6	A 7	A 8	A 9	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	D 1	D 2	D 3	D 4	D 5	D 6	D 7
Weights	0.0460	0.7474	0.0196	0.0026	0.0175	0.0524	0.0528	0.0087	0.0281	0.0003	0.0084	0.0557	0.0529	0.0480	0.0779	0.0121	0.0298	0.0119	0.0114	0.0182	0.0406	0.0261	0.0039	0.0372	0.0112	0.0026	0.0255	0.0115	0.0442	0.0338	0.0863	0.0555
	Air strip ping Me mbr ane Prec ipita tion	0.1354	0.1136	0.0061	0.0001	0.0372	0.0174	0.0037	0.0049	0.0000	0.0021	0.0094	0.0151	0.0282	0.2565	0.0009	0.0080	0.0009	0.0021	0.0083	0.0064	0.0282	0.0307	0.0087	0.0008	0.0000	0.0318	0.0003	0.0012	0.0371	0.0066	0.0433
	0.0048	0.1136	0.0061	0.0004	0.0062	0.1162	0.2013	0.0027	0.0159	0.0000	0.0017	0.1247	0.0472	0.0986	0.3844	0.0009	0.0170	0.0026	0.0020	0.2727	0.0909	0.0146	0.0071	0.0300	0.0000	0.0131	0.0303	0.1212	0.0303	0.7070	0.3333	
		0.0048	0.2502	0.0001	0.0801	0.0308	0.0303	0.0003	0.0000	0.0400	0.0504	0.0205	0.1502	0.0015	0.0000	0.0100	0.0001	0.0000	0.0000	0.0200	0.0002	0.0000	0.0100	0.0000	0.0100	0.0000	0.0100	0.0010	0.0101	0.0606	0.0909	
	0.4856	0.7777	0.0196	0.3296	0.4132	0.4112	0.8686	0.0000	0.1497	0.6666	0.8282	0.1818	0.1818	0.0909	0.0909	0.3939	0.6767	0.6483	0.0000	0.7070	0.0808	0.0031	0.1616	0.9797	0.0303	0.7070	0.0370	0.3333	0.7070	0.3333		
	Sum	0.1449	0.4828	0.0400	0.0406	0.2330	0.2531	0.0029	0.0576	0.0095	0.0053	0.2002	0.1264	0.1535	0.7970	0.0072	0.0297	0.0088	0.0087	0.0270	0.0554	0.0574	0.0007	0.0603	0.0086	0.0001	0.0580	0.0022	0.1721	0.0277	0.1806	0.2799
SQ RT(Sum)	0.3806	0.6948	0.2000	0.0239	0.2074	0.4828	0.5028	0.0872	0.2438	0.0022	0.0726	0.4475	0.3555	0.3918	0.8927	0.0847	0.1725	0.0936	0.0931	0.1643	0.3813	0.2395	0.0270	0.2455	0.0928	0.0097	0.2409	0.0472	0.4148	0.1664	0.4250	0.5291

Table 5.39: Second step of vector normalization (dividing performance values by square sum of columns).

	A	A	A	A	A	A	A	A	A	B	B	B	B	B	B	B	C	C	C	C	C	C	C	C	C	D	D	D	D	D	D	D
	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7
Wei ghts	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	6	1	0	1	5	5	0	2	0	0	5	5	4	7	1	2	1	1	1	4	2	0	3	1	0	2	1	4	3	8	5
	6	7	9	2	7	2	2	8	8	0	8	5	2	8	7	2	9	1	1	8	0	6	3	7	1	2	5	1	4	3	6	5
Air stri ppi ng	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	9	4	3	3	6	3	2	6	2	3	6	3	4	4	5	3	5	3	4	5	4	8	9	3	3	5	7	3	4	5	5	5
	6	8	9	8	3	8	6	9	8	0	3	1	4	2	6	5	1	1	9	5	2	1	5	7	0	2	3	6	2	0	0	7
	6	5	1	0	2	0	2	6	7	1	3	1	6	8	7	8	8	8	0	4	5	5	0	9	1	9	9	6	5	7	7	7
Me mbr ane	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	1	4	3	8	3	7	8	5	5	9	5	8	5	7	6	7	6	8	5	6	7	4	2	7	9	5	4	3	4	6	6	5
	8	8	9	1	7	0	9	9	1	0	7	0	9	9	9	8	0	9	5	6	9	3	1	5	0	2	7	6	2	0	0	7
	1	5	1	5	9	6	2	7	7	4	5	9	4	5	8	7	4	2	1	5	8	5	9	8	4	9	5	6	5	9	9	7
Pre ci pi tati on	2	1	8	9	6	1	3	0	9	5	4	3	6	6	3	7	7	6	8	6	4	1	4	1	5	8	7	5	8	2	2	4
	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	1	7	8	4	6	5	3	3	8	3	5	4	6	4	4	5	6	3	6	4	4	3	2	5	3	6	4	8	7	6	6	5
	8	2	3	3	7	9	6	9	0	0	1	9	6	2	3	0	0	1	7	9	2	8	1	3	0	6	7	5	9	0	0	7
	1	7	2	5	4	7	7	8	5	1	7	8	9	8	6	1	4	8	4	9	5	0	9	0	1	2	5	5	8	9	9	7
	2	6	5	1	9	4	4	0	6	5	9	1	0	4	4	3	7	8	5	2	8	7	4	7	5	3	7	2	4	2	2	4

5.8.7. Detection of positive and negative ideal solution

Then, positive ideal and negative ideal solutions of each feature are found. For positive ideal solutions, a^* is used and since all attributes are utility attributes (higher is better), the maximum performance values of each attribute are chosen. For negative ideal solutions, a^- is used and since all attributes are utility attributes (low is worse), the minimum performance values of each attribute are chosen. Then, the separation measures of each alternative from the positive and negative ideal solution are measured separately with the Equations 4.8 and 4.9 mentioned in the previous section. Then the similarities to the positive ideal solution are calculated according to the Equation 4.10 expressed in the previous section. Among alternatives maximum value and negative value is found 0.966 and 0.181 with respect to attribute A1 which is alternative for energy supply, respectively. Positive ideal and negative ideal solution is calculated below. In the evaluation process of air stripping technologies, several steps were undertaken to determine their performance and identify the ideal solutions. Initially, the weighted normalized ratings were calculated, taking into account various factors and criteria. These ratings played a crucial role in measuring the separation from both the positive and negative ideal solutions (Table 5.40). The positive ideal solution represents the highest achievable performance, while the negative ideal solution represents the lowest desirable performance. By assessing the separation from the positive ideal solution (Table 5.41), the effectiveness and efficiency of each technology were evaluated. Simultaneously, measuring the separation from the negative ideal solution (Table 5.42) allowed for the identification of potential drawbacks or limitations.

$$S_{i,air stripping}^* = \left[\sum_{j=1}^{24} [0.966 - 0.966]^2 + [0.727 - 0.485]^2 + \dots \right]^{0.5} = 1.6259 \quad (5.19)$$

$$S_{i,air stripping}^- = \left[\sum_{j=1}^{24} [0.966 - 0.181]^2 + [0.485 - 0.485]^2 + \dots \right]^{0.5} = 1.2571 \quad (5.20)$$

Table 5.40: Weighted Normalized Ratings and Identification of Positive and Negative Ideal Solutions.

	A 1	A 2	A 3	A 4	A 5	A 6	A 7	A 8	A 9	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	D 1	D 2	D 3	D 4	D 5	D 6	D 7
Wei	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ghts	04	06	01	00	01	05	05	00	02	00	00	05	05	04	07	01	02	01	01	01	04	02	00	03	01	00	02	01	04	03	08	05
Air	60	74	96	26	75	24	28	87	81	03	84	57	29	80	79	21	98	19	14	82	06	61	39	72	12	26	55	15	42	38	63	55
strip	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ping	96	48	39	38	63	38	26	69	28	30	63	31	44	42	56	35	51	31	49	55	42	81	95	37	30	52	73	36	42	50	50	57
Me	66	51	18	07	27	02	24	65	77	15	30	13	60	84	74	81	83	88	05	47	58	59	07	90	15	98	99	65	58	77	77	74
mbr	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ane	18	48	39	81	37	70	89	59	51	90	57	80	59	79	69	78	60	89	55	66	79	43	21	75	90	52	47	36	42	60	60	57
Prec	12	51	18	59	96	61	23	70	79	45	54	93	46	56	83	77	47	26	18	56	84	51	94	81	45	98	57	65	58	92	92	74
ipita	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
tion	18	72	83	43	67	59	36	39	80	30	51	49	66	42	43	50	60	31	67	49	42	38	21	53	30	66	47	85	79	60	60	57
	12	76	25	51	49	74	74	80	56	15	79	81	90	84	64	13	47	88	45	92	58	07	94	07	15	23	57	52	84	92	92	74
Posit	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ive	96	72	83	81	67	70	89	69	80	90	63	80	66	79	69	78	60	89	67	66	79	81	95	75	90	66	73	85	79	60	60	57
ideal	66	76	25	59	49	61	23	65	56	45	30	93	90	56	83	77	47	26	45	56	84	59	07	81	45	23	99	52	84	92	92	74
Nega	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
tive	18	48	39	38	37	38	26	39	28	30	51	31	44	42	43	35	51	31	49	49	42	38	21	37	30	52	47	36	42	50	50	57
ideal	12	51	18	07	96	02	24	80	77	15	79	13	60	84	64	81	83	88	05	92	58	07	94	90	15	98	57	65	58	77	77	74

Table 5.41: Measuring the separation from positive ideal solution for air stripping.

