REPUBLIC OF TURKEY

YILDIZ TECHNICAL UNIVERSITY

GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

DETERMINATION OF SUSTAINABLE WASTE MANAGEMENT STRATEGIES IN SMART CITIES USING FUZZY MULTI-CRITERIA DECISION APPROACH

Bihter Gizem DEMIRCAN

MASTER OF SCIENCE THESIS

Department of Environmental Engineering

Environmental Engineering Program

Supervisor

Prof. Dr. Kaan YETILMEZSOY

February, 2023

REPUBLIC OF TURKEY

YILDIZ TECHNICAL UNIVERSITY

GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

DETERMINATION OF SUSTAINABLE WASTE MANAGEMENT STRATEGIES IN SMART CITIES USING FUZZY MULTI-CRITERIA DECISION APPROACH

A thesis submitted by Bihter Gizem DEMIRCAN in partial fulfillment of the requirements for the Master Degree is approved by the committee on 27.02.2023 in Department of Environmental Engineering, Environmental Engineering Program.

Prof. Dr. Kaan YETILMEZSOY
Yıldız Technical University
Supervisor

Approved By the Examining Committee

Prof. Dr. Kaan YETILMEZSOY, Supervisor
Yildiz Technical University _____

Assoc. Prof. Dr. Ebru AKKAYA, Member
Yildiz Technical University _____

Assoc. Prof. Dr. Emine ELMASLAR OZBAS, Member
Istanbul University _____

I hereby declare that I have obtained the required legal permissions during data collection and exploitation procedures, that I have made the in-text citations and cited the references properly, that I haven't falsified and/or fabricated research data and results of the study and that I have abided by the principles of the scientific research and ethics during my Thesis Study under the title of Determination of Sustainable Waste Management Strategies in Smart Cities Using Fuzzy Multi-Criteria Decision Approach supervised by my supervisor, Prof. Dr. Kaan YETILMEZSOY. In the case of a discovery of false statement, I am to acknowledge any legal consequence.

Bihter Gizem DEMIRCAN

Signature

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my thesis supervisor Prof. Dr. Kaan YETILMEZSOY for his encouragement, invaluable guidance and endless and forever patience throughout this study. It is an honour for me to be a student of him.

I would also thank to committee members Assoc. Prof. Dr. Ebru AKKAYA and Assoc. Prof. Dr. Emine ELMASLAR OZBAS for their precious suggestions and contributions to this study.

I would like to extend my gratitude to Hazal CEYLAN, Busra ALTIN and Sena GOKCEOGLU for their invaluable support during this study. Thank you for being always there when I needed.

Finally, I am deeply grateful to my dear parents, my brother, my sister-in-law, and my cat (son) Yigit who make my life meaningful. Thank you for your love, support and encouragement.

Bihter Gizem DEMIRCAN

TABLE OF CONTENTS

LIST OF SYMBOLS vii
LIST OF ABBREVIATIONS ix
LIST OF FIGURES xii
LIST OF TABLES xiii
ABSTRACT xiv
ÖZET xvi
1 INTRODUCTION 1
1.1 Literature Review 1
1.1.1 Smart City Concept 2
1.1.2 Sustainable Waste Management in Smart Cities....5
1.1.3 Multi-Criteria Decision-Making (MCDM)....10
1.1.4 Classification of MCDM Techniques....11
1.1.5 Fuzzy Set Theory....12
1.1.6 Fuzzy AHP....14
1.1.7 Fuzzy TOPSIS....16
1.1.8 MCDM in Sustainable Waste Management....19
1.2 Objective of the Thesis....23
1.3 Hypothesis....23
2 SMART SUSTAINABLE WASTE MANAGEMENT APPROACHES 25
2.1 Integrating Informal Recyclable Waste Collection Into a Formal Smart System 25
2.1.1 Informal Collection of Recyclables: Current Situation and Its Negative Consequences 25
2.1.2 Good Examples: Waste Collection in Cooperatives....27
2.1.3 Proposed Alternative 29
2.2 A Pay As You Throw Application Leveraging Blockchain Technology 31
2.2.1 Pay As You Throw: Historical Development and Basic Principles 31
2.2.2 Good Examples: PAYT Applications in Various Cities....34
2.2.3 Proposed Alternative 35
2.3 IoT-Based Community Composting 37
2.3.1 Food Waste as a Global Problem 37
2.3.2 Good Examples: Community Composting 38
2.3.3 Proposed Alternative 41

2.4 Preventing Illegal Sewage Discharge By Utilizing IoT 43
2.4.1 Illegal Sewage Discharge: General Framework and Negative Consequences 43
2.4.2 Good Examples: Monitoring and Detecting Illegal Sewage Discharges 45
2.4.3 Proposed Alternative 47
3 MATERIALS AND METHODS **50**
3.1 Constructing the Hierarchical Structure of the Problem 50
3.2 Obtaining Decision Maker Opinions 52
3.3 Computational Analysis 53
4 RESULTS AND DISCUSSIONS **54**
4.1 Determination of Criterion Weights 54
4.2 Ranking of the Strategy Alternatives According to the Weighted Criteria 59
4.3 Sensitivity Analysis 68
4.4 Implications for Smart Sustainable Waste Management 70
4.5 Final Outcomes and Limitation of the Study 72
REFERENCES **74**
A REPRESENTATIVE SECTIONS FROM THE QUESTIONNAIRE **83**

LIST OF SYMBOLS

B:	Benefit criteria
C:	Cost criteria
$\tilde{x}_{ij}$:	Criterion value of the alternatives
$\widetilde{w}_j$:	Criterion weight
DM:	Decision maker
K:	Evaluation criteria
$M^m{}_{gi}$:	Extent analysis value obtained for m-th object
M_1:	First convex triangular fuzzy number
μ_{M1}:	First membership function
$\widetilde{W}$:	Fuzzy criterion weight matrix
$\widetilde{D}$:	Fuzzy multi-criteria group decision-making problem matrix
A^-:	Fuzzy negative-ideal solution
A^*:	Fuzzy positive-ideal solution
Cj:	J-th decision criteria
$\widetilde{R}$:	Normalized fuzzy decision matrix
$\tilde{r}_{ij}$:	Normalized fuzzy decision matrix element
W:	Normalized weight vector
An:	N-th alternative or scenario for a MCDM problem
M_2:	Second convex triangular fuzzy number
μ_{M2}:	Second membership function
CC_i:	The closeness coeffcient of each alternative
V:	The degree possibility for a convex fuzzy number
d_i^-:	The distance of the alternatives from fuzzy negative-ideal solution
d_i^*:	The distance of the alternatives from fuzzy positive-ideal solution
a_{ij}:	The performance of alternative *Ai*
S_i:	The value of fuzzy synthetic extent with respect to the i-th object
W':	Weight vector
$\tilde{V}$:	Weighted normalized fuzzy decision matrix

$\tilde{v}_{ij}$: Weighted normalized fuzzy decision matrix element

LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
AQI	Air Quality Index
ASMARE	Associação dos Catadores de Papel Papelão e Material Reaprovitável
BOS	Baltimore Office of Sustainability
CE	Circular Economy
COD	Chemical Oxygen Demand
CODAS	Combinative Distance-based Assessment
COOPAMARE	Cooperativa de Catadores Autônomos de Papel, Aparas e Materiais Reprovitáveis
DEA	Data Envelopment Analysis
DEMATEL	Decision-Making Trail and Evaluation Laboratory
DL	Deep Learning
DMI	Definitely More Important
EEC	European Economic Community
EI	Equally Important
ELECTRE	Elimination and Choice Expressing Reality
F	Fair
FMCDM	Fuzzy Multi-Criteria Decision-Making
FNIS:	Fuzzy Negative Ideal Solution
FPIS:	Fuzzy Positive Ideal Solution
G	Good
GESIKOOP	Tepebaşı Geri Dönüştürülebilir Atık Toplayıcıları Sosyal İşletme Kooperatifi
GIS	Geographic Information System
GPRS	General Packet Radio Service

GPS	Global Positioning System
GRA	Gray Relation Analysis
H	High
HCTs	High Capacity Trucks
ICT	Information Communication Technology
IIMS	Integrated Information Management System
IOT	Internet of Things
IT	Information Technology
IUCN	International Union for Conservation of Nature
KATIS	Kocaeli Atıksu Transfer İzleme Sistemi
LCA	Life Cycle Analysis
LCTs	Low Capacity Trucks
LORA	Long Rage
M	Medium
MADM	Multi-Attribute Decision-Making
MAUT	Multi-Attribute Utility Theory
MBBR	Moving Bed Biofilm Reactor
MBR	Membrane Mioreactor
MCDM	Multi-Criteria Decision-Making
MG	Medium Good
MH	Medium High
ML	Machine Learning
MP	Medium Poor
MODM	Multi-Objective Decision-Making
MSW	Municipal Solid Waste
NFC	Near Field Communication

NRDC	Natural Resources Defense Council
PAYT	Pay As You Throw
PROMETHEE	Preference Ranking Organization and Method for Enrichment Evaluation
QR	Quick Response
RFID	Radio Frequency Identification
SCADA	Supervisory Control and Data Acquisition
SD	Secure Digital
SOB	Smart Organic Bins
SMI	Slightly More Important
SRB	Smart Recycling Bins
StMI	Strongly More Important
SWACH	Seva Sahakari Sanstha
SWOT	Strengths, Weaknesses, Opportunities, Threats
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UASB	Upflow Anaerobic Sludge Blanket
UN	United Nations
VG	Very Good
VH	Very High
VHFR	Very High Frequency Radio
VL	Very Low
VSMI	Very Strongly More Important
WI-FI	Wireless Fidelity
WSM	Weighted Sum Model

LIST OF FIGURES

Figure 1.1 The share of the total population living in urban areas, with UN urbanization projections to 2050....1
Figure 1.2 Characteristics and tools that define smart cities 4
Figure 1.3 IoT architecture 4
Figure 1.4 A triangular fuzzy number Ã 13
Figure 1.5 The intersection between M_1 and M_2....16
Figure 2.1 Generic flow of recyclables through an informal recycling system....26
Figure 2.2 Door-to-door collection of recyclable waste using ICT tools....30
Figure 2.3 Most common PAYT methods....32
Figure 2.4 A food waste drop off point in Baltimore....40
Figure 2.5 A smart composting approach....42
Figure 2.6 Wireless IoT module with pH and conductivity sensor....46
Figure 2.7 Citizen reporting interface for possible illegal sewage discharges 49
Figure 3.1 The hierarchical structure of the problem....52
Figure 3.2 Distribution of expertise and work area of the decision maker group....53
Figure A.1 Evaluation of technical sub-criteria in linguistic terms 83
Figure A.2 Evaluation results of technical sub-criteria in linguistic terms (x-axis: number of experts) 83
Figure A.3 Evaluation of alternatives in linguistic terms according to less surface water pollution sub-criterion....84
Figure A.4 Evaluation results of alternatives in linguistic terms according to less surface water pollution sub-criterion (x-axis: number of experts) 85

LIST OF TABLES

Table 1.1 Commonly cited Smart City definitions....3
Table 1.2 Various ICTs and their application in SWM....7
Table 1.3 A typical decision matrix....12
Table 1.4 Linguistic terms and corresponding triple fuzzy numbers....14
Table 1.5 Linguistic terms for the importance weight of each criterion....17
Table 1.6 Linguistic terms for alternative evaluation....17
Table 3.1 Smart waste management strategy alternatives to be evaluated....50
Table 3.2 Main criteria and sub-criteria to be considered....51
Table 4.1 Pairwise comparison matrix for environmental criteria....54
Table 4.2 Pairwise comparison matrix for technical criteria....56
Table 4.3 Pairwise comparison matrix for economic criteria....57
Table 4.4 Pairwise comparison matrix for social criteria....58
Table 4.5 Fuzzy decision matrix....60
Table 4.6 Normalized fuzzy decision matrix....62
Table 4.7 Weighted normalized fuzzy decision matrix....63
Table 4.8 Distance of the alternatives from A^* (d^*)....65
Table 4.9 Distance of the alternatives from A^- (d^-)....66
Table 4.10 Total d^* and d^- values of the alternatives....67
Table 4.11 The closeness coefficient (CC_i) and the ranking of the alternatives....68
Table 4.12 The new closeness coefficient values (CC_i) of the alternatives....69

ABSTRACT

Determination of Sustainable Waste Management Strategies in Smart Cities Using Fuzzy Multi-Criteria Decision Approach

Bihter Gizem DEMIRCAN

Department of Environmental Engineering

Master of Science Thesis

Supervisor: Prof. Dr. Kaan YETILMEZSOY

The integration of smart city technologies into waste management is a challenging field for decision-makers due to its multi-variate, multi-limiting and multi-stakeholder structure, despite its contribution to the ecological and economic understanding of cities' sustainability. The success of smart sustainable waste management strategies depends on many environmental, technical, economic and social variables, and many stakeholders are involved in the processes. Using fuzzy Multi-Criteria Decision-Making methods helps decision makers determine effective, affordable, and acceptable smart waste management strategies. Although MCDM methods are widely used in various environmental engineering applications, the determination of smart sustainable waste management strategies using these methods has not yet received enough attention in the literature. This study aims to contribute to this gap in the literature by evaluating four different smart waste management strategies using a hybrid fuzzy MCDM method. The performance of the proposed strategy alternatives according to fifteen sub-criteria under four main criteria selected from the literature was evaluated by a combined application of fuzzy Analytic Hierarchy Process (Fuzzy AHP) and fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS). For this evaluation, the subjective opinions of ten

different experts working in academia, in the private sector or in the public sector were obtained using the prepared questionnaires. To test the reliability and stability of the obtained performance ranking results, a sensitivity analysis was performed using eighteen different scenarios in which the weights of the sub-criteria were increased, decreased or changed at different rates. As a result of the analysis, it turned out that the initially obtained ranking is robust to the sub-criteria weight changes, since the performance ranking of the alternatives did not change.

Keywords: Smart cities, smart waste management, fuzzy multi-criteria decision-making, technique for order preference by similarity to ideal solution, analytic hierarchy process.