	A 1	A 2	A 3	A 4	A 5	A 6	A 7	A 8	A 9	B 1	B 2	B 3	B 4	B 5	B 6	B 7	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	D 1	D 2	D 3	D 4	D 5	D 6	D 7
Air stripping	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
Posi	96	48	39	38	63	38	26	69	28	30	63	31	44	42	56	35	51	31	49	55	42	81	95	37	30	52	73	36	42	50	50	57
tive	66	51	18	07	27	02	24	65	77	15	30	13	60	84	74	81	83	88	05	47	58	59	07	90	15	98	99	65	58	77	77	74
ideal	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
[Vij	96	72	83	81	67	70	89	69	80	90	63	80	66	79	69	78	60	89	67	66	79	81	95	75	90	66	73	85	79	60	60	57
-	66	76	25	59	49	61	23	65	56	45	30	93	90	56	83	77	47	26	45	56	84	59	07	81	45	23	99	52	84	92	92	74
Vj*]	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	00	05	19	18	00	10	39	00	26	36	00	24	04	13	01	18	00	32	03	01	13	00	00	14	36	01	00	23	13	01	01	00
	00	88	42	93	18	62	67	00	82	36	00	81	97	48	71	46	75	93	38	23	88	00	00	37	36	75	00	88	88	03	03	00

Table 5.42: Measuring the separation from negative ideal solution for air stripping.

	A 1	A 2	A 3	A 4	A 5	A 6	A 7	A 8	A 9	B1	B2	B3	B4	B5	B6	B7	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	D 1	D 2	D 3	D 4	D 5	D 6	D 7
Air stripping	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
Negat	96	48	39	38	63	38	26	69	28	30	63	31	44	42	56	35	51	31	49	55	42	81	95	37	30	52	73	36	42	50	50	57
ive	66	51	18	07	27	02	24	65	77	15	30	13	60	84	74	81	83	88	05	47	58	59	07	90	15	98	99	65	58	77	77	74
ideal	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	18	48	39	38	37	38	26	39	28	30	51	31	44	42	43	35	51	31	49	49	42	38	21	37	30	52	47	36	42	50	50	57
	12	51	18	07	96	02	24	80	77	15	79	13	60	84	64	81	83	88	05	92	58	07	94	90	15	98	57	65	58	77	77	74
	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	61	00	00	00	06	00	00	08	00	00	01	00	00	00	01	00	00	00	00	00	00	18	53	00	00	00	06	00	00	00	00	00
	68	00	00	00	41	00	00	91	00	00	32	00	00	00	71	00	00	00	00	31	00	93	48	00	00	00	98	00	00	00	00	00

In the next step, the similarities with the positive ideal solution are calculated with the following formula (Equation 4.10);

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-} = \frac{1.235}{1.912 + 1.235} = 0.392 \quad (5.21)$$

In the final stage, the alternatives are ranked according to their similarities and the alternative with the highest similarity result is selected as the best wastewater recovery technology in terms of sustainability. As a result of TOPSIS, membrane has the highest similarity with 0.542 which means that nutrient recovery from wastewater is again the best wastewater recovery technology among the 3 alternatives in terms of 32 qualities air stripping has the 2nd highest similarity result with 0.392, precipitation was found to be the worst alternative with the lowest similarity result with 0.339 (Table 5.43).

Table 5.43: Separation measures, similarity results and ranking of the alternatives.

	S*	S⁻	C*	Ranking
Air stripping	1.912	1.235	0.392	2
Membrane	1.324	1.569	0.542	1
Precipitation	1.780	0.916	0.339	3

6. RESULTS AND DISCUSSION

In this thesis, a sustainability index approach is proposed for wastewater recovery technologies based on fuzzy analytical hierarchy process (AHP), analytical network process (ANP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) multi criteria decision making methods.

In addition to being vital for the continuity of life and ecosystems, water is of great importance for the development of countries. It is one of the indispensable elements of life in human use, industry, agriculture, energy production and economy. Increasing population and temperature cause fresh water problem.

Due to water scarcity, material recovery from wastewater is accelerating in order to preserve natural resources and leave a sustainable environment for future generations. However, the selection wastewater recovery systems requires professionalism. In order to obtain maximum efficiency, it is necessary to conduct extensive research from the very beginning of the problem and examine all situations with expert opinions.

Sustainability assessment tools are a precedent indicator for balancing the integrity and sustainability of water resources on a regional and global scale. Sustainability index, in the integrative and systematic approach of recycling, recovery and reuse activities in cities, governments and administrations evaluate all economic, social, environmental and technical aspects to ensure sustainability.

In this thesis, the proposed methodology is demonstrated with the selection of the best nutrient recovery technology from wastewater by using multi-attribute decision making (MADM). First, possible features and possible alternatives are identified from the extensive literature review. Then, some possible qualifications and possible alternatives were eliminated based on the low frequency and expert opinions in the literature. Then the criteria are classified into 4 clusters considering the sustainability pillars: technical, economic, environmental and social. First of all, fuzzy AHP method in which fuzzy numbers are assigned and the scoring range widens, then ANP and TOPSIS methods which associate the relations between the attributes with the related alternatives were used. Before taking the preferences from the decision

makers, it was checked whether the ANP is an appropriate tool to be used in this study, since the model has sufficient dependency.

6.1. Ranking of alternatives and contribution of priority weights to sustainability index

Air stripping, membrane and precipitation technologies are listed in all three decision making methods in which the sustainability index approach is discussed. Figure 6.1 below shows the sustainability index values and rankings of the technologies according to the results obtained according to the AHP, ANP and TOPSIS methods.

In addition to the common steps of AHP and ANP in the proposed method, specific steps for ANP are explained and applied in an example case. As a result, membrane technology with the SI of 4.31 seems to be the best recovery technology from wastewater in all three decision-making methods.

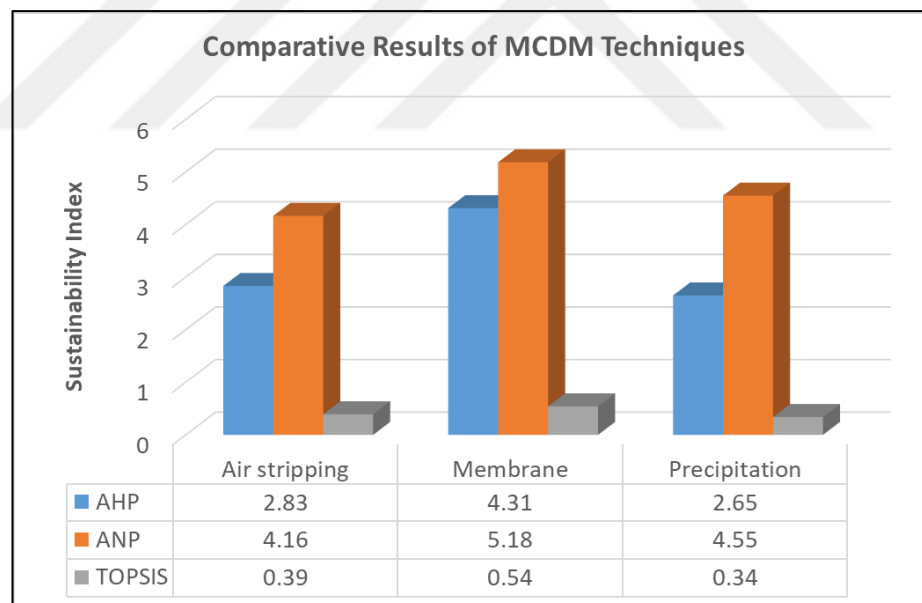


Figure 6.1: Comparison of sustainability indexes of three selected technology.

Considering the factors, it is seen that economic and environmental factors are important for the high sustainability of membrane technology in AHP method (Table 5.18 and Table 5.19). System complexity, land requirement and product quality are technically substantial (Table 5.16). Although membrane technologies are known as complex systems, they can be easily monitored and managed with an automation

system due to the low number of parameters to be controlled [Naghieb et al., 2018]. For this reason, the low system complexity of membrane technologies with high priority contributes to their sustainability in AHP method. In addition to system complexity, land requirement has a huge impact on sustainability. Although priority weight of land requirement is low (Table 5.16) the high score for land requirement of membrane technologies (Table 5.3) overall factor index has a huge impact on sustainability. Since the membranes are generally compact, the land requirement for the system is less [Gong et al., 2018]. Products obtained from membrane technologies cannot be used directly. This situation reduces the sustainability of the membrane technology in terms of the product quality recovered with the low score (Table 5.3). From an economic point of view, revenue, installation cost and investment cost have the highest priority for the sustainability of wastewater recovery treatment technologies in AHP (Table 5.17).