ÖZET

Akıllı Şehirlerdeki Sürdürülebilir Atık Yönetimi Stratejilerinin Bulanık Çok Kriterli Karar Verme Yaklaşımı ile Belirlenmesi

Bihter Gizem DEMİRCAN

Çevre Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

Danışman: Prof. Dr. Kaan YETİLMEZSOY

Atık yönetimine akıllı şehir teknolojilerinin entegrasyonu, kentlerin çevresel ve ekonomik sürdürülebilirlik anlayışlarına sağladığı katkıya karşın çok değişkenli, çok sınırlayıcılı ve çok paydaşlı yapısı nedeni ile karar vericiler için zorlayıcı bir çalışma alanıdır. Akıllı sürdürülebilir atık yönetimi süreçlerinin başarısı, çevresel, teknik, ekonomik ve sosyal birçok değişkene bağlıdır ve süreçlerde çok sayıda paydaş yer alır. Etkin, ekonomik yönden karşılanabilir ve kent sakinlerince kabul görebilir akıllı atık yönetimi stratejilerinin belirlenmesinde Bulanık Çok Kriterli Karar Verme yöntemlerinden yararlanılması, karar vericilere yardımcı olur. Çeşitli çevre mühendisliği uygulamalarında ÇKKV yöntemlerinden sıklıkla faydalanılsa da, akıllı sürdürülebilir atık yönetimi stratejilerinin söz konusu yöntemler kullanılarak değerlendirilmesi literatürde henüz yeterli ilgiyi görmemiştir. Bu çalışmada, önerilen dört farklı akıllı atık yönetimi stratejisinin hibrit bir bulanık ÇKKV yöntemi kullanılarak değerlendirilmesi ile literatürdeki bu boşluğa katkı sunmak amaçlanmıştır. Önerilen strateji alternatiflerinin literatürden seçilen dört ana kriter başlığı altında yer alan on beş alt kritere göre

performansı, Bulanık Analitik Hiyerarşi Prosesi (Fuzzy Analytic Hierarchy Process (AHP)) ve Bulanık İdeal Çözüme Benzerliğe Göre Tercih Sıralaması Tekniği (Fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)) birlikte uygulanarak değerlendirilmiştir. Bu değerlendirme için akademi, özel sektör ya da kamuda görev yapan on uzmanın anketler yolu ile elde edilmiş subjektif görüşlerinden yararlanılmıştır. Elde edilen performans sıralaması sonuçlarının güvenilirlik ve stabilitesini test etmek için alt kriter ağırlıklıklarının farklı oranlarda arttırıp azaltıldığı ya da değiştirildiği on sekiz farklı senaryo ile duyarlılık analizi gerçekleştirilmiştir. Analiz sonucunda alternatiflerin performans sıralamasının değişmemesi ile ilk elde edilen sıralamanın alt kriter ağırlık değişimine dayanıklı olduğu ortaya çıkmıştır.

Anahtar Kelimeler: Akıllı şehirler, akıllı atık yönetimi, bulanık çok kriterli karar verme, ideal çözüme benzerliğe göre tercih sıralaması tekniği, analitik hiyerarşi prosesi.

1
INTRODUCTION

1.1 Literature Review

For reasons such as greater employment potential, desire for access to better education and health care, and social or political migration, urban populations are increasing rapidly around the world. While the total urban population was only 30% of the total world population in 1950, it was already 55% of the total world population in 2018, (4.2 billion urban dwellers vs. 3.4 billion rural dwellers) and this share is expected to reach 60% in 2030 and 68% in 2050 [1]. Figure 1.1 shows the share of the total population living in urban areas, with United Nations (UN) urbanization projections to 2050:

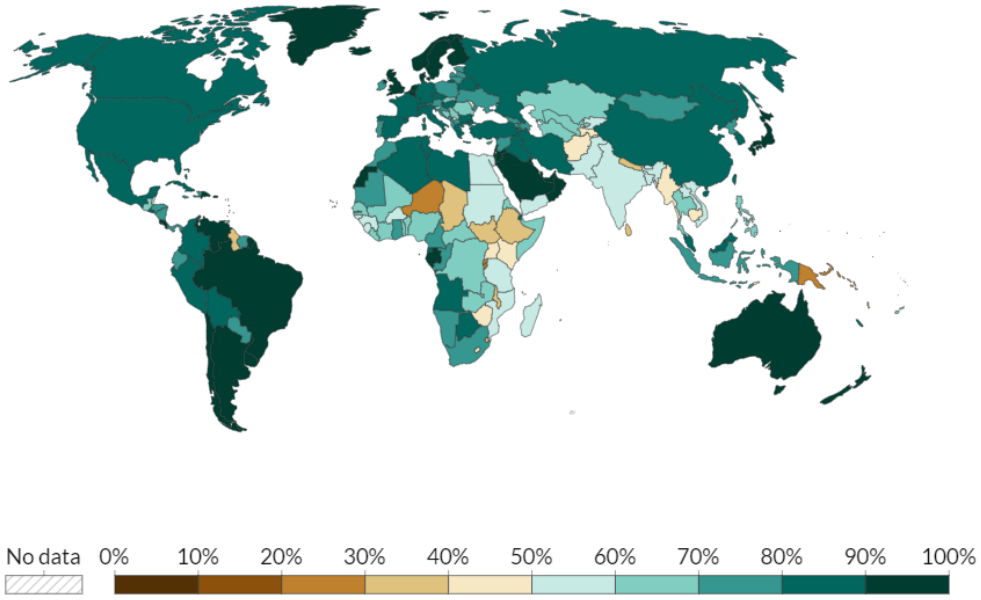


Figure 1.1 The share of the total population living in urban areas, with UN urbanization projections to 2050 [2]

This high urbanization trend makes cities key players in both the global climate crisis and the global water crisis. It has been reported that two-thirds of the world's energy is consumed in cities, and cities are responsible for 70% of global carbon emissions [3]. In addition to emissions from the use of large quantities of fossil fuels, cement-related emissions from the creation and use of urban infrastructure in cities are also serious. (9.2 $GtCO_2e$ and 9.6 $GtCO_2e$, respectively) [4]. Per capita water consumption, which is

increasing in parallel with rising income levels in cities, poses a drought threat. On the other hand, problems such as unsanitary water consumption and lack of access to improved water resources occur in cities where the welfare level of people is low. According to a recent report [5], 700 million urban dwellers lack improved sanitation facilities and 156 million urban dwellers lack improved water resources.

On the other hand, today, for the administrators who carry out people-oriented city policies and have an understanding that puts the welfare of their citizens first, issues such as convenient travel without long waits in traffic, effortless parking of vehicles, quick and hygienic disposal of garbage and sewage, less electricity and water bills, etc. have become more important.

The situation mentioned above reveals that cities are becoming more complex and dynamic by the day. So, it is becoming increasingly difficult for administrations to make the most efficient use of existing natural and economic resources and to cause as little harm to the environment as possible, while meeting the basic needs of urban dwellers, such as water, housing, transport, education and healthcare. As a result, creating innovative and technological approaches for providing city services are more crucial than ever. Since the 1990s, this urgency has brought a new concept known as "Smart City" into urban life.

1.1.1 Smart City Concept

The term "Smart City" does not have a single, widely accepted definition. In its most general form, the smart city is a city in which information and communication technologies (ICTs) are used to deliver urban services faster, in a more environmentally friendly and economical way, and to better respond to people's needs. In practice, however, there is a multi-dimensional, multi-stakeholder and much more complex structure to be understood. Hence, in the literature, this structure has been defined in many different ways according to desired characteristics and technical competencies of a city. In addition, although the most widely used term is "Smart City" in terms of being more inclusive than others, it is possible to come across concepts such as "Intelligent City", "Digital City", "Information City", "Wired City" in the literature. Table 1.1 shows the Smart City definitions that are commonly cited in the literature and Figure 1.2 summarizes the characteristics of a "Smart City" and the tools used by city authorities to make cities “Smart”.

Table 1.1 Commonly cited Smart City definitions [6]

Reference	Definition
[7]	"A city that monitors and integrates conditions of all of its critical infrastructures, including roads, bridges, tunnels, rails/subways, airports, seaports, communications, water, power, even major buildings, can better optimize its resources, plan its preventive maintenance activities, and monitor security aspects while maximizing services to its citizens… systems and structures will monitor their own conditions and carry out self-repair, as needed"
[8]	"Connecting the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city"
[9]	"We believe a city to be smart when investments in human and social capital and traditional (transport) and modern (Information and Communications Technology, ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance"
[10]	"A Smart City is a city seeking to address public issues via ICT-based solutions on the basis of a multi-stakeholder, municipally based partnership"
[11]	"A smart city is a well defined geographical area, in which high technologies such as ICT, logistic, energy production, and so on, cooperate to create benefits for citizens in terms of well being, inclusion and participation, environmental quality, intelligent development; it is governed by a well defined pool of subjects, able to state the rules and policy for the city government and development"

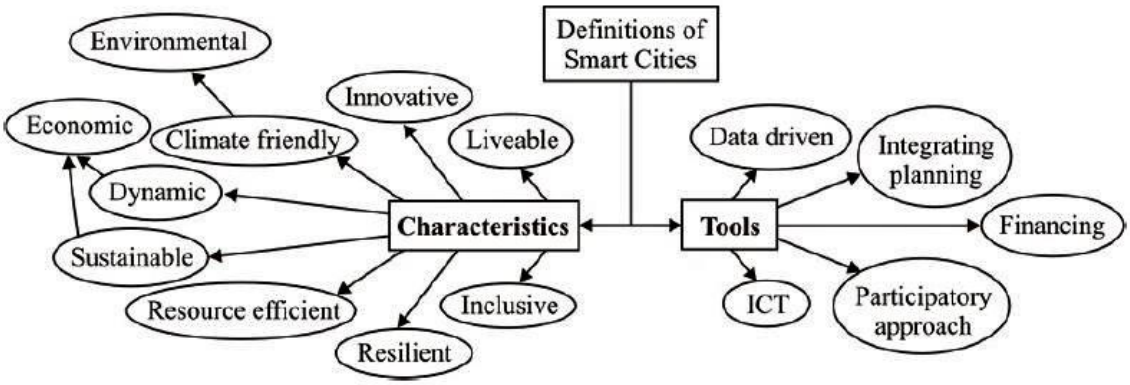


Figure 1.2 Characteristics and tools that define smart cities [12]

Internet-of-Things (IoT) technology, which is at the heart of Smart Cities applications, is typically based on receiving (sensors, actuators, radio frequency identification (RFID) readers, etc.), sending (Wireless Fidelity (Wi-Fi), mobile Internet, Zigbee, Bluetooth, etc.), storing (cloud technology) and processing (statistical methods, machine learning, deep learning, etc.) data to be used in decision-making processes [13]. In the aforementioned technology, the specific layers in which the data travels are shown in the Figure 1.3:

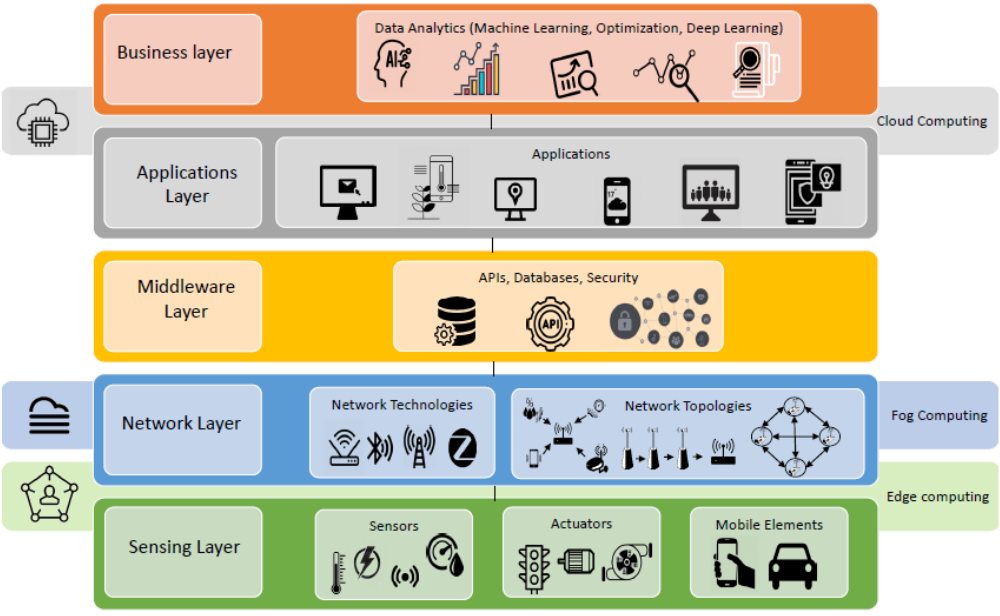


Figure 1.3 IoT architecture [14]

As can be seen from the figure, it could be said that Cloud Computing, Fog Computing and Edge Computing are models in which data processing is performed using the

elements of different layers. Researchers defined Cloud Computing [15] as a model for enabling ubiquitous, convenient, and on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or interaction with the service provider. Contrary to Cloud Computing, Edge Computing is based on a distributed decentralized infrastructure and processes the data in real time. As in Edge Computing, data processing in the Fog Computing model takes place near the point where they are obtained. The difference is that after processing, the data is sent back to the edge to perform the necessary action. The researchers have shown the advantages and disadvantages of the three models in relation to each other. It was emphasized that the models do not replace each other, but complement each other depending on the conditions in which they are used.

Although the uses of Smart City applications are already incredibly extensive, it could be said that it is a concept that is still evolving and needs more attention. Day after day, innovative solutions are created in various fields, especially in the areas of transport, infrastructure, environment, energy, health, education and culture. To this end, public authorities, the private sector, universities, institutes and living laboratories continue their work and implement projects in collaboration.

1.1.2 Sustainable Waste Management in Smart Cities

The term sustainability has been used in forms related to the environment since the 1970s, with the understanding of proactive solutions to environmental problems. It was first mentioned in the literature in the 1980 IUCN (The International Union for Conservation of Nature) World Conservation Strategy [16] as "sustainable development", which oversees the protection of ecological life and natural resources. Sustainable development has been shown to have three dimensions, namely social, economic and environmental [17], and these dimensions have been examined separately or together in various studies.

Considering the environment from these three pillars, it is seen that environmental sustainability is defined as “a set of rules to be followed on the use of recyclable and non-recyclable resources and waste and pollution removal” by Goodland [18] , who introduced this concept into the literature. Another perspective [19] on environmental sustainability defines the term as meeting the needs of resources and services for present

and future generations without compromising the health of the ecosystems that provide them.

Public administrations and businesses, which play a major role in ensuring environmental sustainability, have over time moved away from traditional waste management approaches to plans and strategies that follow the principle of viewing the processes of waste generation, collection and disposal as parts of a whole that influence each other. A strong sustainable waste management system focuses on processes rather than products and its products, functions and organisational structures must also be adaptable and versatile [20]. As a contribution to this view, it could be added that the most effective management of MSW has to relate to local environmental, economic, and social priorities, and must go beyond traditional consultative approaches that require the use of experts [21]. To put it more simply, for a waste management system to be sustainable, it must be environmentally effective, economically affordable and socially acceptable [22].

In the literature, one comes across many studies that propose different approaches to sustainable waste management. Some of them focus on waste prevention, some on waste-to-value strategies and some on remediation applications [23]. Although a lot of work has been done on the sustainable waste management topic, the concept of IoT-enabled waste management is quite new and the number of publications in this field is still growing. With various studies, it has been acknowled by researchers that the integration of Smart City technologies with the sustainable waste management approaches contributes to the understanding of environmental sustainability in terms of efficient use of resources, reducing pollution loads and energy and time savings. Since environmental sustainability is one of the main characteristics of smart cities, it is quite understandable that the use of smart city technologies for sustainable waste management is a valid trend that is becoming more prevalent every day.

A look at the literature shows that IoT-based smart waste management studies mainly focus on the management of solid waste. However, there are a number of studies using various ICT tools for source separation, collection, transportation, and disposal of different types of waste. Depending on the technologies used and the scope of application, a classification made for solid waste management is shown in Table 1.2:

Table 1.2 Various ICTs and their application in SWM [24]

ICT classification	ICT Sub-Class	Applications
Spatial Technologies	GIS	Site selection; planning; management; estimation; optimization
	GPS	Route and collection optimization; vehicle tracking; planning; scheduling
	RS	Site selection; environmental impact assessment; features monitoring
Identification Technologies	Barcode	Intelligent recycling; waste disposal; reduce landfill space; risk managem
	RFID	Bin and driver tracking; optimization; sorting and recycling
Data Acquisition Technologies	Sensors	Sorting; optimization; moisture; energy and odor measurement; scheduli
	Imaging	Waste sorting; route and collection optimization; monitoring
Data Communication Technologies	GSM/GPRS	Long range communication
	ZigBee	Short range communication
	Wi-Fi	Short range communication
	Bluetooth	Short range communication
	VHFR	Long range communication

The studies on dynamic route optimization for the improvement of household waste collection are based on the simultaneous transmission of data generated by sensors of different types placed in containers to a database through different communication protocols and their processing using decision support tools and mathematical models. In 2006, in one of the earliest studies [25] in the field of route optimization, researchers investigated different scheduling and routing strategies using real-time data, and a case study conducted at the recycling center in the city center of Malmoe, Sweden. The results showed that the dynamic routing and scheduling applications are more beneficial in terms of operating costs, collection distances, and working hours than the traditional waste collection approach with fixed routes and predetermined collection frequencies.

Another common solid waste management approach in smart cities is landfill site selection utilizing GIS technology. In 2010, researchers [26] combined GIS with Decision Support Systems to determine the most suitable landfill site for the Lake Beysehir catchment are in Konya, Turkey. The data obtained with the help of DSS was mapped using GIS.

In 2011, in order to carry out waste collection processes more effectively, researchers proposed a system [27] which allows container and garbage truck monitoring. For the successful implementation of the proposed system, a novel integrated theoretical framework, hardware architecture, and interface algorithm between technologies were introduced. RFID, GPS, GPRS and GIS together with camera technologies have been integrated and developed the intelligent monitoring system for containers and trucks. Simultaneous tests and experiments have proven the feasibility of the proposed approach.

In 2013, various implementation alternatives of RFID tags, sensors and QR code into waste management were discussed [28]. Using three different scenarios in which the aforementioned IoT tools are used in different ways, an attempt was made to make the

separation processes more efficient at the source by minimizing the possibility of waste consumer errors in selecting the appropriate container depending on the type of waste.

A 2015 study [29] proposed a dynamic routing algorithm for waste collection along with an IoT-based system. The dynamic algorithm is designed to adapt to situations such as waste collection vehicle failure, truck overload, road construction, or unexpected traffic volume that may occur during waste collection. In the proposed system, each container is equipped with an RFID tag, a capacity sensor and an actuator. When the bin is full, the system is notified via a wireless sensor network and initiates a dynamic route to empty the bin. Truck navigation is provided via an Android app. Truck location is tracked via GPS, which is integrated into the truck. Scenarios that assume two kinds of trucks usage for waste collection, the Low Capacity Trucks (LCTs) and the High Capacity Trucks (HCTs) have been evaluated using synthetic and real data from the city administration of St. Petersburg, Russia.

In a 2017 study [30] conducted in Suzhou, China, an IoT-based management platform was proposed to prevent illegal or incorrect management of restaurant food waste. Thanks to the RFID tags, weight sensors, GPS, GIS and wireless camera used, it was possible to obtain data simultaneously at each stage from waste production to collection, transfer and disposal. With the implementation of the platform, an increase in the legal generators of restaurant waste was achieved and, thanks to the traceability of the system, incorrect waste management practices could be better sanctioned legally.

Although the studies on smart containers to make waste collection and separation at source more effective are mostly about household and recyclable waste, there are similar studies focusing on electronic waste. In a 2019 study [31], smart management of e-waste on campus was enabled by level sensors in smart collection boxes installed at Monash University in Malaysia and a mobile application connected to a cloud database and Wi-Fi module. The mobile application directs users to the nearest e-waste collection box on campus based on their current location using the Global Positioning System (GPS).

In a 2020 research [32] that aims to contribute to decision-makers by examining the consumption patterns of city dwellers based on the waste they dump, IoT tools were used. Data such as the amount of daily collected waste and incorrect waste sorting behaviors are stored in the cloud system through QR codes owned by the residents of a neighborhood. To test the effectiveness of the approach, a case study was conducted in

Shanghai. Important results were obtained on the frequency of waste disposal, hours of waste disposal per day, and changes in waste disposal behavior depending on weather conditions.

As can be seen from the examples, the integration of IoT technologies into waste management is mostly in the area of solid waste management. Yet, as mentioned before, it is possible to come across studies that include other types of waste. Two examples of this could be seen in 2020. The first one [33] aimed at managing landfill leachate using IoT technology, and a mechanical waste segregator was developed that segregates incoming waste based on whether it is dry or wet. The device includes an Arduino microcontroller, an infrared light proximity sensor, and a soil moisture sensor. Also, to treat leachate, a leachate reactor - Upflow Anaerobic Sludge Blanket (UASB) Reactor system with microchips for imaging and a Wi- Fi module for data transmission to a cloud server was proposed. A fuzzy control system was developed based on real-time data on turbidity, suspended solids, dissolved oxygen and chemical oxygen demand (COD) collected by sensors. In the second one [34], an air quality monitoring system using Fog computing based Internet of Things (IoT) was proposed. To evaluate the effectiveness, the sensor module, the Fog computing device, and the IoT cloud platform were integrated. Experiments in different environments were conducted during 15 days. As an air quality metric, the Air Quality Index (AQI) is calculated by measuring six main pollutants.

In 2020, there are also DL and ML based studies. An artificial intelligence tool was used to label the images based on a specific trained set. In a study conducted in Vietnam [35], the objective was to estimate the amount of waste generated in waste bins and optimize the distance between bins so that the emptying of bins is as short as possible. For this purpose, the waste data obtained from the bins with IoT tools and used in two different algorithms ML. The performance of the proposed system was evaluated through operational tests at Ton Duc Thang University. In another study [36] , deep learning enabled the smart bin to classify the waste to be disposed of and, thanks to servo motors, open the appropriate compartment for each type of waste (E.g. plastic, metal, paper or general waste) With sensor data received via the Long Range (LoRa) communication protocol, object detection and waste classification was performed in the TensorFlow framework using a pre-trained object detection model. This object recognition model was trained with images of waste to create a frozen inference graph that was used for object recognition performed with a camera connected to the Raspberry Pi 3 Model BCas the

main processing unit. An elevator company that produces scrap metal and a waste management company collaborated in a field study [37] as part of a European project aimed at making operations more efficient through the development of an integrated information management system (IIMS) conducted in the same year. Thanks to the simultaneous monitoring and notification provided by the sensors installed in the containers, the elevator company's scrap metal waste management was more effective, while the private company's waste management activities were effectively planned thanks to the online analytics platform developed. With the help of the deep learning method, it was possible to make price estimates for possible future waste types based on past company data.

Recently, there have been initiatives aimed at further advancing IoT-based applications for waste management through integration with blockchain technology. In a 2021 study [38], to improve the management of hospital waste and wastewater, researchers created a framework based on blockchain technology combined with the Internet of Things developed using smart contracts. Data from waste containers and waste water treatment plant is collected by smart IoT tools is transmitted to the blockchain via available communication technologies, and peripheral nodes then group the collected information into data blocks that are temporarily stored and added to the blockchain after the verification process, allowing steakholders to process this data and make decisions in real time. In another study [39] conducted in the same year, researchers proposed a smart waste management system and while designing it, they utilized smart contracts on the Ethereum blockchain. They aimed to prove the superiority of their proposed system over traditional waste management by developing different algorithms for each step, from the moment the waste is thrown into the smart waste container to its collection and disposal, and rewarding the waste producer.

1.1.3 Multi-Criteria Decision-Making (MCDM)

Because of their multi-dimensional and complex structure, problems that arise in academic research and in the public or private sector often make decision-making processes more complicated. It is not always easy for decision makers to choose between different alternatives or scenarios, to rank them according to their expectations or to compare them with each other. In such cases, regardless of the topic and domain of the problem to be solved, the use of multi-criteria decision-making (MCDM) techniques

helps decision makers achieve the optimal outcome. In its most general definition, MCDM is the ranking, selection, or comparison of different scenarios, alternatives, or factors of a problem using various mathematical models according to the subjective evaluation of relevant stakeholders based on a set of predetermined criteria.

1.1.4 Classification of MCDM Techniques

Despite a variety of MCDM methods are used in the literature and in practise, and it is possible to classify them differently according to the different characteristics they have, a basic classification for MCDM according to the alternatives and criteria used would be Multi-Attribute Decision-Making (MADM) and Multi-Objective Decision-Making (MODM). In MODM problems, the alternatives are infinite, and the selection among the available criteria is shown by continuous functions [40]. MODM is generally used in operational applications such as route optimization studies that require taking action in a relatively short time. On the other hand, the MADM approach requires that choice be made between decision alternatives described by their attributes. In MADM problems there is a given, finite number of decision alternatives [41].

MADM approaches which include also the methods to be used in this study are divided into various types, but most of the approaches follow these main steps below:

- Identifying the problem: A multi-dimensional and multi-stakeholder problem is clearly stated.
- Identifying the problem alternatives/scenarios: Different alternatives and scenarios for the problem are determined and denoted as $A = \{A_1, A_2, A_n\}$.
- Selection of the criterias: In the decision-making process, there are more than one criteria associated with the problem, which will allow the comparison of alternatives.
- Selection of the attributes: They are verbal or numerical measures of alternatives to the problem, chosen to reflect the effectiveness of the specified criteria [42].
- Determining the weightage of the criteria: Criteria are weighted by decision makers using selected attributes to determine the extent to which each criterion contributes to the evaluation of available alternatives.
- Applying the selected MCDM method based on the data obtained: The selected method should be well defined and easy to understand, especially in terms of its key elements such as modeling the criteria and setting the weights [43]. The data

obtained by the subjective evaluations of the decision makers are used in mathematical models suitable for the selected MCDM method.

- Ranking or selecting of the alternatives: For this purpose, a decision matrix is generated. In a *m* x *n* decision matrix, the element a_{ij} shows the performance of alternative *Ai* when evaluated using the decision criteria C_j (for *i*= 1, 2, 3, ..., *m*, and *j*= 1, 2, 3, ..., *n*) [44]. An example decision matrix *A* is shown in Table 1.3:

Table 1.3 A typical decision matrix [45]

	Criteria			
	C_1	C_2	...3	C_n
Alternatives	(w_1	w_2		w_n)
A_1	a_{11}	a_{12}	...	a_{1n}
A_2	a_{21}^*	a_{13}	...	a_{2n}
...	...	...	...	...
A_m	a_{m1}	a_{m3}	...	a_{mn}

- Final decision: The authoritative actors make the final decision on the problem.

MADM can be divided into three main categories, which are essentially as follows:

1. Value-based approaches:

- Multi-Attribute Utility Theory (MAUT)
- The Analytic Hierarchy Process (AHP)
- Weighted Sum Model (WSM)

2. Outranking approaches:

- Preference Ranking Organization and Method for Enrichment Evaluation (PROMETHEE)
- Elimination and Choice Expressing Reality (ELECTRE)

3. Goal-based approaches:

- Technique for Order Preference by Similarity (TOPSIS)
- Data Envelopment Analysis (DEA)

1.1.5 Fuzzy Set Theory

In traditional MADM approaches, the criteria present and their weights are given with precise and clear values. Thus, it is assumed that the selection or ranking of alternatives to be made with them is absolutely correct. In real problems, however, the nature of the

problem makes it impossible to know exactly what the goals or constraints of the problem are. This uncertainty can be caused by reasons [46] such as unmeasurable information, incomplete information, inaccessible information, and partial ignorance. On the other hand, it would be unrealistic to claim that the decisions made by decision makers are absolutely correct or complete. Human subjectivity should also be taken into account in decision-making processes.

Fuzzy logic that was proposed by Zadeh makes it possible to work with unmeasurable, incomplete or improper information. Fuzzy sets allow partial membership in a set. In this approach, there are different degrees of membership. Bellman and Zadeh [47] and Zimmermann [48] have integrated fuzzy sets into the MCDM field. Today once can say that fuzzy decision-making aprroaches form a branch of fuzzy set theory.

A fuzzy set $\tilde{A}$ can be defined mathematically by a membership function $\mu_{\tilde{A}}(x)$ which assigns to each element x in the verbal universe X a real number in the range [0,1] [49]. A triangular fuzzy number $\tilde{A}$ can be defined by a triplet (a, b, c) as shown in Figure 1.4:

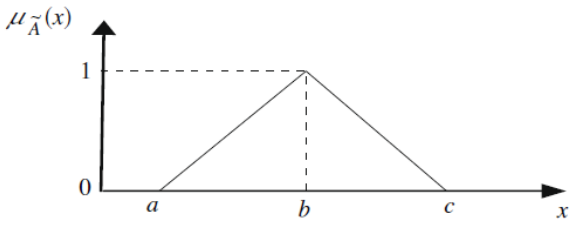


Figure 1.4 A triangular fuzzy number Ã [50]

The membership function $\mu_{\tilde{A}}(x)$ is defined as in Equation (1.1):

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{x-a}{b-a} & a \le b, \\ \frac{x-c}{b-c} & b \le x \le c, \\ 0 & other \end{cases} \tag{1.1}$$

In fuzzy logic, linguistic terms are used for situations that are very complex or difficult to describe quantitatively. These linguistic terms can also be expressed as fuzzy numbers.