It is seen that the carbon footprint of membrane-based technologies is low in the analyzed life cycle analyzes [Lin et al., 2016], [Yang et al., 2020]. This situation has increased its contribution to the sustainability of membrane technology in terms of carbon neutral and environmental impact criteria (Table 5.9). On the other hand, the fact that the membrane systems do not have a supportive effect in terms of energy recovery caused it to remain in the fall behind in terms of green energy (Table 5.9). Membrane technologies are expected to provide social benefits as they support circular cities and guide cities in their sustainability goals (Table 5.12). Figure 6.2 depicts the criteria distribution of membrane technology in AHP method.

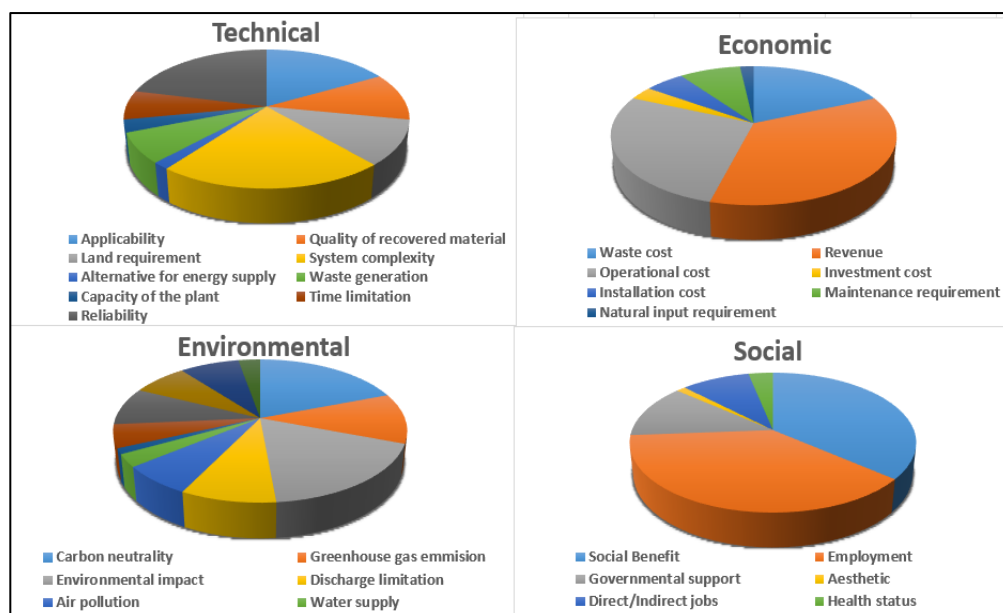


Figure 6.2: Distribution of technical, economic, environmental, and social sub criteria of membrane technology.

Air stripping was ranked in the second place for AHP and TOPSIS and third place for ANP. Technical and social criteria are the main ones that greatly affect as shown in Table 5.23 with the high class. Combining the energy recovery technology technically with air stripping has a positive effect on the alternative energy supply criterion (Table 5.2). Recovering with air stripping can only be effective in strong wastewater characterization, cannot be applied in cold climates and requires constant pH adjustment [Perera et al., 2019] (low scores for applicability and system complexity in Table 5.2) can be seen as the reasons for the low class of the technology as shown in Table 5.23. The initial investment cost is also a criterion that raises sustainability from low to medium (Table 5.23). It is seen that the initial investment costs (Table 5.5) of air stripping technology are lower than that of activated sludge systems [Robles et al., 2020a]. Thermal pollution and greenhouse gas emissions (Table 5.8) are two criteria that contribute significantly to its low sustainability (Figure 6.2). The fact that air stripping technology requires heat treatment during the process may cause a potential thermal pollution [van der Hoek et al., 2018]. There is a large gap in the literature for evaluating the social aspects of air stripping. No study has been found that deals with technology from an aesthetic point of view.

In AHP and TOPSIS method, the least sustainable technology is precipitation. Although it is advantageous in terms of being applicable and receiving government

support, it lagged in terms of economic and environmental criteria (Table 5.27). The fact that the products obtained with the precipitation technology can be easily used as soluble fertilizer (Table 5.1) technically enhances the contribution of technology to sustainability (Table 5.4). In addition, exceeding a certain level of suspended solids in wastewater complicates the system as shown in Table 5.4 because it increases many parameters that need to be monitored (Table 5.1). Since it is not a compact system, the installation cost may be higher as both reinforced concrete, pipe and valve system are required (Table 5.7). Discharge limitation makes high contribution to sustainability of the precipitation technology (Table 5.10) Incentives are provided for precipitation technology through practices such as eco-labeling or tax breaks (Kehrein et al., 2020b], but support is still needed. In terms of governmental support, this criterion has a very high contribution to sustainability (Table 5.13). On the other hand, increasing health research and public surveys for recovery technology simplifies the application process.

6.2. Comparison of multicriteria decision making methodologies for the proposed approach

AHP and ANP can be compared based on the priority weights. Although the scores used in the AHP and ANP method are the same, the priority weights of the criteria were found to be different compared to the AHP due to the relationships established between the attributes in the ANP. However, since the sum of the priority weights in both methods is 1, the priority weights found for the two methods can be compared.

In Figure 6.3 below, the priority weights of the criteria in the AHP method and the ANP method are compared. It is said that the most important criterion is social benefit, while public acceptance comes second in fuzzy AHP method. In ANP, on the other hand, while public acceptance is in the first place with the degree of importance, revenue comes in the second place. While the criterion with the lowest degree of importance in ANP is land requirement, the educational/cultural criterion remains in the background in AHP. For example, although the waste cost in AHP is high, it is of quite low importance compared to the result in ANP. The reason for this is that the waste cost is affected by the capacity of plant and waste generation criteria rather than the economic criteria in its cluster, according to the cognitive map created in the ANP

method. However, in the AHP method, the waste cost criterion is compared with all the economic criteria in its cluster. On the other hand, the importance weight of the revenue criterion is high in both methods. In the ANP method, the revenue criterion is tied to both technical and social criteria. Consequently, relationships conducted in the cognitive map may affect the importance of the criteria relatively more than AHP, since it also compares with different clusters.

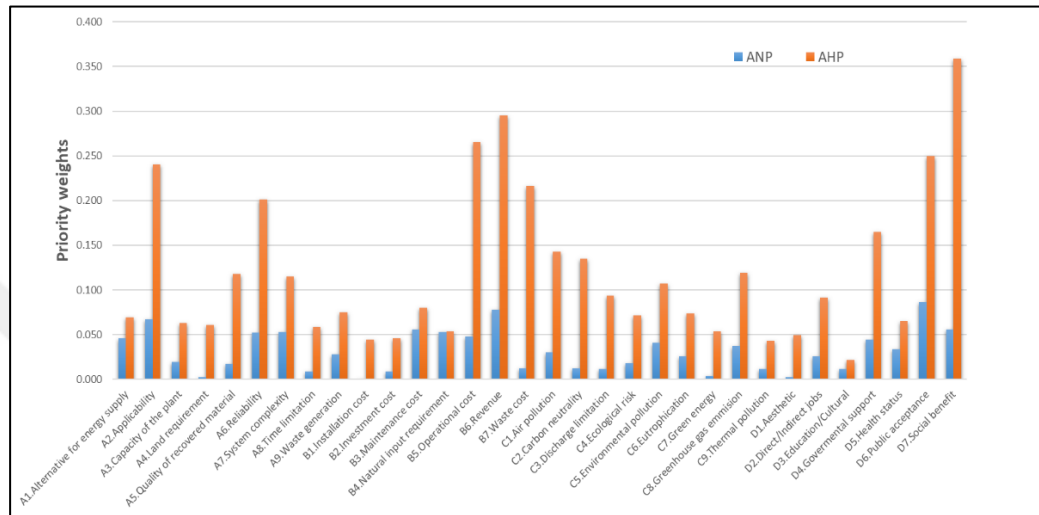


Figure 6.3: Comparison of priority weights of attributes in AHP and ANP methods.

Although the scores were the same, the sustainability indices were different according to all three methods. Membrane was the technology with the highest sustainability index in all three methods. SI of air stripping (2.83) and precipitation technology (2.65) were almost equal in AHP and ANP methods. While air stripping (2.83) is in the second place in the AHP method, precipitation (0.39) is in the second place in the TOPSIS method (Figure 6.2). For example, as shown in Figure 5.11 operational cost is compared against highly important technical criteria such as reliability, applicability, and system complexity in the ANP method. In the AHP method, on the other hand, the operational cost has a higher degree of importance compared to the others (Table 5.18), since the degree of importance in its own cluster is relatively low compared to the natural input requirement and installation cost. Considering the criteria weights, operation cost has high impact on precipitation compared to air stripping (Table 5.18). Therefore, this criterion has negatively affected the sustainability of precipitation technology and may cause it to rank third in AHP.