If $\tilde{m} = (m_1, m_2, m_3)$ and $\tilde{n} = (n_1, n_2, n_3)$ are triangular fuzzy numbers, the distance between them is calculated by Vertex method [51] as in Equation (1.2):

$$d(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{3}[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2]} \tag{1.2}$$

1.1.6 Fuzzy AHP

Although there are a variety of fuzzy AHP approaches in the literature and it was van Laarhoven and Pedrycz [52] who first introduced this approach, Chang's Extent Analysis [53] which is widely used due to its ease of application will be used also in this study. The method is based on pairwise comparisons of criteria and alternatives. For these comparisons, linguistic terms selected for this study and the corresponding triple fuzzy numbers are shown in Table 1.4:

Table 1.4 Linguistic terms and corresponding triple fuzzy numbers

Linguistic Term	Triangular Fuzzy Number Equivalent
Equally Important (EI)	(1, 1, 1)
Slightly More Important (SMI)	(2/3, 1, 3/2)
Strongly More Important (StMI)	(3/2, 2, 5/2)
Very Strongly More Important (VSMI)	(5/2, 3, 7/2)
Definitely More Important (DMI)	(7/2, 4, 9/2)

Here, by taking each object, extent analysis is applied for each goal, respectively. In this way, *m* extent analysis values are obtained for each object and are indicated by using the notation $M^1_{gi}, M^2_{gi}, \ldots, M^m_{gi}$, $i = 1, 2, \ldots, n$,

The steps of the Extent Analysis method [54] are shown below:

Step 1: The value of fuzzy synthetic extent with respect to the i-th object is defined as in Equation (1.3):

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} \tag{1.3}$$

To obtain $\sum_{j=1}^{m} M_{g_i}^j$, the fuzzy addition operation of m extent analysis values for a particular matrix is performed as in Equation (1.4):

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{1.4}$$

and to obtain $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1}$, the fuzzy edition operation of m extent analysis values for a particular matrix is performed as in Equation (1.5):

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \tag{1.5}$$

and then the inverse of the vector in Equation (1.5) is computed as in Equation (1.6):

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}\right), \left(\frac{1}{\sum_{i=1}^{n} m_i}\right), \left(\frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{1.6}$$

Step 2: The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as in Equation (1.7):

$$V(M_2 \geq M_1) = \sup[\min(\mu_{M1}(x), \mu_{M2}(y))] \tag{1.7}$$

and is equivalently shown as in Equation (1.8):

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M1}(d) \begin{cases} 1 & if\ m_2 \geq m_1, \\ 0 & if\ \ l_1 \geq u_2, \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \tag{1.8}$$

where *hgt* and *d* represent the highest intersection point and *x* coordinate of the two fuzzy numbers, respectively, as can be seen in Figure 1.5. To compare M_1 and M_2, both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are needed.

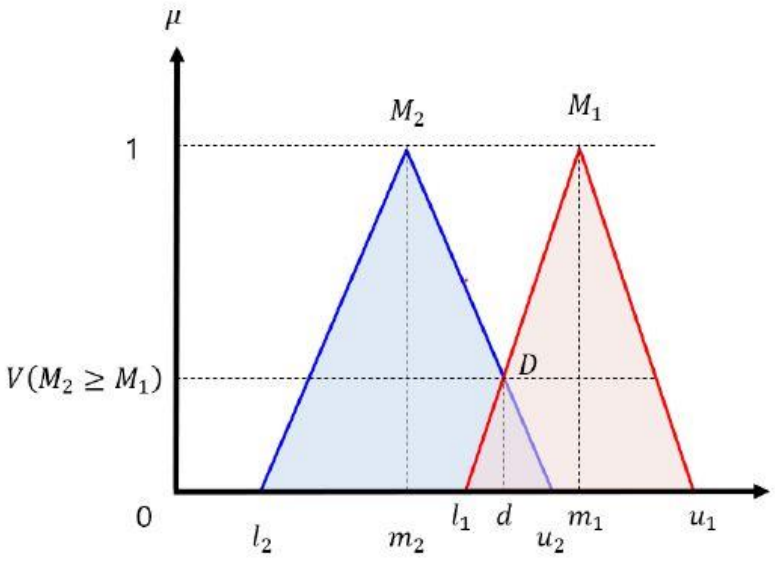


Figure 1.5 The intersection between M_1 and M_2 [55]

Step 3: The degree possibility for a convex fuzzy number to be greater than convex fuzzy numbers Mi (i = 1,2, . ,k) can be defined as in Equation (1.9):

$$V(M \gg M_1, M_2, \ldots\ldots, M_k) = V[(M \gg M_1)\ and\ \ (M \gg M_2)\ and\ \ldots\ldots\ and\ (M \gg M_k)] \\ = min\, V(M \gg Mi), \qquad i = 1, 2, \ldots\ldots, k \tag{1.9}$$

Assume that

$d'(A_i) = min\, V(S_i \gg S_k)$

For $k = 1,2, \ldots, n; \quad k \neq 1$. Then the weight factor for k_i is shown by Equation (1.10):

$$W' = \left(d'(A_1), d'(A_2), \ldots\ldots, d'(A_n)\right)^T, \tag{1.10}$$

where $A_i(i = 1,2, \ldots\ldots, n)$ are *n* elements.

Step 4: Via normalization, the normalized weight vectors would be as in shown Equation (1.11):

$$W = \left(d(A_1), d(A_2), \ldots\ldots, d(A_n)\right)^T, \tag{1.11}$$

where W is a nonfuzzy number.

1.1.7 Fuzzy TOPSIS

This method, firstly introduced by Hwang and Yoon [56], is an example of MADM that is widely used in all fields. It is based on the assumption that the chosen alternative is

closest to the positive-ideal solution and farthest from the negative-ideal solution. The steps of the fuzzy TOPSIS method, which was selected to be used in this study and developed by Chen et al. [57] are as follows:

As a first step in this method, a decision maker group is formed from people who have expertise on the problem, and the cluster consisting of K decision makers is shown as $E = \{DM_1, DM_2, \ldots\ldots, DM_K\}$. The alternatives of the problem $A = \{A_1, A_2, \ldots\ldots, A_m\}$ and the criteria to be used in the evaluation of the alternatives $K = \{K_1, K_2, \ldots\ldots, K_n\}$ are determined. Then, the linguistic expressions that decision makers will use when weighting the criteria and evaluating the alternatives according to the relevant criteria are selected. The linguistic terms and corresponding triangular fuzzy number equivalents used in this method are as in Table 1.5 and Table 1.6 respectively:

Table 1.5 Linguistic terms for the importance weight of each criterion [58]

Linguistic Term	**Triangular Fuzzy Number Equivalent**
Very Low (VL)	(0, 0, 0.1)
Low (L)	(0, 0.1, 0.3)
Medium Low (ML)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
Medium High (MH)	(0.5, 0.7, 0.9)
High (H)	(0.7, 0.9, 1.0)
Very High (VH)	(0.9, 1.0, 1.0)

Table 1.6 Linguistic terms for alternative evaluation [58]

Linguistic Term	**Triangular Fuzzy Number Equivalent**
Very Poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium Poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium Good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very Good (VG)	(9, 10, 10)

In the group consisting of *K* decision makers, where $\tilde{x}_{ij}$ represents the criterion value of the alternative which was evaluated by the decision makers, and where $\widetilde{w}_j$ represents the criterion weight, the criterion values and criteria weights, respectively, are calculated as in Equation (1.12) and in Equation (1.13):

$$\tilde{x}_{ij} = \frac{1}{K}[\,\tilde{x}_{ij}{}^{1} + \tilde{x}_{ij}{}^{2} + \ldots + \tilde{x}_{ij}{}^{K}] \tag{1.12}$$

$$\widetilde{w}_j = \frac{1}{K}[\widetilde{w}_j{}^{1} + \widetilde{w}_j{}^{2} + \ldots + \widetilde{w}_j{}^{K}] \tag{1.13}$$

A fuzzy multi-criteria group decision-making problem that can be succinctly expressed in matrix form as in Equation (1.14) and Equation (1.15), respectively:

$$\widetilde{\boldsymbol{D}} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \tag{1.14}$$

$$\widetilde{\boldsymbol{W}} = [\widetilde{w}_1, \widetilde{w}_2, \ldots, \widetilde{w}_n] \tag{1.15}$$

Here, $\tilde{x}_{ij}\ \forall\, i, j$ and $\widetilde{w}_j,\ \ j = 1, 2, \ldots., n$ are linguistic variables. They could be described by triangular fuzzy numbers, $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ and $\widetilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$

When the normalized fuzzy decision matrix ($\widetilde{\mathrm{R}}$) is shown as in Equation (1.16):

$$\widetilde{\mathrm{R}} = [\tilde{r}_{ij}]_{\mathrm{mxn}} \tag{1.16}$$

With B and C being the benefit and cost criteria, respectively, the normalization is performed as in Equation (1.17) and in Equation (1.18):

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \qquad \mathrm{j} \in \mathrm{B}; \qquad c_j^* = \max_i c_{ij} \quad \text{if} \quad \mathrm{j} \in \mathrm{B} \tag{1.17}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \qquad \mathrm{j} \in \mathrm{C}; \qquad a_j^- = \min_i a_{ij} \quad \text{if} \quad \mathrm{j} \in \mathrm{C} \tag{1.18}$$

Considering the different importance of each criterion, the weighted normalized fuzzy decision matrix could be constructed as in Equation (1.19):

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{mxn} \qquad i = 1,2,\ldots.,m \quad j = 1,2,\ldots\ldots,n \tag{1.19}$$

where $\tilde{v}_{ij} = \tilde{r}_{ij}(.)\,\tilde{w}_j$.

Fuzzy positive-ideal solution (FPIS, A^*) and fuzzy negative ideal solution (FNIS, A^-) could be defined as in Equation (1.20) and in Equation (1.21):

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*) \tag{1.20}$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-) \tag{1.21}$$

where $\tilde{v}_j^* = (1,1,1)$ and $\tilde{v}_j^- = (0,0,0), \quad j = 1,2,\ldots\ldots n.$

The distance of the alternatives from A^* and A^- is calculated as in Equation (1.22) and in Equation (1.23):

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*), \qquad \mathrm{i} = 1,2,\ldots\ldots,\mathrm{m}, \tag{1.22}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), \qquad \mathrm{i} = 1,2,\ldots\ldots,\mathrm{m}, \tag{1.23}$$

where d(. , .) is the measurement of distance between two fuzzy numbers.

After the d_i^* and d_i^- of alternatives have been calculated, the closeness coeffcient of each alternative is calculated as in Equation (1.24). With this value, the ranking of the alternatives is determined.

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-} \tag{1.24}$$

1.1.8 MCDM in Sustainable Waste Management

When combining MCDM with sustainable waste management applications, researchers generally aim to: [59]

1. Investigate optimal decision-making among various alternative waste management strategies (e.g. landfill disposal, incineration, recycling, reuse, etc.).

2. Investigate possible technologies (e.g. mass incineration, pyrolysis, gasification, plasma incineration in cement kilns, etc.).

3. Investigate the optimal locating of a waste management facility (e.g. landfill, waste treatment facility, recycling facility, etc.).

In 1981, in one of the earliest studies [60] in the area of identifying waste management strategies utilizing MCDM, to asses the strategic alternatives for waste management in Ontario, the researchers applied fuzzy set theory to aggregate weights derived from different groups of people for multicriteria analysis.

In 1991, an AHP approach [61] has been used to determine the most ideal location for a newly constructed landfill site in Edmonton, Canada. In the study, nine candidate regions were evaluated according to three environmental, six social and one economic factor determined before.

In 1993 and 1997 researchers proposed systems [62, 63], that integrate fuzzy set theory and analytic hierarchy process (AHP) into a geographic information system (GIS) for the preliminary assessment of potential landfill sites.

In 2007, fuzzy AHP was used [64] to evaluate potential technologies for fly ash reuse in Taiwan. five different technology alternatives were prioritized based on environmental, economic, technological, management and social factors with seventeen sub-criteria.

In 2008, five candidates for the location of a waste transshipment site in Istanbul, Turkey, evaluated [65] by the fuzzy TOPSIS method. Weighting of five criteria, including criteria such as proximity to industrial solid waste and simplicity of transportation, was performed using the AHP method.

In a 2010 study [66], three different optimization scenarios for improving waste management in Beijing, China, were determined in accordance with relevant policies and environmental regulations of the city and evaluated using three different fuzzy MCDA methods, including fuzzy TOPSIS. In another study [67] carried out in the same year, a modified fuzzy TOPSIS method was proposed to select most optimal disposal method and disposal site for the MSW of Istanbul, Turkey. The weighting of the criteria was performed by using Fuzzy AHP. After RDF combustion was determined to be the best disposal alternative for Istanbul, the same method was applied to determine the location of an RDF combustion plant in the city.

In a 2013 study [68] in India, four different wastewater treatment technology alternatives were ranked based on three main criteria with various sub-criteria. For this purpose, fuzzy AHP was integrated and applied separately with PROMETHEE and Gray Relation Analysis (GRA).

A 2015 study [69] using fuzzy AHP and fuzzy TOPSIS together evaluated three different options for landfill sites in Istanbul, Turkey. Four criteria were used, including soil conditions and topography, climatologic and hydrologic conditions.

In a technology selection study [70] in the same year, ten different solid waste disposal technologies were evaluated with Fuzzy TOPSIS according to eighteen criteria set by experts, with the aim of identifying the most viable alternative for Istanbul, Turkey.

A hybrid fuzzy MCDA method was applied in a 2017 study [71] evaluating six different wastewater treatment technologies, including membrane bioreactor (MBR), moving bed bio-film reactor (MBBR) and activated sludge process. Fuzzy AHP was used for weighting the criteria, and fuzzy TOPSIS was used for ranking the alternatives according to these criteria.

In a 2021 study [72], which aims to determine the best disposal method for healthcare waste during and after COVID -19, the results obtained by using fuzzy TOPSIS were compared with the results obtained by another fuzzy MCDM method. Four main criteria with ten subcategories were used to determine the most optimal of nine different disposal alternatives for healthcare waste.

In one of the most recent studies in this field [73], a hybrid fuzzy MCDM application was applied to evaluate eight different solid waste management scenarios for India. Fuzzy AHP was used for criterion weighting and fuzzy TOPSIS was used for ranking alternatives.

Looking at recent MCDM studies in the area of sustainable waste management, it is seen that in addition to evaluating traditional waste management approaches, more specific waste management strategies tailored to countries' socioeconomic conditions are also being evaluated using this methodology. For example, in a study [74] conducted in Pakistan in 2022, fuzzy TOPSIS and fuzzy AHP were used together to identify the barriers that may be encountered in the transition to a circular economy (CE) in the management of food waste in that country.

In recent years, it has been observed that waste management strategies have been developed in accordance with the understanding of using waste for the benefit of a sustainable environment and economy, rather than seeing it as a problem that needs to be eliminated. It is seen that MCDM techniques are used also in the evaluation of these strategies. In two very recent studies, fuzzy MCDM methods were utilized to determine the most optimal option for the location of a waste-to-energy plant. In the study [75] used in a renewable energy project in Vietnam, fuzzy AHP was used to determine the solid waste-to-energy plant location in the country. In the other study [76], four possible waste-to-energy plant locations determined for Kırıkkale, Turkey were evaluated using fuzzy AHP and fuzzy TOPSIS according to four criteria determined by expert opinion and literature research.

As can be seen from the above examples, fuzzy MCDM methods are often applied to problems in environmental engineering. However, since smart sustainable waste management approaches are still a new research area, the evaluation of these approaches using these methods also very not common in the literature.

In the study [77] in which four different alternatives for smart solid waste collection using information and communication technologies were proposed for Tepebasi region in Turkey, the alternatives were evaluated using type 2 fuzzy TOPSIS method considering seven criteria set by experts. In another recent study [78], seven different smart strategies selected for medical waste disposal were prioritized using the Decision-Making Trail and Evaluation Laboratory (DEMATEL) method. A hybrid MCDM method (Modified entropy and Combinative Distance-based Assessment (CODAS)) under interval-valued fuzzy sets at q-level) was used in the study [79], which investigated different smart waste collection methods for a municipality in Istanbul, Turkey. In another study [80] that addresses smart waste management approaches in a more general form, the researchers used the spherical AHP method to evaluate three different alternatives for smart waste management.

The examples given were related to either the collection or disposal of waste. However, this study encompasses broader strategies for smart waste management from production to disposal. Moreover, it differs from the aforementioned studies by using a fuzzy hybrid approach.

1.2 Objective of the Thesis

Although different types of MCDM methods are widely used in various environmental engineering applications, the determination of smart sustainable waste management strategies using these methods has not yet received enough attention in the literature. So far, a study evaluating different smart waste management strategies using a hybrid fuzzy MCDM method was not found. This study aims to contribute to this gap in the literature by evaluating four different smart waste management strategies using a hybrid Fuzzy Analytical Hierarchy Process - Fuzzy TOPSIS application that can support decision makers in determining sustainable waste management strategies in smart cities.

While constructing the hierarchical structure of the problem, as a first step, four different smart sustainable waste management strategies combining different sustainable waste management strategies and smart waste management technologies in literature and practice are proposed. To evaluate the performance of the strategies, a total of fifteen sub-criteria were then identified under four main criteria from the literature. For linguistic evaluations, a decision-making expert group of ten people from academia, the private sector and the public sector was formed. A criteria weighting was carried out using the verbal and subjective evaluations of the decision-makers through the prepared questionnaires in the fuzzy AHP procedure. Decision makers also evaluated the performance of each strategy alternative according to each sub-criterion verbally and subjectively in the questionnaires. Finally, the performance ranking of the alternatives was obtained with the Fuzzy TOPSIS method, which was applied using these evaluation results and the sub-criteria weights obtained with Fuzzy AHP.

The study also performed a sensitivity analysis using eighteen different scenarios to investigate whether different weightings of the sub-criteria would change the ranking of the alternatives. In these scenarios, the existing sub-criteria weight values were increased or decreased by different amounts, or were not taken into account.

1.3 Hypothesis

The integration of recent technologies into sustainable waste management approaches is becoming increasingly important in smart cities, where it is essential to deliver city services in a greener, more economical and faster manner and to meet citizens' expectations. However, this integration is directly related to the climatic, geophysical, economic and socio-cultural characteristics of cities. Therefore, the implementation and

maintenance of smart sustainable waste management strategies depends on many technical, economic, political and social variables. These variables influence and change each other, further complicating management processes. On the other hand, the number of stakeholders involved in the relevant processes is usually quite high. It is often difficult for public authorities, private sector managers, researchers and residents to act in a coordinated and harmonious manner in a seamless and interconnected structure.

When determining smart sustainable waste management strategies that are both technically, scientifically and economically feasible while being responsive to residents' needs, a Fuzzy Multi-Criteria Decision-Making (FMCDM) approach could be used as a solution to all the above mentioned problems being faced. In this approach, it is possible to rank, compare or prioritize different smart sustainable waste management strategy alternatives through various mathematical operations after subjective expert evaluation based on a set of predetermined criteria. FMCDM, which includes fuzzy sets that allow partial degrees of membership, makes it possible to work with incomplete, unmeasurable, or imprecise information. In this respect, it would be more appropriate to use this approach instead of the traditional MCDM methods in the field of smart waste management strategies, which are still under development and have not yet reached a satisfactory level of knowledge.

It cannot be said that there is only one ideal method for solving a particular problem using FMCDM. Although the method to be chosen depends on the nature of the problem, the available data, and the preferences of the decision maker, hybrid approaches in which two or more FMCDM methods are used together give researchers confidence in the reliability of the results.

2
SMART SUSTAINABLE WASTE MANAGEMENT APPROACHES

2.1 Integrating Informal Recyclable Waste Collection Into a Formal Smart System

1.1.1 Informal Collection of Recyclables: Current Situation and Its Negative Consequences

In developing countries, it is a widespread problem that recyclable waste cannot be managed in accordance with a sustainable environmental and economic understanding. The main reason for this is the lack of a comprehensive and effective waste management system that covers in detail all steps from collection to processing to returning this type of waste to the market. The situation is further complicated by the lack of legal regulations and effective control mechanisms, as well as the necessary budgetary resources and technical equipment, resulting in very limited efforts by local authorities. As a result of these conditions, it is inevitable that the informal recycling sector will find a wide field of activity in cities.

Informal recycling could be defined as [81] recycling activities which are not sponsored, financed, recognised, supported, organised or acknowledged by the formal solid waste authorities, or the ones which operate in violation of, or in competition with, formal authorities.

One can say that the main features [82] of the informal recycling system are small-scale, low-technology, low-paid, unrecorded and unregulated work, often completed by individuals or family groups and operations with low capital investment. An informal recycling process with its main actors is shown in Figure 2.1:

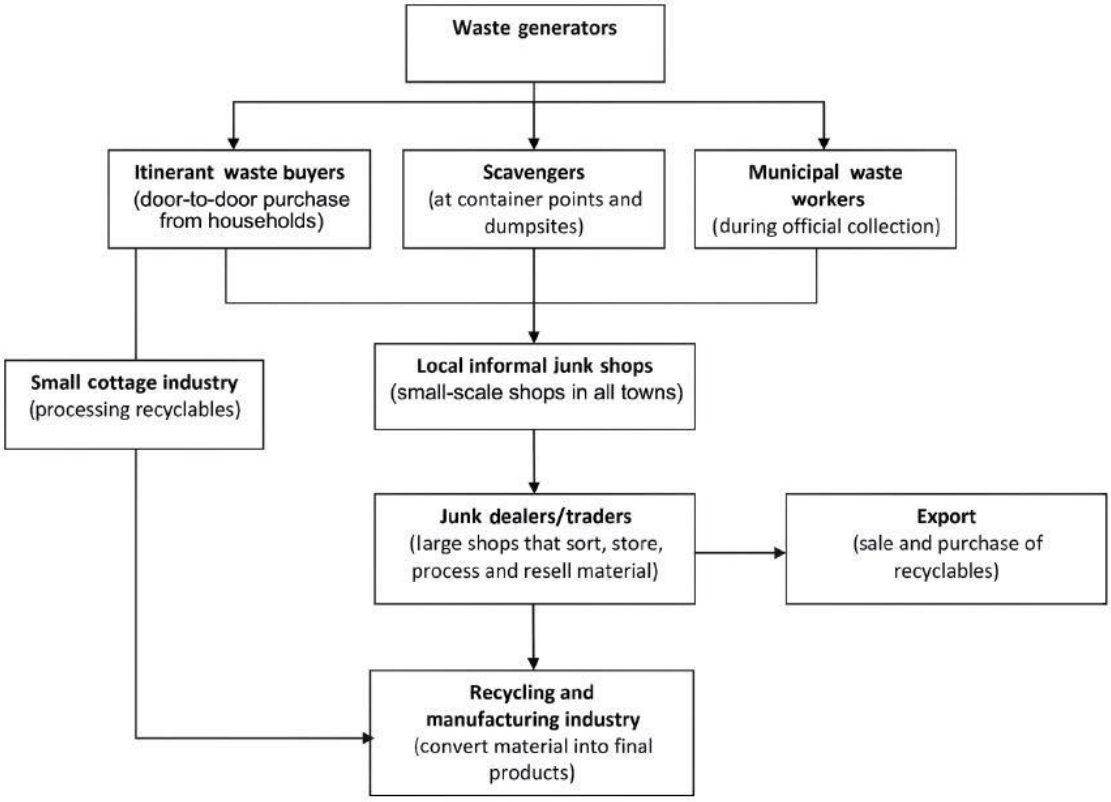


Figure 2.1 Generic flow of recyclables through an informal recycling system [83]

Informal recycling activities contribute to resource conservation and energy recovery by reducing the extraction of new raw materials and introducing secondary raw materials into the production cycle. It also helps municipalities reduce the amount of waste they need to collect, thereby lowering collection costs and meeting their recycling goals. However, contrary to all these contributions to the environment and the cost of waste management, they also cause significant environmental and economic damage. Executing processes in an unsystematic and non-standardised way, using low technology and with people who lack technical knowledge and equipment, creates a variety of water pollution and emisisons and threatens human health. On the other hand, a huge informal economy is created by untaxed and uncontrolled flows of money.

Informal waste collection workers form the first pillar of the informal recycling system. Their task [84] is mainly to sort and collect recyclable waste from residential and commercial areas, transfer points or storage containers, dumpsites, transfer stations, vacant plots and landfill sites. Commonly collected wastes are the ones that contain market value materials such as [85] plastics, paper, cardboard, aluminium, steel, other metals, glass and textiles. Waste collectors make a living by selling these type of wastes to intermediary buyers (middle men) [86] who may be well established private

companies, or un-registered individuals/informal groups of individuals operating in the recyclable waste management market in the country. In developing countries, an estimated [87] 1% of the urban population earns a living this way.

Because collectors often separate the recyclables from mixed waste with their hands, they come into direct contact with the waste, which poses numerous health risks. They are at risk of assault by third parties or stray animals on the street. They have no social security. Their earnings are variable and low due to other middlemen. They are discriminated against in society. Considering that it is a socially unstable, insecure and poorly paid work, associated with health risks and threats to the safety of life and has a bad reputation, it is understandable that recyclable collection workers are among the most disadvantaged groups in society, such as immigrants, women, children, the elderly and criminals. Local governments' perceptions of the work they do vary from country to country. Although in some cities their contribution to the recycling process is appreciated and cooperation takes place, in most countries there are ignorant, exclusionary or preventive policies towards informal collectors. The main problems faced by these people due to the work they carry out are given in the Table 2.1:

Table 2.1 Key health hazards for informal recycler communities [88]

Health hazards	Description
Chemical	Toxic chemicals (e.g. heavy metals and brominated flame retardants).
Hygiene	Lack of hand washing facilities or proper toilets.
Disease	Headache, respiratory issues, dermatological problems, eye infections, flu, bronchitis, ulcers, high blood pressure, musculoskeletal injuries (i.e. chronic back ache and soreness in arms, legs and shoulders), typhoid fever, tuberculosis, dysentery, poliomyelitis, malaria, dengue, leishmaniasis, diarrhoea, anthrax, cholera.
Accident	Falls and others leading to cuts and bone breaks, fires (from burning of waste), explosions, landfill slides
Psychological	Insecurity, perceived shame, humiliation.

2.1.2 Good Examples: Waste Collection in Cooperatives

As can be understood from the general framework presented above, it is not possible for informal recyclable activities to deliver healthy outcomes in terms of a sustainable environment and economy. On the other hand, the sector allows disadvantaged groups to be exploited as informal collectors. What needs to be done is to integrate informal collection workers into a legal and systematic waste management system and to create healthy and safe working conditions for them. However, it is a fact that they represent a

unique group because of their socio-cultural and socio-economic characteristics. The employment of the people who are accustomed to working independently in a formal setting, can create difficulties for both themselves and the local authorities. The existence of a structure in which collection workers can organize themselves but work in cooperation with the official authorities seems to be a more reasonable solution.

In Latin America, particularly in Brazil and Colombia, there are many good examples of effective recycling schemes where waste collection workers are organized into cooperatives and work in harmony with local authorities. In Brasil, thanks to laws enacted at the government level, recycling activities are supported and the rights of collection workers are guaranteed [89]. The best known of the country's current 500 or so cooperatives are ASMARE (Associação dos Catadores de Papel, Papelão e Material Reaprovitável), with 380 members and a monthly recycling volume of 500 tons, and COOPAMARE (Cooperativa de Catadores Autônomos de Papel, Aparas e Materiais Reprovitáveis)), with around 280 members and a monthly recycling volume of about 100 tons [87].

SWaCH (Seva Sahakari Sanstha), the waste collectors' cooperative operating in Pune, India, collects solid waste, including household waste, door-to-door with its trained members, in compliance with occupational health and safety, and assists the city government in areas where waste collection is lacking [90].

Another project of preventing unregistered collection of recyclables and providing safe work opportunities for waste collectors has been realized with the initiative of Tepebasi Municipality in Eskisehir, Turkey. A tripartite protocol was signed between the licensed recycling facility of the city, the municipality and the GESIKOOP which has been established specifically for the project [91]. The waste collection is carried out by the cooperative members using electric bicycles with a capacity of 150 kg, which are marked with the logo of the cooperative. At the end of shifts at various workplaces from different business sectors, they collect packaging waste that has escaped the municipality's recyclables collection system. During the interview with the Environmental Protection and Control Manager of Tepebasi Municipality, it was noted that there are currently 32 cooperative members, of which 2 are women and 6 are immigrants, with the number changing frequently. Although the project is still very new and some difficulties have been encountered in integrating unregistered collectors into the program, it is said that the feedback from the residents of the district has been very positive.

2.1.3 Proposed Alternative

Initiatives aimed at integrating waste collectors into a formal waste management system require detailed analysis beforehand. These analyzes should include the number of workers to be included in the system, their sociocultural profile, their expectations of working conditions, and the economic contribution they make through their activities. To obtain this data, interviews with relevant stakeholders such as municipal administrators and managers of recycling facilities in the city, as well as with workers, would be appropriate.

This study proposes an alternative application that contributes to the implementation of a sustainable recycling system in cities, thanks to the organization of informal waste collectors in a cooperative and waste collection carried out in collaboration with local authorities. Cooperative members will collect recyclable waste directly from residential areas or commercial businesses instead of mixed waste on the streets. Utilizing ICT technologies during waste collection activities will enable the processes to be carried out more effectively. The alternative presented is inspired by the study [92] in which ICT tools are used in human-to-human operations carried out by companies conducting smart collection activities in China.