While scoring is done without considering the relationship between the criteria in the AHP method, in the ANP method, if there is a sufficient relationship between the criteria, scoring is made by considering the relationship between them. Therefore, the ANP method could be more sensitive than the AHP method in this sense. On the other hand, TOPSIS method can be used to rank the alternatives. Values between 0 and 1 are ranked according to their closeness to 1 which is the ideal.

Multi-criteria decision-making methods help the decision maker to make better decisions by creating appropriate options when there is uncertainty, complexity, and conflicting goals. Three different decision-making methods are proposed in the thesis. First, although the use of Fuzzy AHP is not as common as AHP, the attraction of Fuzzy AHP which is more suitable for human thought system is increasing. Fuzzy AHP method can be preferred to eliminate verbal ambiguity between pairwise comparisons. ANP is a specific form of AHP, where AHP allows one-way relationships of units while ANP allows complex relationships for decision levels and properties. The most important difference of AHP compared to ANP is that it uses an interactive hierarchical structure instead of a top-down hierarchical structure. The ANP method has feedback and dependency features. The AHP method does not consider the internal and external dependence between the criteria, sub-criteria, and lower criteria. Therefore, ANP method is to provide a more effective and realistic analysis of decision-making methods. On the other hand, The TOPSIS method, which has an analysis process that does not contain complex algorithms and mathematical models, finds application in many fields due to its ease of use and easy understanding and interpretation of the results (Figure 6.4). The weighting approach of the TOPSIS method for decision making reveals its subjective aspect. Because the weighting process is done according to the importance of the criteria. Although a small number of decision makers are sufficient and easy to implement, the correct determination of criteria and weights with this method depends on the objective attitude of the decision makers.

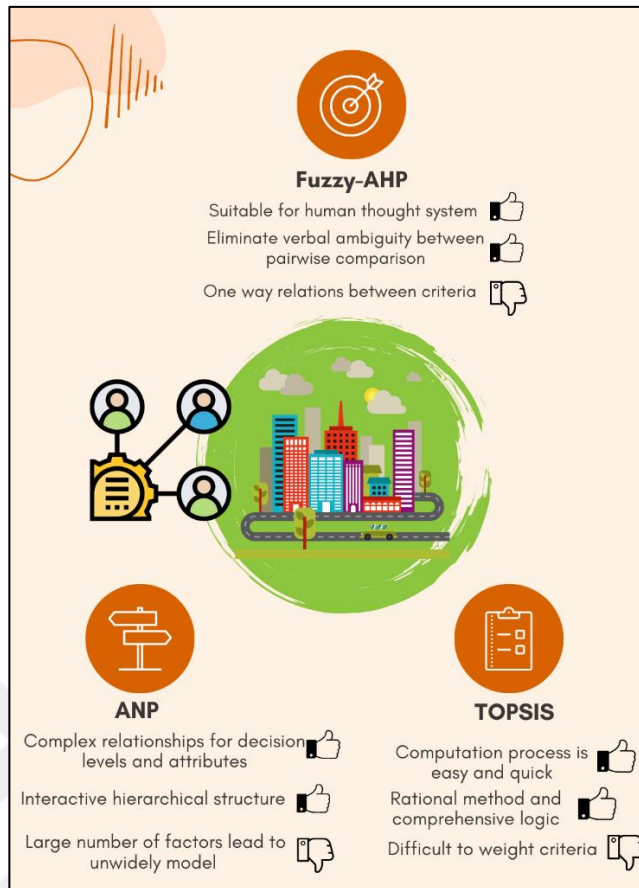


Figure 6.4: Advantages and disadvantages of Multi Criteria Decision Making Techniques.

7. CONCLUSION

This thesis proposed an approach for assessing the sustainability of wastewater resource recovery technologies using multi-criteria decision-making (MCDM) methods. The study demonstrated the significance and practicality of various MCDM methods in selecting resource recovery technologies for nutrient recovery.

The decision-making process for selecting nutrient recovery technologies involves multiple criteria that are often conflicting and uncertain. To account for these uncertainties and ensure a comprehensive evaluation of the options, the study employed not only AHP but two different multi-criteria decision-making (MCDM) methods, namely ANP and TOPSIS. By utilizing two distinct MCDM methods, the study was able to cross-validate the results and provide a more robust evaluation of the nutrient recovery technologies.

There is no study in the literature combining two or more mathematical methods in the selection of wastewater resource recovery technology. In addition, the proposed model provides flexibility by changing the criteria and their weights and can be easily adapted to other waste management problems by changing the criteria and their importance.

The use of Fuzzy AHP, ANP, and TOPSIS methods to determine the sustainability index of different technologies in the context of membrane technology, air stripping, and precipitation has yielded interesting results. According to the Fuzzy AHP approach, membrane technology ranks first with a sustainability index of 4.31, while air stripping and precipitation have scores of 2.83 and 2.65, respectively. This suggests that membrane technology is the most sustainable option among the three. On the other hand, the ANP approach shows that membrane technology is still in the first place with a score of 5.18, followed by precipitation with a score of 4.55 and air stripping with a score of 4.16. This implies that, while membrane technology remains the most sustainable option, the difference in sustainability among the three technologies is not as significant as suggested by the Fuzzy AHP approach. Finally, the TOPSIS method yields a different ranking, with a sustainability index of 0.54 for membrane technology, 0.39 for air stripping, and 0.34 for precipitation. This suggests that the differences in sustainability among the three technologies are relatively small, and that the TOPSIS method is less sensitive to small differences in performance

compared to the Fuzzy AHP and ANP methods. The choice of method for evaluating sustainability is critical, and different methods can yield different results depending on the criteria and weights used. Therefore, it is important to carefully select the most appropriate method for a given context and to consider the results in light of their limitations and assumptions. Based on the results obtained, the Fuzzy AHP method seems to be the most appropriate method for evaluating the sustainability of these technologies, as it yields a clear ranking with a significant difference in sustainability index between the first and second-ranked technologies. The advantage of Fuzzy AHP is that it allows the consideration of multiple criteria and their relative importance, which is particularly useful for sustainability evaluations that involve complex and interdependent factors.

Moreover, the Fuzzy AHP method allows for the incorporation of uncertainty and imprecision in decision-making, which is often encountered in sustainability assessments. The Fuzzy AHP method can accommodate vague or fuzzy linguistic expressions to reflect the degree of uncertainty in decision-making. However, if the TOPSIS method is used, the differences in sustainability among the three technologies are relatively small, and the method is less sensitive to small differences in performance compared to the Fuzzy AHP and ANP methods. The TOPSIS method considers only the distance between the evaluated alternatives and the ideal solution, and the sensitivity of the results to changes in the criteria and their weights is relatively low. If the ANP method is used, the ranking of the technologies is like that of the Fuzzy AHP method, but the difference in sustainability among the technologies is not as significant as suggested by the Fuzzy AHP approach. The advantage of ANP is that it allows for the consideration of complex interdependencies among the criteria, which is particularly relevant for sustainability assessments that involve multiple criteria that may affect each other.

The evaluation of membrane technology, air stripping, and precipitation technologies has shown that each technology has its strengths and weaknesses in terms of sustainability. While membrane technology appears to be the most sustainable option based on the results of all methods, it is also possible to choose air stripping and precipitation technology as alternatives, with improvements to their sustainability index. To improve the sustainability index of air stripping and precipitation technologies, the land requirement can be improved, and for precipitation, the time

limitation can be addressed to enhance its technical performance. Additionally, reducing the waste cost criterion for air stripping and operational costs for both air stripping and precipitation can further improve their sustainability.

However, the use of air stripping technology should be carefully considered, as it can cause thermal pollution and destruction of water resources. Therefore, measures should be taken to improve these criteria to increase sustainability. Moreover, to improve the sustainability index of precipitation technology, the incorporation of green energy and carbon neutrality criteria is necessary. Finally, from a social perspective, providing sufficient training and job opportunities to raise qualified personnel in the selected technologies can further enhance their sustainability. By considering all these aspects, the overall sustainability of the evaluated technologies can be improved.

Therefore, this thesis may be guiding study for circular city adaptations. In future studies, other techniques such as Fuzzy ANP, ELECTRE, VIKOR and other combinations will also be tried and comparison of the results from other integrated techniques will help to better understand the relevant criteria and selection process.

To sum up, decision support systems may be very useful in process selection or technology adaptation in circular cities. Considering the circular cities, various alternatives are put forward to prevent resource scarcity in the world and to step into sustainable technologies. For investments to be made wisely, proposed approach in this study offers a great tool to consider all relevant criteria for sustainability. Moreover, proposed approach provides decision makers to modify or improve the importance of the criteria according to their own situation. For example, since economic attributes have high priority in selection of wastewater resource recovery technologies in ANP method, social attributes can be in high priority in other case studies. To produce an analytical solution for decision making, the advantages and disadvantages of these three decisions making methods are presented. In circular cities, it is recommended to define and score the relations with the ANP method among the criteria for the selection of waste recovery technology, while TOPSIS in which the near-ideal alternative is determined is recommended as the method that can be preferred for the selection of alternatives.