A pilot study can be used to determine the weaknesses and strengths of the application. Considering the cost of the ICT tools to be used by the cooperative members and the easier control of the system operation, it would be appropriate to choose a neighbourhood with a relatively small population as the study area. The main steps of the application can be summarized as follows:

1. Household members or company officials in the neighborhood create a collection request for their recyclable waste at a time specified by them through the developed mobile application.

2. The system assigns the nearest cooperative collector to the respective location for the particular collection operation.

3. The collector travels to the address assigned to him for the particular collection operation and receives the waste.

4. In the mobile application, he enters data such as the type, quantity, and collection time of the collected waste into the interface provided for him.

5. Dependig on the type and quantity of waste collected, the user is assigned a reward credit via the mobile application. This credit can be used for public transportation, payment of garbage fees and water bills, or cultural and artistic events.

6. GIS technology is used for locating employees in the system, and Wi- FI or GPRS technologies are used for data communication.

Figure 2.2 summarizes a door-to-door collection process for recyclable waste using ICT tools:

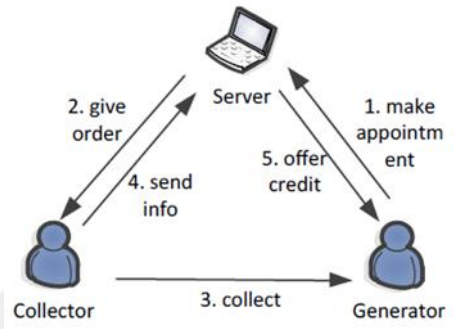


Figure 2.2 Door-to-door collection of recyclable waste using ICT tools [92]

The benefits of implementing the proposed alternative application can be detailed as follows:

1. Informal recyclable collection workers will be integrated into healthy, safe and secure working conditions in a way that will allow them to organize and make their voices heard.

2. By preventing informal recycling activities in the first step, potential losses of value of recyclables during their circulation in the market as well as unregistered cash flows are prevented. Collection activities using smart and innovative technologies will help local authorities achieve their targeted recycling rates.

3. Thanks to the regular, traceable and reliable flow of data, collection processes will be more organized, faster and more efficient. The data obtained will also make it possible to analyze the behavior of waste producers and to prepare more realistic waste management plans.

4. The gift credits they receive and the reception of their waste at the doorstep at the times they specify will encourage residents and businesses to actively participate in sustainable recycling activities, thus in protecting the environment and creating a circular economy.

2.2 A Pay As You Throw Application Leveraging Blockchain Technology

2.2.1 Pay As You Throw: Historical Development and Basic Principles

It is becoming increasingly difficult for local authorities to deal with solid waste generated in cities. Not only is this type of waste harmful to the environment and public health, but it is also one of the largest items of municipal expenses due to the cost of collection and disposal activities. On the other hand, city dwellers are often unaware of the price they pay for these services. The cost of waste management in cities is generally included in or along with other taxes. Unlike many other taxes, however, the use of this service at different rates does not change the waste collection fee paid by citizens. For instance, a four-person household and a single person living in the same neighborhood pay the same amount in garbage fees.

With the waste management policies implemented since the 1990s, a new understanding that puts more responsibility on the producer of the waste both in terms of protecting the environment and in economic terms has prevailed. As a result of this understanding, statements implying that the party causing the generation of a waste is directly responsible for the cost of disposal were included in the 1991 update of the European Economic Community's Waste Framework Directive (75/442/EEC) [93]. Meanwhile in Europe and in United States of America concrete practices which distribute this responsibility fairly according to the amount of waste generated by the citizens began to be implemented.

A current practice, "Pay As You Throw" (PAYT) has also become recently one of the well accepted methods compatible with the above understanding, as it realistically and fairly reflects the waste consumption of city residents. In this system, to cover waste collection and disposal costs, local governments charge a fixed fee that all citizens are obliged to pay. Addition to this, there’s another type of fee which is based on the amount of waste generated and/or services used by households. In order to calculate this, predetermined unit fees are used. For this reason, this method is also referred to as "Unit Pricing" in the literature. The unit fees are sometimes set for a single garbage bag or a garbage container to be used, or/and it can set for the volume or the weight of the waste generated in a period of time. It is also possible to come across various applications where the frequency of container visits by waste collectors is also calculated as a separate cost item.

The most common PAYT pricing methods in practice are shown in Figure 2.3, as an adoption version of another study [94] Local authorities utilize one or more of the multi-component fee types in the figure together with the fixed fee.



Figure 2.3 Most common PAYT methods [95]

A good and fair combination of fixed and variable fee components, which ultimately form a household's individual waste fee, will be a decisive factor for the acceptance and long-term success of a PAYT system. Since the characteristics and needs of each city and its citizens are different, the method(s) to be chosen should be determined based on detailed calculations and in accordance with the opinions of city residents. However, the general steps for building any PAYT system can be summarized as follows [96]:

1. Identification of the waste producer for accountability purposes: User identification varies depending on the type of container used (personal or curbside). If the container is allocated individually or to a single household, the following methods [97] can be selected:

- Stickers with barcodes on the containers
- QR code on containers

- RFID tags on containers

If a container is allocated for the use of more than one person (curbside container), it has a lock system. The identification of users [98] throwing waste into it can be achieved by:

- During container rental recording by municipal staff
- Smart electronic cards using RFID technology
- - User's smartphone or tablet using NFC technology

2. Calculation of the amount of waste generated or services availed of: Data on the amount of waste collected can be obtained manually by garbage collection workers (e.g., by recording the number of prepaid garbage bags collected) or automatically by cameras, level sensors in bins, or scales or weight sensors in garbage collection vehicles.

3. Unit pricing for individual charging in accordance with the services requested and or provided: When determining unit prices for both fixed and multi-component fees the initial costs (e.g., implementing a new billing system, technologic investments, training staff, informing the public) and ongoing costs (e.g., landfill rental fees, maintenance costs, salaries to be paid) that will occur while the system is in progress should be taken into account. After determining the estimated costs to be obtained by the implementation of the system, costs and revenues are compared and unit pricing is made accordingly. Also, in setting unit prices for the fixed fees, groups with different waste generation, such as single people, the elderly, low-income people and large families, are taken into account, and appropriate discounts and other benefits are offered.

Although the targeted gains vary depending on the socioeconomic and sociocultural structure of cities, the expectations of residents, and the waste management strategies pursued by managers, when the good examples are examined, the most common goals of implementing PAYT are:

- To reduce the amount of domestic waste to be generated and thus to ensure that less waste is sent to landfill or incineration
- To contribute to the increase of recycling activities by increasing the rate of recyclable waste in the total waste produced
- To save on waste management costs

- To encourage citizens to act more responsibly on behalf of sustainable waste management with the peace of mind that they are involved in a fair system which includes an appropriate, transparent charging policy

2.2.2 Good Examples: PAYT Applications in Various Cities

In the last two decades, with the adaption of electronic identification systems resistant to external interference to waste management [93], various applications of PAYT have been introduced in Europe Municipalities. Weight or volume-based billing systems for waste collection have been implemented according to the expectations and specificities of the city, along with the legal requirements that form the basis for PAYT. As in the case of Sweden [98], both weight-based and volume-based PAYT applications are observed in different cities in the same country. In the pilot studies conducted and large regional studies, it has been shown that organic waste in the collected mixed waste has decreased significantly thanks to the application of the different PAYT alternatives [93].

The system introduced in the county of Aschaffenburg, Germany in 1997, which is one of the most successful examples of PAYT in terms of a high recyclables collection rate and a low annual per capita volume of household waste [99], is based on measuring waste weight. Along with the basic fee, two different types of fees are charged to citizens (collection fee and weight fee). Identification of the bins is done by crisps placed in the bins, waste identification and simultaneous billing are done by a reader and a weighing system in the waste collection vehicles.

In a pilot study of IoT-based smart containers in Gangnam, Korea [100], although a PAYT system based on waste weight was applied, no unit fee per kg of waste was set in determining the flexible fee to be paid in addition to the basic fee. Instead, a system was introduced in which the variable fee changes depending on the amount of waste generated each month. In other words, the amount of waste collected in one month is used to calculate the flexible fee that citizens have to pay in the next month. In this way, the amount of food waste has decreased significantly (33%) with the implementation of the proposed concept.

Although the number of successful examples is large enough, it has been observed that PAYT systems do not always give the desired results, even when implemented with detailed calculations and rational expectations. The importance of legal regulations and informative training to increase the efficiency of the system was emphasized by those

working in the field. In a study [101] highlighting the importance of the participation of city residents in the processes, the level of citizen participation in the established system PAYT was investigated with a pilot application in Kifissia, Greece. In particular, in some PAYT guidebooks [102] and PAYT studies [103, 104] it was suggested that a comprehensive recycling program should be implemented in cooperation with PAYT.

2.2.3 Proposed Alternative

For the reason mentioned above in addition to the PAYT, a recycling alternative based on monetary incentives is proposed with the aim of making the system more effective. In contrast to the most PAYT applications utilizing cloud system, the proposed alternative uses blockchain technology. Blockchain, known as distributed ledger technology, is a technology that allows users to implement smart contracts and store information in a decentralized manner in various nodes [105]. Adapting this technology, which has proven itself in the financial sector, to a smart waste management application will be encouraging factors for both waste producers and the local authorities in the following ways:

- The decentralized storage of data instead of a central database (e.g. cloud database) improves data security.

- Interactions between stakeholders are monitored by different entities of the smart contract. All entities interact with each other to ensure that they do not engage in a transaction that is not valid for the participants. Information is obtained from the various participants so that transactions can be verified against this information by applying the consensus algorithm by all participants in the network. This enables transparency and trust between the parties involved [106].

- System will be locked against malicious outside interference that creates the possibility of manipulating the data.

Here, a PAYT system Leveraging Blockchain Technology approach is proposed which can be the subject of a pilot study to determine whether it is feasible through more detailed analysis and calculations. The work area could be chosen as a residential group consisting of several apartments. Thus, the availability of a limited number of containers for use by a limited number of user groups will provide an advantage in terms of both system control and initial capital and operating costs. The system will consist of three layers, namely the physical layer with the weight sensor and microcontrollers used for data collection and

transmission, the blockchain service layer where the data is processed, and the application layer that enables administration user management and data visualization.

The basic steps of the PAYT and recycling application to be carried out together in the selected residential group are summarized below:

1. A container of corresponding volume will be allocated for each residential building on the site, and these containers are recorded in the blockchain system.

2. Each household will register with the system through the mobile application intended for it. By entering the apartment information, the container information to be used by the household member will be visible to the user.

3. For their household waste, the dwellers of the residential group are required to buy garbage bags identified by a spesific color. If this type of waste is left in a container with a bag other than the one previously purchased, the waste will not be picked up. Normally these bags are found in municipal service centers, supermarkets, local stores, or libraries. Fort this case, they could be available at the administration. For recyclable waste, any bag may be used as long as it is clean and undamaged.

4. Each container visit by waste collection vehicles will be entered into the blockchain system as a new record. The weight of the household waste will be measured by the weight sensor in the vehicle and the corresponding data is transferred to the Blockchain. The type of recyclable material collected will be determined and the performance of separation at source will be evaluated by the operator and will be entered into the system. In addition to all this waste information, container information and collection time will also be recorded.

6. The entry of recyclable waste into the recycling facility will be recorded on the blockchain. All subsequent waste identification, classification, and processing activities will also be recorded. As during waste collection, residents' separation performance can be evaluated and recorded as additional information for the reward system. Finally, which recyclables are made available for sale at the facility and in what quantities will be recorded, as well as how much profit would be generated by selling these materials to customers.

7. The unit price for each kilogramme of household waste to be collected on the site shall be determined by the local government responsible for the collection of waste on the residential group. With the transfer of the weight data of the household waste collected

from the relevant container to the Blockchain, the calculations based on these unit prices result in the fee to be paid per household using the container.

In order to increase the efficiency of the PAYT system by performing recycling activities more effectively, a reward plan will be created. For this purpose, a performance scale will be established for the waste separation at source to be carried out by the members of the residential group. The types and quantities of recyclable waste offered for sale at the recycling facility will also be taken into account when creating the reward plan. The tokens to be calculated through these two parameters will automatically be transferred to the user's electronic wallet after the waste is made available for sale at the recycling facility. The system allows the tokens to be used for other municipal services and cultural activities. The fee for household waste collection can also be covered with the purchased tokens. To achieve this, unit prices should be set for the token in question as well as the currency used.

8. With a mobile app, users (residents) will have access to information such as:

- Waste collection times

- Type and quantity of waste collected at relevant times.

- Performance of the residential group member on waste separation at source

- Type of recyclable waste made available for sale at the recycling facility, its quantity and the revenue to be generated from its sale

- The amount they have to pay due to the household waste they throw away

- Tokens they receive thanks to the recyclable waste they separate at source

- A guide listing the areas in which the tokens earned can be used and instructions for seperation at source.

The application also allows for payment with tokens in the electronic wallet. (Waste collection fees, credits for public transportation, tickets for cultural events, etc.

2.3 IoT-Based Community Composting

2.3.1 Food Waste as a Global Problem

The world's food crisis is growing exponentially due to agricultural problems caused by global climate change and wild consumerism. Studies [107] have shown that the number

of people facing the problem of food insecurity has increased by 40 million compared to the previous year and reached 193 million in 2021.

On the one hand, access to healthy food is becoming more difficult by the day, while on the other hand, tons of food waste are generated every day in increasingly densely populated cities. A recent report reveals that around 568 million tons of food waste was generated in households in 2019 [108]. The report also shows that contrary to the common assumption that the amount of food waste per capita is higher in high-income countries, the amounts of household food waste per capita are very close in countries with different income levels. These data show that there is a need to develop policies and strategies against food waste in all parts of the world.

As the amount of food waste generated increases, so does the level of environmental degradation caused by this type of waste. It pollutes soil and water resources due to its high organic content, threatens public health due to its toxic and pathogenic properties. Carbon dioxide and methane gas, produced by the decomposition of it in the natural process, are the main actors of global climate change. All these negative aspects make it necessary for governments and local authorities to manage this waste effectively.

In most parts of the world, landfilling of household food waste is still preferred because of its convenience and lower cost. However, due to the understanding that considers waste as a raw material in terms of natural resource protection and circular economy, it can be observed that modern applications of a method, of composting, whose foundations date back hundreds of years are in demand, especially in developed countries, both at the level of citizens and municipalities.

2.3.2 Good Examples: Community Composting

Composting is the process of obtaining stable substances that can be used as insect-free, pathogen-free, toxicity-free, odor-free and nutrient-rich organic fertilizer as a result of biodegradation of organic materials under controlled moisture, heat, and aerobic conditions with macro and microorganism activity. Some of the main benefits of its use are the following:

1. Waste management costs are reduced as less waste goes into landfills.

2. Water retention capacity, productivity and resistance of the soil increase thanks to the nitrogen, phosphorus and potassium that compost contains, as well as traces of other

important elements such as calcium, magnesium, iron and zinc. In this way, water use in agricultural irrigation and erosion risk are also reduced [109].

3. The formation of methane gas from landfills is prevented.

4. Thanks to its commercial value, local governments can use the end product as an income item for themselves and as an incentive reward for city residents in proportion to their contribution to the composting processes.

Until recently, the greatest interest has been in composting activities carried out at the state level or by large corporations. However, the importance of decentralized composting at the community level, carried out by volunteers and non-environmental organizations, is increasingly being recognized. Community composting is the organization of voluntary individuals or groups who share the common ideal of recycling organic waste in an environmentally friendly manner and jointly carry out various composting activities. In addition to composting, these activities include setting up organic waste drop off points, collecting food waste from farmers' markets, creating arable land in neighborhoods and organizing informative and instructional workshops on composting. Thus, the amount of food waste generated is reduced, and local production is supported by saving water, agrochemicals, and energy for food production by giving the compost produced to farmers in the area. The activities also strengthen the sense of trust and belonging between people in the community, increase environmental awareness and enable socialization.

Although community composting is based on civil solidarity and voluntarism, the processes can be carried out more quickly and easily thanks to technical and economic support from local governments, non-governmental organizations, universities or private entities willing to cooperate. Below are three different good examples that have been implemented in this way.

"The Food Matters" is a food waste reduction program that includes composting activities in Baltimore, United States, in partnership with the Natural Resources Defense Council (NRDC), The Rockefeller Foundation and the Baltimore City [110]. Food waste collected at farmers' markets and a variety of drop-off locations is collected and composted by volunteers from the Baltimore Compost Collective. Some of the compost is given to farmers who sell their produce at the farmers' market, and some is used in "community farms" set up between neighborhoods to provide food to those in need. Figure 2.4 shows one of the food waste drop off points in Baltimore:



Figure 2.4 A food waste drop off point in Baltimore [111]

In another food waste reduction project [112] in the country, The Prescott Farmers Market has partnered with the City of Prescott to implement a small community composting program where food waste collected at the Saturday farmers market are turned into compost that can be used in gardens and on farms throughout the Prescott area. Each week, 125 customers drop off food waste at the farmers' market. This waste, along with kitchen scraps collected from 7 Prescott restaurants, is processed by 20 volunteers. The finished compost is distributed to gardeners at the farmers' market. In the first year of the project 120 volunteers helped process over 40 tons of food waste.

As part of a 2021 project in Turkey led by Ebru Baybara Demir, chief executive/social entrepreneur, and Eda Dalgic Cetinkaya, environmental engineer, and in collaboration with the Diyarbakir Kayapinar Municipality, biodegradable waste discarded at markets in the region was collected by volunteers and municipal employees and started to be composted through batch composting. The project aimed to improve soil quality and water holding capacity by making the compost produced available to farmers in the region, thereby reducing the cost of agricultural inputs such as irrigation, energy and fertilizer consumption, while protecting natural water resources [113]. In addition, to reduce food waste and provide social support, about 300-700 kg of edible vegetable and fruit waste collected on a day was distributed to the soup kitchen and food bank established specially for the project.

The following section presents a step-by-step approach based on the above examples of community composting projects to deal with food waste.

2.3.3 Proposed Alternative

Since composting consists of various biochemical and heterogeneous phases, it is very sensitive to changes in external factors, especially temperature, humidity and pH. Interruption of the process is easily possible. For example, the material will rot if it is watered too much. Excessive heat destroys the organisms. Even when the process is complete, a stable, nutrient-rich compost is not obtained. In the worst case, the resulting product may have ecotoxic characteristics [114]. For this reason, the entire process must be controlled without interruption. This requires the use of qualified personnel. Even though some types of composting machines are in use, they are not capable of dealing with changes in temperature, humidity, etc., so the processes do not run as smoothly as they do under human supervision [115].

In recent years, initiatives have emerged that use ICT tools to manage a controlled composting process, without the need for human intervention, and ultimately obtain a quality compost. By receiving and processing simultaneous data such as temperature, moisture and oxygen content of the compost, the necessary actions can be taken simultaneously and automatically. Expert opinions obtained from previous experimental results are used to determine which interventions (irrigation, heating, aeration, mixing, etc.) are made for which parameter changes and for how long. Some recent studies [115] have proven that with intelligent composting the desired results can be achieved in less time than with conventional methods. Figure 2.5 shows a smart composting approach using ICT tools.

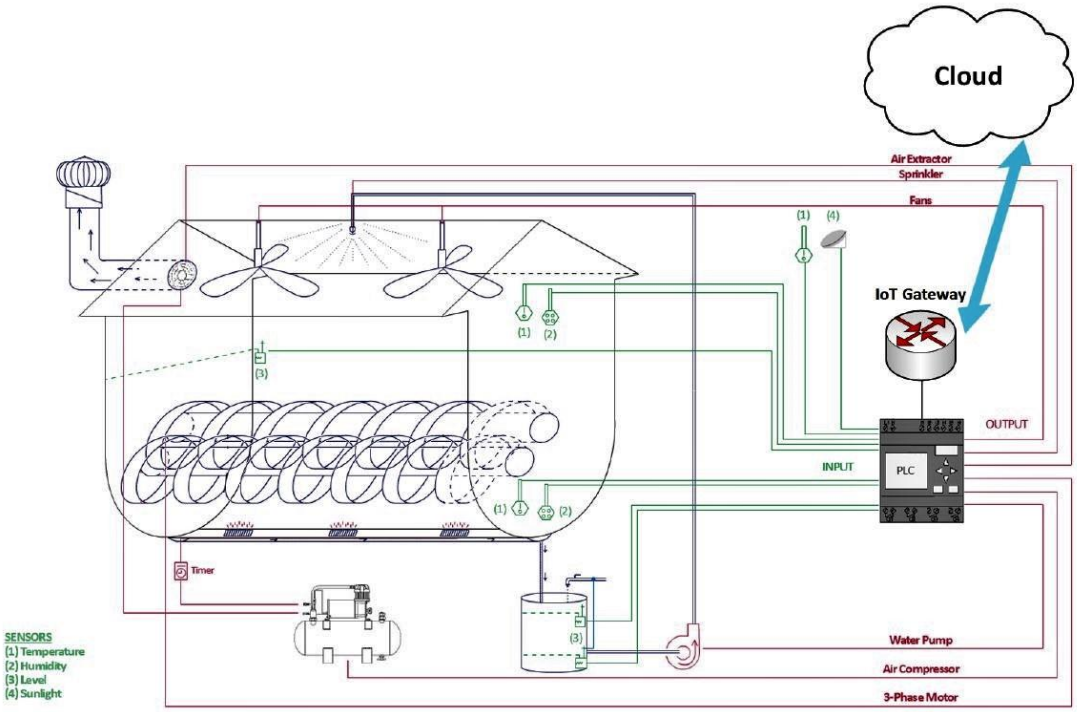


Figure 2.5 A smart composting approach [116]

The proposed alternative in this study is a pilot-scale project that includes a collaborative composting application with the integration of ICT tools that has the potential to further improve in terms of process times and product quality. The general framework of the approach is explained below:

1. At a farmers' market set up in a neighborhood selected as part of the project, groups of volunteers collect the vegetable and fruit waste discarded by sellers, such as from softening or deformation, and separate it from other type of wastes for composting.

2. Residents who want to participate in the project voluntarily sign up through a website. An informative guide about the process and composting in general, as well as a calendar of events, will be sent to registered participants' email addresses.

3. Farmers selling fruits and vegetables at the market included in the project will also submit a compost application on the above website. In order to benefit from the compost produced by the project, the farmers will undertake to deliver a certain amount of the harvested material free of charge each month to two school canteens selected within the framework of the project.

4. The food waste collected at the market will be transported to the designated composting area by the vehicles and personnel of the unit assigned by the municipality for this task.

5. The composting tanks placed in the composting area will contain a mixer connected to an electric motor, a sprinkler system connected to a water pump, and two separate fans with heating and cooling capabilities. The number of tanks and their capacity will be determined according to the estimated amount of waste collected in the market.

6. Temperature and humidity sensors will be placed in the tanks to instantly display the temperature and humidity values of the compost.

7. Thanks to the IoT gateway, daily tasks such as mixing, irrigation, heating and cooling will be defined to the system and executed automatically thanks to the actuators that run the motors and pumps at the specified times of the day and for the specified periods.

8. Thanks to the microservices in the cloud service used, the system immediately processes and analyzes the temperature and humidity data transmitted by the sensors and ensures that the necessary measures are taken. Thus, in addition to the daily tasks, effective interventions against changes that could disrupt the functioning of the composting process are made immediately. (e.g., operation of cooling due to a drop in temperature, irrigation due to a drop in humidity) Data analysis is performed by training artificial neural networks with data obtained from experiments conducted by experts in the field.

7. In addition, a web-based dashboard will be used in the system to allow manual intervention in the actuators, determination of task hours and durations, and instant data display.

Thanks to the project, the benefits and weaknesses of IoT-based composting method compared to traditional methods will be tested. Food waste will be prevented by composting. Farmers' production will be supported, and a benefit will be created for students whose access to healthy food at a developmental age is of great importance.

2.4 Preventing Illegal Sewage Discharge By Utilizing IoT

2.4.1 Illegal Sewage Discharge: General Framework and Negative Consequences

Rapid urbanization and the intense industrialization that accompanies it make it even more important for local authorities to deal with wastewater in a way that protects the environment and public health. The most important role is played by sewerage networks, which prevent the uncontrolled spread of sewage-related pollution in the environment by

conveying wastewater to treatment plants, and treatment plants, that make the wastewater less harmful before it is discharged into the receiving environment.

In regions where there is no sewerage system, wastewater from residental areas or industries is taken from septic tanks by vacuum trucks and discharged into the sewerage system from points determined by the municipality. The municipality shall issue a work permit to sewer trucks working for public and private entities so that they can discharge their wastewater to the points determined in the sewer system. The work permit is issued separately for each vehicle. In addition, it is the responsibility of the municipalities to legally supervise the activity of the vacuum trucks.

It is a common problem in cities that some industrial enterprises and households illegally discharge their wastewater into the sewer system directly or by utilizing vacuum trucks. Illegal discharges of wastewater include discharges to the municipal sewer system or stormwater system that occur outside of the legal permits established by local authorities and government agencies. The most common illicit discharges from industry are ore processing wastewater, surface washing wastewater, cooling water wastewater, wastewater from dyeing factories, wastewater containing petroleum, wastewater containing oil grease, wastewater from mines, wastewater from pharmaceutical plants, and wastewater from the cement and concrete industries. Illegal discharges from residential areas are mainly sanitary wastewater, wastewater from car washes, motor oil and pet waste. Among the main reasons for illegal dumping are that the wastewater in question has characteristics that are prohibited by legislation, companies want to avoid the cost of discharge, and there is a lack of awareness of environmental protection.

The first problem area caused by illegal discharges is the sewage system. Depending on the amount and nature of wastewater, a variety of problems can occur here. Some of these include clogging of sewage pipes, damage to pipes due to high pH, overflowing of the sewage system, and endangering the health and safety of workers.

The aim of wastewater treatment plants is to render wastewater as harmless as possible and to discharge it into the receiving environment in the most economical way possible and with high energy efficiency. Possible illegal wastewater inflow from the sewer system poses a huge problem for the effective functioning of treatment plants. Since they are designed and put into operation in accordance with the general characteristics of each city's wastewater, sudden and extreme changes in the plant's influent due to illegal

discharges have a direct negative impact on the plant's treatment performance. The presence of toxic factors such as heavy metals, sudden pH changes and decreasing oxygen levels may reduce or even terminate the efficiency of biological treatment. Reversing these unfavorable situations that disrupt the operation of the plant means both a waste of time (e.g., the reproduction of bacteria involved in the treatment) and a waste of money (more energy and chemicals used). In addition, wastewater discharged into the receiving environment without proper treatment may not meet discharge standards, and the facility may be subject to administrative and monetary penalties.

As a result of illegal discharges, the wastewaters that enter the water bodies without proper treatment in the treatment treatment plant contain heavy metals, petroleum - petrochemicals, micropollutants, drugs, pesticides, etc. For this reason, they cause significant damage especially in sensitive aquatic ecosystems and small aquatic ecosystems. This situation is also a threat to public health in the city. Untreated wastewaters will have a direct negative effect also on plant growth and soil structure as they contain high alkali or acid content, salinity, trace elements and heavy metals.

2.4.2 Good Examples: Monitoring and Detecting Illegal Sewage Discharges

In order to prevent illegal dumping of wastewater, making the necessary legal regulations both at local and government scale is crucial. In addition, it is essential that regular and accurate engineering controls and inspections are performed in accordance with these regulations. However, for municipalities, it is not always easy to determine the exact location, time and frequency of these dumpings. The use of information and communication technologies in carrying out technical inspections enables such processes to be more effective. With the different types of sensors and data transmission and visualization tools used, the detection of improper discharges becomes faster and more accurate.

In studies aiming to detect possible unregistered discharges to sewage systems by using sensor technology, it is seen that various characteristics of wastewater such as conductivity [117], flow rate [118], solid matter concentration [119] and also water levels [120] are utilized. After receiving data via sensors located in sewage, transmitting it to a computer server and processing it, the system issues an alarm if there is a critical change in the above-mentioned water characteristics.

In another recent study, researchers developed and tested IoT modules equipped with different communication technologies, with sensors measuring different wastewater characteristics, placed at four different strategic points of the sewer system's main line to detect the entry of harmful wastewater into the sewer network and its source. The system was able to successfully detect the leakage of wastewater and its location and alert the end users with an alarm. Figure 2.6 shows a wireless IoT module with pH and electrical conductivity sensors placed in the sewer system during the test.

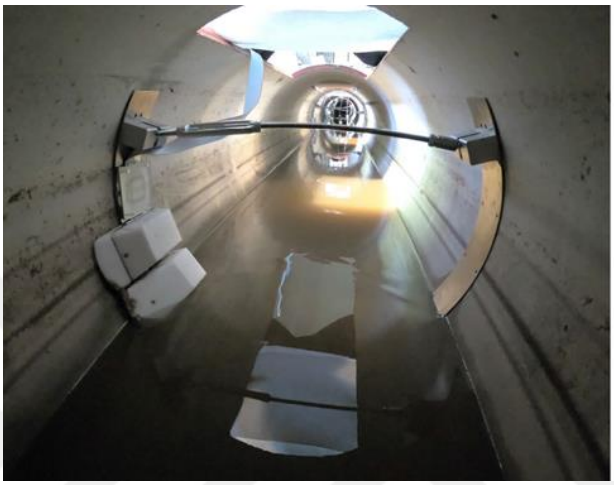


Figure 2.6 Wireless IoT module with pH and conductivity sensor [121]

In addition to the detection of illegal discharges to the sewer systems using ICT tools, a very recent work [122] uses machine learning to detect wastewater that escapes from the treatment plants and is discharged into water sources without being properly treated. In the study, mathematical models were first trained using the leaks previously reported by the plant operators and the observed imbalances in the effluent flow due to these leaks. Then, inserting the simultaneous data obtained with ultrasonic flow meters into these models makes it possible to detect the water leaving the system without treatment.