REFERENCES

- Abdullah L., Zulkifli N., (2015), "Integration of fuzzy AHP and interval type-2 fuzzy DEMATEL: An application to human resource management", *Expert Systems with Applications*, 42 (9), 4397–4409.
- Ahmed M., Hasan C. K., Rahman H., Ali Hossain M., Uddin S. A., (2015), "Prospects of using wastewater as a resource-nutrient recovery and energy generation", *American Journal of Environmental Sciences*, 11 (2), 99–114.
- Alemayehu Y. A., Asfaw S. L., Terfie T. A., (2020), "Nutrient recovery options from human urine: A choice for large scale application", *Sustainable Production and Consumption*, 24, 219–231.
- Alpay M., (2010), "Kredi Değerliliğinin Ölçülmesinde TopsisYöntemi ve Bir Uygulama", *Yüksek Lisans Tezi, Dokuz Eylül Üniversitesi*, 136.
- Amann A., Zoboli O., Krampe J., Rechberger H., Zessner M., Egle L., (2018), "Environmental impacts of phosphorus recovery from municipal wastewater", *Resources, Conservation and Recycling*, 130, 127–139.
- Ansari A. J., Hai F. I., Price W. E., Drewes J. E., Nghiem L. D., (2017), "Forward osmosis as a platform for resource recovery from municipal wastewater - A critical assessment of the literature", *Journal of Membrane Science*, 529, 195–206.
- Arbolino R., De Simone L., Carlucci F., Yigitcanlar T., Ioppolo G., (2018), "Towards a sustainable industrial ecology: Implementation of a novel approach in the performance evaluation of Italian regions", *Journal of Cleaner Production*, 178 220–236.
- Aydi A., Abichou T., Nasr I. H., Louati M., Zairi M., (2016), "Assessment of land suitability for olive mill wastewater disposal site selection by integrating fuzzy logic, AHP, and WLC in a GIS", *Environmental Monitoring and Assessment*, 188 (1), 1–13.
- Babí Almenar J., Elliot T., Rugani B., Philippe B., Navarrete Gutierrez T., Sonnemann G., et al., (2021), "Nexus between nature-based solutions, ecosystem services and urban challenges", *Land Use Policy*, 100, 104898.
- Bamigbetan O., Eikevik T. M., Neksa P., Bantle M., Schlemminger C., (2019), "The development of a hydrocarbon high temperature heat pump for waste heat recovery", *Energy*, 173 1141–1153.
- Barry D., Barbiero C., Briens C., Berruti F., (2019), "Pyrolysis as an economic and ecological treatment option for municipal sewage sludge", *Biomass and Bioenergy*, 122, 472–480.

Baykara H. V., (2012), "TOPSIS Yöntemi ile Katılım Bankalarının Etkinliği ve Verimliliği Üzerine Bir Uygulama an Implementation upon Efficiency and Productivity of Participation Banks with TOPSIS Method", *Business and Economics Research Journal*, 3 (4), 21–42.

Belér-Baykal B., (2015), "Stream Segregation in Household Use: A Review of Grey Water as an Alternative Source of Water and Yellow Water as an Alternative Source of Fertilizers", *Water Quality, Exposure and Health*, 7 (1), 27–37.

Bhatia S. K., Mehariya S., Bhatia R. K., Kumar M., Pugazhendhi A., Awasthi M. K., et al., (2021), "Wastewater based microalgal biorefinery for bioenergy production: Progress and challenges", *Science of the Total Environment*, 751 141599.

Bohra S. S., Anvari-Moghaddam A., (2021), "A comprehensive review on applications of multicriteria decision-making methods in power and energy systems", *International Journal of Energy Research*, 1–31.

Bolognesi S., Cecconet D., Callegari A., Capodaglio A. G., (2021), "Combined microalgal photobioreactor/microbial fuel cell system: Performance analysis under different process conditions", *Environmental Research*, 192, 110263.

Brown J. A., (2005), "The early history of wastewater treatment and disinfection", *World Water Congress 2005: Impacts of Global Climate Change - Proceedings of the 2005 World Water and Environmental Resources Congress*, 288.

Bui N. T., Kawamura A., Bui D. Du, Amaguchi H., Bui D. D., Truong N. T., et al., (2019), "Groundwater sustainability assessment framework: A demonstration of environmental sustainability index for Hanoi, Vietnam", *Journal of Environmental Management*, 241, 479–487.

Burian S. J., Nix S. J., Pitt R. E., Rocky Durrans S., (2000), "Urban Wastewater Management in the United States: Past, Present, and Future", *Journal of Urban Technology*, 7 (3), 33–62.

Campos J. L., Crutchik D., Franchi Ó., Pavissich J. P., Belmonte M., Pedrouso A., et al., (2019), "Nitrogen and Phosphorus Recovery From Anaerobically Pretreated Agro-Food Wastes: A Review", *Frontiers in Sustainable Food Systems*, 1–11.

Candido L. A., Coêlho G. A. G., de Moraes M. M. G. A., Florêncio L., (2022), "Review of Decision Support Systems and Allocation Models for Integrated Water Resources Management Focusing on Joint Water Quantity-Quality", *Journal of Water Resources Planning and Management*, 148 (2),.

Cao L., Wang J., Xiang S., Huang Z., Ruan R., Liu Y., (2019), "Nutrient removal from digested swine wastewater by combining ammonia stripping with struvite precipitation", *Environmental Science and Pollution Research*, 26 (7), 6725–6734.

Capodaglio A. G., (2020), "Critical perspective on advanced treatment processes for water and wastewater: AOPs, ARPs, and AORPs", *Applied Sciences (Switzerland)*, 10 (13),.

Carmon N., Shamir U., (2010), "Water-sensitive planning: Integrating water considerations into urban and regional planning", *Water and Environment Journal*, 24 (3), 181–191.

Cavallaro F., (2015), "A Takagi-Sugeno fuzzy inference system for developing a sustainability index of biomass", *Sustainability (Switzerland)*, 7 (9), 12359–12371.

Chang H. M., Sun Y. C., Chien I. C., Chang W. S., Ray S. S., Cao D. T. N., et al., (2019), "Innovative upflow anaerobic sludge osmotic membrane bioreactor for wastewater treatment", *Bioresource Technology*, 287, 121466.

Chatterjee P. K., Neogi S., Saha S., Jeon B. H., Dey A., (2019), "Low pH treatment of starch industry effluent with bacteria from leaf debris for methane production", *Water Environment Research*, 91 (5), 377–385.

Chen C., Dong T., Han M., Yao J., Han L., (2020), "Ammonium recovery from wastewater by Donnan Dialysis: A feasibility study", *Journal of Cleaner Production*, 265 121838.

Chia W. Y., Chong Y. Y., Chew K. W., Vimali E., Jayaram M., Selvarajoo A., et al., (2020), "Outlook on biorefinery potential of palm oil mill effluent for resource recovery", *Journal of Environmental Chemical Engineering*, 8 (6), 104519.

Chong Y. T., Teo K. M., Tang L. C., (2016), "A lifecycle-based sustainability indicator framework for waste-to-energy systems and a proposed metric of sustainability", *Renewable and Sustainable Energy Reviews*, 56 797–809.

Chrispim M. C., Scholz M., Nolasco M. A., (2020), "A framework for resource recovery from wastewater treatment plants in megacities of developing countries", *Environmental Research*, 188, 109745.

Cipolletta G., Lancioni N., Akyol Ç., Eusebi A. L., Fatone F., (2021), "Brine treatment technologies towards minimum/zero liquid discharge and resource recovery: State of the art and techno-economic assessment", *Journal of Environmental Management*, 300, 113681.

de Ferreira A. C., Fuso-Nerini F., (2019), "A framework for implementing and tracking circular economy in cities: The case of Porto", *Sustainability (Switzerland)*, 11 (6), 1–23.

Delvigne F., Jacqueline D., Maesen P., (2015), "Biorefine Recycling inorganic chemicals from agro- and bio-industrial waste streams Netherlands and the United Kingdom", *Renewable Resources and Biorefineries*, 1-21.

Diaz-Elsayed N., Rezaei N., Guo T., Mohebbi S., Zhang Q., (2019), "Wastewater-based resource recovery technologies across scale: A review", *Resources, Conservation and Recycling*, 145, 94–112.

Diaz-Elsayed N., Rezaei N., Guo T., Mohebbi S., Zhang Q., (2019), "Wastewater-based resource recovery technologies across scale: A review", *Resources, Conservation and Recycling*, 145, 94–112.

Ding A., Zhang R., Ngo H. H., He X., Ma J., Nan J., et al., (2021), "Life cycle assessment of sewage sludge treatment and disposal based on nutrient and energy recovery: A review", *Science of the Total Environment*, 1-76, 769.

Donevska K. R., Gorsevski P. V., Jovanovski M., Peševski I., (2012), "Regional non-hazardous landfill site selection by integrating fuzzy logic, AHP and geographic information systems", *Environmental Earth Sciences*, 67 (1), 121–131.

Dos Santos P. H., Neves S. M., Sant’Anna D. O., Oliveira C. H. de, Carvalho H. D., (2019), "The analytic hierarchy process supporting decision making for sustainable development: An overview of applications", *Journal of Cleaner Production*, 212, 119–138.

Duque A. F., Campo R., Rio A. V. Del, Amorim C. L., (2021), "Wastewater valorization: Practice around the world at pilot-and full-scale", *International Journal of Environmental Research and Public Health*, 102, 5-18 (18),.

Egle L., Rechberger H., Krampe J., Zessner M., (2016), "Science of the Total Environment Phosphorus recovery from municipal wastewater: An integrated comparative technological , environmental and economic assessment of P recovery technologies", *Science of the Total Environment*, 571, 522–542.

Egle L., Rechberger H., Zessner M., (2015), "Overview and description of technologies for recovering phosphorus from municipal wastewater", *Resources, Conservation and Recycling*, 105 325–346.

Ellen MacArthur Foundation, (2023), "Let’s build a circular economy".

ElMekawy A., Srikanth S., Bajracharya S., Hegab H. M., Nigam P. S., Singh A., et al., (2015), "Food and agricultural wastes as substrates for bioelectrochemical system (BES): The synchronized recovery of sustainable energy and waste treatment", *Food Research International*, 73, 213–225.

Fetanat A., Tayebi M., Mofid H., (2021), "Water-energy-food security nexus based selection of energy recovery from wastewater treatment technologies: An extended decision making framework under intuitionistic fuzzy environment", *Sustainable Energy Technologies and Assessments*, 43, 100937.

Gabriel M. S. L., William P., Juan D. L. V., (2014), "Fundamentals of a Fuzzy Inference System for Educational Evaluation", Proceedings - 2014 International Conference on Mathematics and Computers in Sciences and in Industry, MCSI 2014, 42–47.

Germer J., (2009), "Urine-diverting vacuum sanitation system Beijing, China", China Construction Research & Design Institute, 1-74.

Ghosh Ray S., Ghangrekar M. M., (2015), "Enhancing organic matter removal, biopolymer recovery and electricity generation from distillery wastewater by combining fungal fermentation and microbial fuel cell", Bioresource Technology, 176 8–14.

Giuseppe Munda, (2009), "Measuring uncertainties in composite indicators of sustainability", International Journal of Environmental Technology and Management, 11, 213.

Gong H., Li Z., Jin Z., Xu H., Wang K., (2018), "Evaluation of direct water reclamation from municipal wastewater by disk tube reverse osmosis membrane (DT-RO) based compact process", Desalination and Water Treatment, 129, 194–200.

Gu Y., Zhang X., Deal B., Han L., (2019), "Biological systems for treatment and valorization of wastewater generated from hydrothermal liquefaction of biomass and systems thinking: A review", Bioresource Technology, 278, 329–345.

Guerrero-Liquet G. C., Oviedo-Casado S., Sánchez-Lozano J. M., García-Cascales M. S., Prior J., Urbina A., (2018), "Determination of the optimal size of photovoltaic systems by using multi-criteria decision-making methods", Sustainability (Switzerland), 2-15 (12).

Guštin S., Marinšek-Logar R., (2011), "Effect of pH, temperature and air flow rate on the continuous ammonia stripping of the anaerobic digestion effluent", Process Safety and Environmental Protection, 89 (1), 61–66.

Hansen É., Rodrigues M. A. S., Aragão M. E., de Aquim P. M., (2018), "Water and wastewater minimization in a petrochemical industry through mathematical programming", Journal of Cleaner Production, 172, 1814–1822.

Hao X., Wang X., Liu R., Li S., van Loosdrecht M. C. M., Jiang H., (2019), "Environmental impacts of resource recovery from wastewater treatment plants", Water Research, 160 268–277.

Hao X., Wang X., Liu R., Li S., van Loosdrecht M. C. M., Jiang H., (2019), "Environmental impacts of resource recovery from wastewater treatment plants", Water Research, 160, 268–277.

Hassan M. F., Saman M. Z. M., Sharif S., Omar B., (2012), "An Integrated MA-AHP Approach for Selecting the Highest Sustainability Index of a New Product", Procedia - Social and Behavioral Sciences, 57 236–242.

Ho W., Ma X., (2018), "The state-of-the-art integrations and applications of the analytic hierarchy process", *European Journal of Operational Research*, 267 (2), 399–414.

Hoang N. H., Fogarassy C., (2020), "Sustainability evaluation of municipal solid waste management system for hanoi (Vietnam)-why to choose the “waste-to-energy” concept", *Sustainability (Switzerland)*, 12 (3), 1–20.

Horn E., Proksch G., (2022), "Symbiotic and Regenerative Sustainability Frameworks: Moving Towards Circular City Implementation", *Frontiers in Built Environment*, 1–21.

Hrabec D., Šomplák R., Nevrlý V., Viktorin A., Pluháček M., Popela P., (2020), "Sustainable waste-to-energy facility location: Influence of demand on energy sales", *Energy*, 207.

Hruška R., Průša P., Babić D., (2014), "The use of AHP method for selection of supplier", *Transport*, 29 (2), 195–203.

İDEP, (2012), "İklim Değişikliği Eylem Planı 2011-2023", Çevre ve Şehircilik Bakanlığı, 1–77.

Iphar M., Alpay S., (2019), "A mobile application based on multi-criteria decision-making methods for underground mining method selection", *International Journal of Mining, Reclamation and Environment*, 33 (7), 480–504.

Ishizaka A., Labib A., (2011), "Review of the main developments in the analytic hierarchy process", *Expert Systems with Applications*, 38 (11), 14336–14345.

Jabłoński K., Grychowski T., (2018), "Fuzzy inference system for the assessment of indoor environmental quality in a room", *Indoor and Built Environment*, 27 (10), 1415–1430.

Jagoda J. A., Schuldt S. J., Hoisington A. J., (2020), "What to Do? Let’s Think It Through! Using the Analytic Hierarchy Process to Make Decisions", *Frontiers for Young Minds*, 106,8.

Jamwal A., Agrawal R., Sharma M., Kumar V., (2021), "Review on multi-criteria decision analysis in sustainable manufacturing decision making", *International Journal of Sustainable Engineering*, 14 (3), 202–225.

Jensen O., Nair S., (2019), "Integrated urban water management and water security: A comparison of Singapore and Hong Kong", *Water (Switzerland)*, 11 (4), 1–18.

Joensuu T., Edelman H., Saari A., (2020), "Circular economy practices in the built environment", *Journal of Cleaner Production*, 276, 124215.

Jonas M., Ometto J. P., Batistella M., Franklin O., Hall M., David M., et al., (2014), "Earth' s Future Sustaining ecosystem services: Overcoming the dilemma posed by local actions and planetary boundaries Earth ' s Future", 407–420.

Julio N., Figueroa R., Ponce Oliva R. D., (2021), "Water resources and governance approaches: Insights for achieving water security", *Water (Switzerland)*, 13 (21), 1–18.

Juwana I., Muttill N., Perera B. J. C., (2012), "Indicator-based water sustainability assessment - A review", *Science of the Total Environment*, 438 357–371.

Kamali M., Persson K. M., Costa M. E., Capela I., (2019), "Sustainability criteria for assessing nanotechnology applicability in industrial wastewater treatment: Current status and future outlook", *Environment International*, 125, 261–276.

Kaur R., Singh A., (2019), "Fuzzy Logic: An Overview of Different Application Areas", *Advances and Applications in Mathematical Sciences*, 18 (8), 677–689.

Kehrein P., Van Loosdrecht M., Osseweijer P., Garfi M., Dewulf J., Posada J., (2020), "A critical review of resource recovery from municipal wastewater treatment plants-market supply potentials, technologies and bottlenecks", *Environmental Science: Water Research and Technology*, 6 (4), 877–910.

Kehrein P., Van Loosdrecht M., Osseweijer P., Garfi M., Dewulf J., Posada J., (2020), "A critical review of resource recovery from municipal wastewater treatment plants-market supply potentials, technologies and bottlenecks", *Environmental Science: Water Research and Technology*, 6 (4), 877–910.

Kerstens S. M., Leusbrock I., Zeeman G., (2015), "Feasibility analysis of wastewater and solid waste systems for application in Indonesia", *Science of the Total Environment*, 530–531 53–65.

Khashei-Siuki A., keshavarz A., Sharifan H., (2020), "Comparison of AHP and FAHP methods in determining suitable areas for drinking water harvesting in Birjand aquifer. Iran", *Groundwater for Sustainable Development*, 10, 100328.

Kjerstadius H., Bernstad Saraiva A., Spångberg J., Davidsson, (2017), "Carbon footprint of urban source separation for nutrient recovery", *Journal of Environmental Management*, 197 250–257.

Kjerstadius H., Bernstad Saraiva A., Spångberg J., Davidsson, (2017), "Carbon footprint of urban source separation for nutrient recovery", *Journal of Environmental Management*, 197 250–257.

Krejčí J., Stoklasa J., (2018), "Aggregation in the analytic hierarchy process: Why weighted geometric mean should be used instead of weighted arithmetic mean", *Expert Systems with Applications*, 114 97–106.

Lam K. L., Zlatanović L., van der Hoek J. P., (2020), "Life cycle assessment of nutrient recycling from wastewater: A critical review", *Water Research*, 173.

Larsen T. A., Riechmann M. E., Udert K. M., (2021), "State of the art of urine treatment technologies: A critical review.", *Water Research X*, 13, 100114.

Li, Xuerui, Yu, Suihuai, and Chu J., (2018), "Optimal Selection of Manufacturing Services in Cloud Manufacturing: A Novel Hybrid MCDM Approach Based on Rough ANP and Rough TOPSIS", *Optimal Selection of Manufacturing Services in Cloud Manufacturing: A Novel Hybrid MCDM Approach Based on Rough ANP and Rough TOPSIS*, 34.

Lin Y., Guo M., Shah N., Stuckey D. C., (2016), "Economic and environmental evaluation of nitrogen removal and recovery methods from wastewater", *Bioresource Technology*, 215 227–238.

Liu F., Moustafa H., El-Din Hassouna M. S., He Z., (2020), "Resource recovery from wastewater can be an application niche of microbial desalination cells", *Environment International*, 142, 105855.

Liu G., Baniyounes A., Rasul M. G., Amanullah M. T. O., Khan M. M. K., (2012), "Fuzzy logic based environmental indicator for sustainability assessment of renewable energy system using life cycle assessment", *Procedia Engineering*, 49 35–41.

Liu Y., Deng Y. Y., Zhang Q., Liu H., (2021), "Overview of recent developments of resource recovery from wastewater via electrochemistry-based technologies", *Science of the Total Environment*, 757 143901.

Lodge B., Judd S. J., Smith A. J., (2004), "The impact of mechanical reliability on the financial return of a water-recycling plant", *Water and Environment Journal*, 18 (1), 50–53.

Lofrano G., Brown J., (2010), "Wastewater management through the ages: A history of mankind", *Science of the Total Environment*, 408 (22), 5254–5264.

Lorick D., Macura B., Ahlström M., Grimvall A., Harder R., (2020), "Effectiveness of struvite precipitation and ammonia stripping for recovery of phosphorus and nitrogen from anaerobic digestate: a systematic review", *Environmental Evidence*, 9 (1), 1–20.

Lu H., Zhang G., He S., Zhao R., Zhu D., (2021), "Purple non-sulfur bacteria technology: a promising and potential approach for wastewater treatment and bioresources recovery", *World Journal of Microbiology and Biotechnology*, 37 (9), 1–15.

Lu H., Zhang G., Zheng Z., Meng F., Du T., He S., (2019), "Bio-conversion of photosynthetic bacteria from non-toxic wastewater to realize wastewater treatment and bioresource recovery: A review", *Bioresource Technology*, 278, 383–399.

Luh J., Baum R., Bartram J., (2013), "Equity in water and sanitation: Developing an index to measure progressive realization of the human right", *International Journal of Hygiene and Environmental Health*, 216 (6), 662–671.

Ma X. (Cissy), Xue X., González-Mejía A., Garland J., Cashdollar J., (2015), "Sustainable water systems for the city of tomorrow-A conceptual framework", *Sustainability (Switzerland)*, 7 (9), 12071–12105.

Magrí A., Carreras-Sempere M., Biel C., Colprim J., (2020), "Recovery of phosphorus from waste water profiting from biological nitrogen treatment: Upstream, concomitant or downstream precipitation alternatives".

Mardani A., Zavadskas E. K., Khalifah Z., Zakuan N., Jusoh A., Nor K. M., et al., (2017), "A review of multi-criteria decision-making applications to solve energy management problems: Two decades from 1995 to 2015", *Renewable and Sustainable Energy Reviews*, 71, 216–256.

Masdari M., Khezri H., (2021), "Service selection using fuzzy multi-criteria decision making: a comprehensive review", Springer Berlin Heidelberg.

Mehta C. M., Khunjar W. O., Nguyen V., Tait S., Batstone D. J., (2015), "Technologies to recover nutrients from waste streams: A critical review", *Critical Reviews in Environmental Science and Technology*, 45 (4), 385–427.

Miller-Robbie L., Ramaswami A., Kumar P., (2013), "Life Cycle Energy Use and Greenhouse Gas Emission Analysis for a Water Resource Recovery Facility in India", *Water Environment Research*, 85 (7), 621–631.

Milošević M. R., Milošević D. M., Stanojević A. D., Stević D. M., Simjanović D. J., (2021), "Fuzzy and interval ahp approaches in sustainable management for the architectural heritage in smart cities", *Mathematics*, 9 (4), 1–29.

Mo W., Zhang Q., (2013), "Energy-nutrients-water nexus: Integrated resource recovery in municipal wastewater treatment plants", *Journal of Environmental Management*, 127 255–267.

Morelli B., Cashman S., Cissy Ma X., Garland J., Turgeon J., Fillmore L., et al., (2018), "Effect of nutrient removal and resource recovery on life cycle cost and environmental impacts of a small scale water resource recovery facility", *Sustainability (Switzerland)*, 10 (10),.

Mosleh L., Negahban-Azar M., (2021), "Role of models in the decision-making process in integrated urban water management: A review", *Water (Switzerland)*, 13 (9),.

Muhammad Yaqub, Lee W., (2019), "Zero-liquid discharge (ZLD) technology for resource recovery from wastewater: A review", *Science of the Total Environment*, 681 551–563.

Mvongo V. D., Defo C., Tchoffo M., (2021), "Indicator-based rural water service sustainability assessment: A review", *Water Supply*, 21 (7), 3267–3281.

Naghib S. D., Di Maio F. P., De Bartolo L., Curcio E., Di Renzo A., (2018), "Automation and control system for fluid dynamic stability in hollow-fiber membrane bioreactor for cell culture", *Journal of Chemical Technology and Biotechnology*, 93 (3), 710–719.

Nenov V., Peeva G., Yemendzhiev H., Stancheva M., Zerouq F., (2020), "Phosphorus consumption. From linear to circular flow", *Moroccan Journal of Chemistry*, 8 (4), 819–829.

Oberascher M., Rauch W., Sitzenfrei R., (2022), "Towards a smart water city: A comprehensive review of applications, data requirements, and communication technologies for integrated management", *Sustainable Cities and Society*, 76, 103442.

Ömürbek N., Demirci N., Akalin P., (2013), "Analitik Ağ Süreci ve TOPSIS Yöntemleri İle Bilimdalı Seçimi", *Akademik Araştırmalar ve Çalışmalar Dergisi*, 5 (9), 118–140.

Orner K. D., Cornejo P. K., Rojas Camacho D., Alvarez M., Camacho-Céspedes F., (2021), "Improving Life Cycle Economic and Environmental Sustainability of Animal Manure Management in Marginalized Farming Communities Through Resource Recovery", *Environmental Engineering Science*, 00 (00), 1–10.

Panagopoulos A., Haralambous K. J., (2020), "Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) strategies for wastewater management and resource recovery-Analysis, challenges and prospects", *Journal of Environmental Chemical Engineering*, 8 (5), 104418.

Papa M., Foladori P., Guglielmi L., Bertanza G., (2017), "How far are we from closing the loop of sewage resource recovery? A real picture of municipal wastewater treatment plants in Italy", *Journal of Environmental Management*, 198 9–15.

Patel A., Mungray A. A., Mungray A. K., (2020), "Technologies for the recovery of nutrients, water and energy from human urine: A review", *Chemosphere*, 259 127372.

Perera M. K., Englehardt J. D., Dvorak A. C., (2019), "Technologies for Recovering Nutrients from Wastewater: A Critical Review", *Environmental Engineering Science*, 36 (5), 511–529.

Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, (2019), "2019 Revision of World Population Prospects".

Prendeville S., Cherim E., Bocken N., (2018), "Circular Cities: Mapping Six Cities in Transition", *Environmental Innovation and Societal Transitions*, 26 171–194.

Rathore P., Sarmah S. P., (2019), "Modeling transfer station locations considering source separation of solid waste in urban centers: A case study of Bilaspur city, India", *Journal of Cleaner Production*, 211 44–60.

Rentizelas A., Shpakova A., Mašek O., (2018), "Designing an optimised supply network for sustainable conversion of waste agricultural plastics into higher value products", *Journal of Cleaner Production*, 189 683–700.

Robles Á., Aguado D., Barat R., Borrás L., Bouzas A., Giménez J. B., et al., (2020), "New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy", *Bioresource Technology*, 300, 122673.

Robles Á., Aguado D., Barat R., Borrás L., Bouzas A., Giménez J. B., et al., (2020), "New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy", *Bioresource Technology*, 300, 122673.

Saaty R. W., (1987), "The analytic hierarchy process-what it is and how it is used", *Mathematical Modelling*, 9 (3–5), 161–176.

Saaty T. L., (1990), "How to make a decision: The analytic hierarchy process", *European Journal of Operational Research*, 48 (1), 9–26.

Saaty T. L., (2003), "Decision-making with the AHP: Why is the principal eigenvector necessary", *European Journal of Operational Research*, 145 (1), 85–91.

Saaty T. L., (2004), "Fundamentals of the analytic network process — Dependence and feedback in decision-making with a single network", *Journal of Systems Science and Systems Engineering*, 13 (2), 129–157.

Saaty T. L., (2006), "Archive of SID The Analytic Network Process Archive of SID", *Network*, 1 (1), 1–26.

Saaty T. L., Tran L. T., (2007), "On the invalidity of fuzzifying numerical judgments in the Analytic Hierarchy Process", *Mathematical and Computer Modelling*, 46 (7–8), 962–975.

Saaty T., (2006), "Chapter 1 the Analytic Network Process", *Network*, 95 (1), 1–27.

Sandoval-Solis S., McKinney D. C., Loucks D. P., (2011), "Sustainability Index for Water Resources Planning and Management", *Journal of Water Resources Planning and Management*, 137 (5), 381–390.

Säumel I., Reddy S. E., Wachtel T., (2019), "Edible city solutions-one step further to foster social resilience through enhanced socio-cultural ecosystem services in cities", *Sustainability (Switzerland)*, 11 (4).

Seiple T. E., Skaggs R. L., Fillmore L., Coleman A. M., (2020), "Municipal wastewater sludge as a renewable, cost-effective feedstock for transportation biofuels using hydrothermal liquefaction", *Journal of Environmental Management*, 270 (December 2019),.

Seki H., Mizumoto M., (2011), "On the equivalence conditions of fuzzy inference methods-Part 1: Basic concept and definition", *IEEE Transactions on Fuzzy Systems*, 19 (6), 1097–1106.

Sengupta S., Nawaz T., Beaudry J., (2015), "Nitrogen and Phosphorus Recovery from Wastewater", *Current Pollution Reports*, 1 (3), 155–166.

Shareefdeen Z., Mishu A. A., (2021), "Air emissions in waste to energy (W2E) plants", *Clean Technologies and Environmental Policy*, (0123456789),.

Shende A. D., Chelani A. B., Rao N. N., Pophali G. R., (2021), "Optimal selection of “zero liquid discharge” (ZLD) system using “analytical hierarchy process” (AHP) and “grey relational analysis” (GRA)", *Environment, Development and Sustainability*, 23 (6), 8506–8523.

Siciliano A., Limonti C., Curcio G. M., Molinari R., (2020), "Advances in struvite precipitation technologies for nutrients removal and recovery from aqueous waste and wastewater", *Sustainability (Switzerland)*, 12 (18),.

Silva J. da, Fernandes V., Limont M., Dziedzic M., Andreoli C. V., Rauen W. B., (2020), "Water sustainability assessment from the perspective of sustainable development capitals: Conceptual model and index based on literature review", *Journal of Environmental Management*, 254, 109750.

Skar S. L. G., Pineda-Martos R., Timpe A., Pölling B., Bohn K., Külvik M., et al., (2020), "Urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future", *Blue-Green Systems*, 2 (1), 1–27.

Slišāne D., Gaumigs G., Lauka D., Blumberga D., (2020), "Assessment of energy sustainability in statistical regions of Latvia using energy sustainability index", *Environmental and Climate Technologies*, 24 (2), 160–169.

Sodiq A., Baloch A. A. B., Khan S. A., Sezer N., Mahmoud S., Jama M., et al., (2019), "Towards modern sustainable cities: Review of sustainability principles and trends", *Journal of Cleaner Production*, 227, 972–1001.

Šomplák R., Kůdela J., Smejkalová V., Nevrlý V., Pavlas M., Hrabec D., (2019), "Pricing and advertising strategies in conceptual waste management planning", *Journal of Cleaner Production*, 602–734, 239.

Sprouse C. E., Hoover C., Obritsch O., Thomazin H., (2020), "Advancing pervious pavements through nomenclature, standards, and holistic green design", *Sustainability (Switzerland)*, 12 (18).

Srdjevic Z., Srdjevic B., (2017), "An Extension of the Sustainability Index Definition in Water Resources Planning and Management", *Water Resources Management*, 31 (5), 1695–1712.

Sweeney M., Kabouris J., (2020), "Modeling, instrumentation, automation, and optimization of water resource recovery facilities (2019) DIRECT", *Water Environment Research*, 92 (10), 1499–1503.

Taherdoost H., (2017), "Decision Making Using the Analytic Hierarchy Process (AHP); A Step by Step Approach Hamed Taherdoost To cite this version : HAL Id : hal-02557320 Decision Making Using the Analytic Hierarchy Process (AHP); A Step by Step Approach", *Journal of Economics and Management Systems*, 2 (International), 244–246.

Theregowda R. B., González-Mejía A. M., Ma X., Garland J., (2019), "Nutrient Recovery from Municipal Wastewater for Sustainable Food Production Systems: An Alternative to Traditional Fertilizers", *Environmental Engineering Science*, 36 (7), 833–842.

Thinusblanc C., (1984), "Tolman cognitive maps - a critical-review", 4, 537–558.

Tilley D., (2011), "Aerobic wastewater treatment processes: history and development", IWA publishing alliance house, 80, 102-158.

Tilmans S., Diaz-Hernandez A., Nyman E., Davis J., (2014), "The potential for financing small-scale wastewater treatment through resource recovery: Experience from bocas del Toro, Panama", *Journal of Water Sanitation and Hygiene for Development*, 4 (3), 449–459.

Tomei M. C., Angelucci D. M., (2021), "Biological wastewater treatment as an opportunity for energy and resource recovery", *Sustainable Industrial Water Use: Perspectives, Incentives, and Tools*, 407–415.

Tonini D., Wandl A., Meister K., Unceta P. M., Taelman S. E., Sanjuan-Delmás D., et al., (2020), "Quantitative sustainability assessment of household food waste management in the Amsterdam Metropolitan Area", *Resources, Conservation and Recycling*, 160, 104854.

Topuz E., Talinli I., Aydin E., (2011), "Integration of environmental and human health risk assessment for industries using hazardous materials: A quantitative multi criteria approach for environmental decision makers", *Environment International*, 37 (2), 393–403.

Torabzadeh Khorasani S., (2018), "Green Supplier Evaluation by Using the Integrated Fuzzy AHP Model and Fuzzy Copras", *Process Integration and Optimization for Sustainability*, 2 (1), 17–25.

Tzanakakis V. E., Paranychianaki N. V., Angelakis A. N., (2007), "Soil as a wastewater treatment system: Historical development", *Water Science and Technology: Water Supply*, 7 (1), 67–75.

UNESCO Office Dakar and Regional Bureau for Education in Africa, (2019), "Annual report 2018", .

United Nations Environment Programme, (2015), "General Assembly of the United Nations",.

United nations, (2022), "No Title", Sustainability Development Goals,.

Valente T. M., Ferreira M. J., Gomes C. L., (2011), "Application of fuzzy logic to qualify the environmental impact in abandoned mining sites", *Water, Air, and Soil Pollution*, 217 (1–4), 303–315.

van der Hoek J. P., Duijff R., Reinstra O., (2018), "Nitrogen recovery from wastewater: Possibilities, competition with other resources, and adaptation pathways", *Sustainability (Switzerland)*, 10 (12),.

Web 1, (2023), <https://www.epa.gov/sustainability>, Access date:12/01/2023_

Web 2, (2023), <https://pacecircular.org/>, Access date: 24/02/2023.

Web 3, (2023), <https://www.superdecisions.com/>, Access date:2/04/2023.

Williams J., (2019), "Circular cities: Challenges to implementing looping actions", *Sustainability (Switzerland)*, 11 (2),.

Wwap, (2017), "The United Nations World Water Development Report 2017", .

Xie M., Shon H. K., Gray S. R., Elimelech M., (2016), "Membrane-based processes for wastewater nutrient recovery: Technology, challenges, and future direction", *Water Research*, 89 210–221.

Xie M., Shon H. K., Gray S. R., Elimelech M., (2016), "Membrane-based processes for wastewater nutrient recovery: Technology, challenges, and future direction", *Water Research*, 89 210–221.

Yalçın Ö., Negiz N., (2020), "Türkiye’ de Kentsel Alanlarda Döngüsel Ekonomi Uygulamaları Üzerine Bir Yazın İncelemesi A Literature Review on Circular Economy Applications in Urban Areas in Turkey", *Akademia Doğa ve İnsan Bilimleri Dergisi*, 6 (1), 25–44.

Yang J., Monnot M., Ercolei L., Moulin P., (2020), "Membrane-based processes used in municipal wastewater treatment for water reuse: State-of-the-art and performance analysis", *Membranes*, 10 (6), 1–56.

Yıldız S., Namal OÖ., Çekim M., (2013), "The Historical Development of Wastewater Treatment Technologies", Selcuk Univ. J. Eng. Sci. Tech., 1 (1), 55–67.

Zadeh L. A., (1994), "The role of fuzzy logic in modeling, identification and control", Modeling, Identification and Control: A Norwegian Research Bulletin, 15 (3), 191–203.

Zadeh L. A., (2008), "Is there a need for fuzzy logic?", Information Sciences, 178 (13), 2751–2779.

Zolfaghary P., Zakerinia M., Kazemi H., (2021), "A model for the use of urban treated wastewater in agriculture using multiple criteria decision making (MCDM) and geographic information system (GIS)", Agricultural Water Management, 243, 106490.



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