Another good example was recently introduced in Kocaeli that uses IOT vehicles to prevent illegal wastewater discharges from vacuum trucks into the sewer system. Kocaeli is a large industrial city in Turkey that hosts many industrial zones from many different sectors. Due to high disposal fees, the illegal discharge of wastewater using vacuum trucks is common in the region. To prevent this illegal action, the local water and sewage authority was using traditional methods such as license plate recognition from camera footage. After 2019, they have implemented the KATIS (Kocaeli Atıksu Transfer İzleme Sistemi) Project which enables the track of vacuum trucks by placing a GPS device on the vehicles and a capacity sensor in the tank compartment. Information about the

industrial facility where the wastewater is collected, the date and time of collection, the amount of wastewater collected, and the location of the vacuum truck are simultaneously displayed and controlled in a SCADA room. If an illegal discharge is detected, administrative fines and penalties are imposed on the owner of the vacuum truck and the company that produced the wastewater.

2.4.3 Proposed Alternative

As mentioned above, studies aiming to detect illegal discharges of wastewater into the sewer system using ICT tools are continuing. In the previous sections, it was mentioned that city residents, one of the main actors of smart cities, should play an active role for a sustainable environment and economy. For this reason, in accordance with the aforementioned understanding, this section includes an alternative in the determination of illicit discharges in which city residents can take the initiative together with the local authority. As a study area, a medium-sized region can be selected where the sewage system is not common, the wastewater is mostly discharged into the sewer system via vacuum trucks, and where there is intensive industrialization.

The proposed alternative is discussed in more detail below:

1. For the vacuum trucks that meet the conditions set by local authorities to operate in the region, GPS system and level sensors are going to be installed. The vacuum trucks may not be licensed until these tools are in located in the vehicle. A 5-digit work permit number will be issued to vacuum trucks equipped with the required ICT tools and issued a work permit. The number will be placed on a visible location on the vehicle in a minimum font size to be determined.

2. The level sensors, designed according to the tank diameter of each vehicle, can measure the level, temperature, humidity, pressure and angle of the water in the vacuum tank every ten seconds.

3. During the vacuum truck operations data of the above-mentioned information is collected and processed with two separate servers used, and can be monitored simultaneously in a control room.

4. Since it is determined in advance when, where, and how much wastewater each vacuum truck will discharge, the system issues an alarm in the event of an unprecedented situation, thanks to developed software.

5. The sensor system does not allow unwanted interference from the outside, as it issues an alarm when the protective cover is opened, or can continue to work with the battery even if its cable is cut. In addition, the SD card stores data in areas where data reception is not possible because GPS technology is not working (e.g., mining site) and the data flow starts again when GPS is active again.

6. If the illicit discharge of vacuum trucks is detected, the work and permit documents of the revelant vacuum truck are canceled and the vehicle shall be banned from traffic. Fines and other administrative penalties will also be imposed. These sanctions will also apply if vacuum trucks are found to be operating without relevant ICT tools.

7. Although the ICT technologies used make it easier to control the activities of registered vacuum trucks, the system cannot provide a solution against vacuum trucks that operate without the required permit applications. As a solution to this situation, with a mobile application developed, residents of the region will have the ability to report possible illegal discharges of wastewater into the sewer system by unregistered vacuum trucks.

8. A citizen witnessing the discharge of a vacuum truck vehicle into the sewer system shall verify that the vehicle is registered in the system by entering the work permit number affixed to the vacuum truck vehicle into the work permit number query screen in the application. If the vehicle is registered in the system, this information is visible to the user. If there is no vehicle registered with the mentioned number or there is no number on the vehicle, the user goes to the reporting section in the application.

9. In this section of the mobile application, the user, who remains anonymous, enters information such as the date and time of the discharge, the location of the discharge, and the license plate number of the vacuum truck, and sends a report of a possible illegal discharge to the control center. The officers at the control center direct the assigned teams to the point in question as quickly as possible. An example application reporting interface for a possible illegal sewage discharge of a vacuum truck is shown in Figure 2.7:

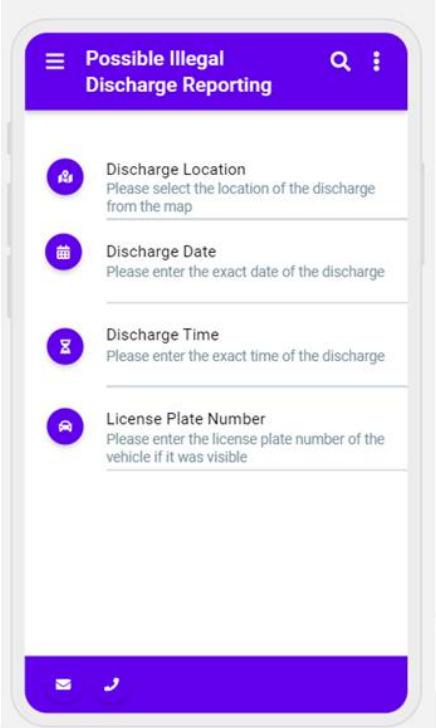


Figure 2.7 Citizen reporting interface for possible illegal sewage discharges

3
MATERIALS AND METHODS

3.1 Constructing the Hierarchical Structure of the Problem

When working with a Multi-Criteria Decision-Making method, the problem to be solved must first be clearly defined. Then the hierarchical structure of the problem in question is created. The hierarchical structure includes the alternatives, scenarios, or constraints of the problem to be evaluated or prioritized, as well as the criteria to be considered in the evaluation or prioritization. In determining the criteria, databases, expert opinions, or studies from the literature on the area in question may be consulted.

In this study, the problem was set to evaluate smart sustainable waste management strategies. The four smart waste management strategies proposed in the previous section were selected as alternatives for the problem. Fifteen sub-criteria belonging to five main criteria were selected from the literature.

The smart waste management strategy alternatives for the problem are shown in Table 3.1:

Table 3.1 Smart waste management strategy alternatives to be evaluated

Alternative No.	Alternative Name
A1	Integrating Informal Recyclable Waste Collection into a Formal Smart System
A2	A Pay as You Throw Application Leveraging Blockchain Technology
A3	IoT-Based Community Composting
A4	Preventing Illegal Sewage Discharge by Utilizing IoT

The main criteria and sub-criteria chosen to consider in the evaluation of alternatives are shown in Table 3.2:

Table 3.2 Main criteria and sub-criteria to be considered

Main Criteria	Sub-Criteria No.	Sub-Criteria Name
Environmental Criteria (C1)	C1.1	Less atmospheric emissions
	C1.2	Less soil pollution
	C1.3	Less surface water pollution
	C1.4	Energy recovery
	C1.5	Natural resources recovery
Technical Criteria (C2)	C2.1	Operational feasibility
	C2.2	Innovativeness
	C2.3	Need for qualified personnel
Economic Criteria (C3)	C3.1	Maintenance costs
	C3.2	Transportation costs
	C3.3	Operational costs
	C3.4	Initial invesment costs
Social Criteria (C4)	C4.1	Increased awareness on sustainable cities
	C4.2	Increased quality of life in the city
	C4.3	New employment opportunities

Accordingly, the hierarchical structure that includes the selected problem, the strategy alternatives of the problem, and the main criteria and subcriteria used in the evaluation of these alternatives will be as shown in Figure 3.1:

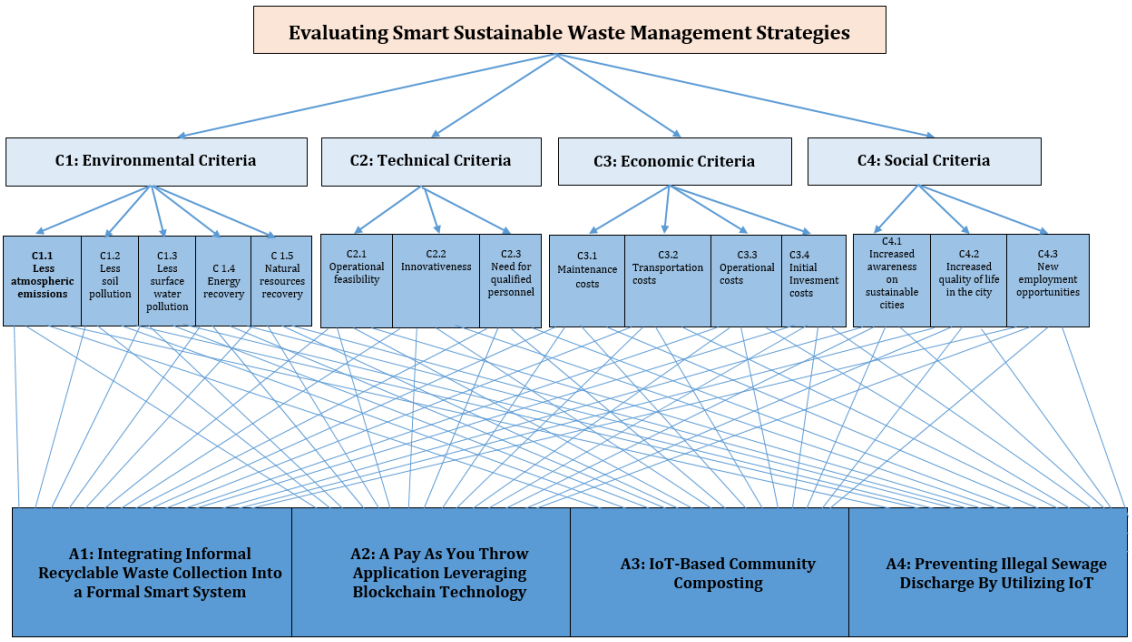


Figure 3.1 The hierarchical structure of the problem

3.2 Obtaining Decision Maker Opinions

In a fuzzy MCDM problem, subjective expert opinions are needed to determine the weighting of the selected criteria and to evaluate the proposed strategy alternatives according to these criteria. As long as there is at least one decision maker, there is no limit to the number of experts whose opinions are obtained [123]. In this study, a group of decision makers consisting of ten experts was formed. Eight of the experts work in the field of environmental engineering and two in the field of smart cities.

Three of the experts working in the field of environmental engineering work in academia. (Two professors and one research assistant) One expert is an environmental engineer in the Ministry of Environment, Urbanization and Climate of the Republic of Turkey. One expert is an environmental engineer working at ÇEVKO Foundation, a non-profit foundation promoting recycling of packaging waste in Turkey. One expert is an electrical and electronics engineer who works at the Bursa Metropolitan Municipality and holds a master's degree in environmental engineering. One of the experts from the private sector works in sustainability, and the other works as an environmental engineer for the company that operates an airport in Istanbul.

The first of the decision makers with smart city expertise is a geomatics engineer who works as a project manager in an international mapping and technology company. The

other expert is an electronics and communications engineer who has been involved in the implementation of thirty different smart city projects in Turkey and is currently a project manager at a defense electronics company in the country.

Figure 3.2 shows the work areas of the experts who make up the decision-making group and the type of institution they work for:

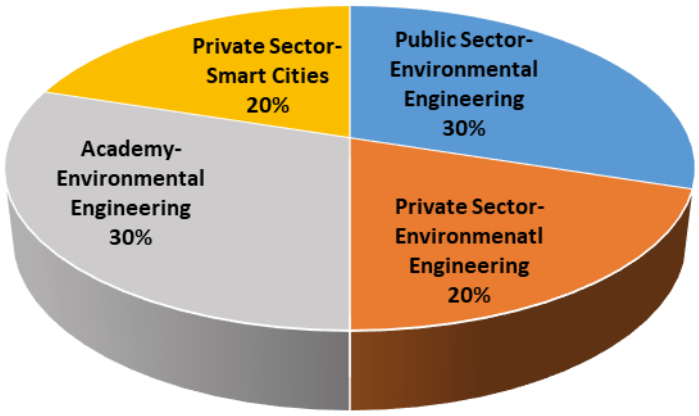


Figure 3.2 Distribution of expertise and work area of the decision maker group

The experts were reached via e-mail and LinkedIn and the questionnaire prepared with Google Forms were sent to them by the same means.

3.3 Computational Analysis

The results of the linguistic expert evaluations were drawn from the survey in Google Forms. Microsoft® Excel® 2016 (Microsoft Inc., Redmond, WA), running under Windows 10 system on a HP Pavilion (Intel® Core™ i5-7200U CPU, 2.50 GHz, 8 GB of RAM, 64-bit) PC platform, was used for the calculations of the fuzzy AHP and fuzzy TOPSIS.

4
RESULTS AND DISCUSSION

4.1 Determination of Criterion Weights

The weights of the sub-criteria within each main criteria group are determined using pairwise comparison matrices based on verbal and subjective expert evaluations. The four comparison matrices in question were created by the experts' interpretation of the superiority of the subcriteria over the others using the linguistic expressions in Table 1.4. Since there were ten experts in the group of decision makers, the geometric mean of the triple fuzzy number equivalents of the linguistic expressions was taken to reduce the result to one. Then the criteria weights were determined by following the calculations given below. Table 4.1 shows the pairwise comparison matrix obtained for environmental criteria:

Table 4.1 Pairwise comparison matrix for environmental criteria

Environmental Criteria	Less atmospheric emissions	Less soil pollution	Less surface water pollution	Energy recovery	Natural resources recovery
Less atmospheric	(1.00,1.00,1.00)	(1.36, 1.69, 2.09)	(1.20, 1.58, 2.06)	(1.56, 1.97, 2.43)	(1.46, 1.74, 2.05)
Less soil pollution	(0.48, 0.59, 0.74)	(1.00,1.00,1.00)	(1.09, 1.32, 1.59)	(1.37, 1.76, 2.24)	(1.28, 1.52, 1.76)
Less surface water pollution	(0.49, 0.63, 0.84)	(0.63, 0.76, 0.92)	(1.00,1.00,1.00)	(1.50, 1.97, 2.54)	(1.35, 1.69, 2.08)
Energy recovery	(0.41, 0.51, 0.64)	(0.45, 0.57, 0.73)	(0.39, 0.51, 0.67)	(1.00,1.00,1.00)	(1.18, 1.52, 1.91)
Natural resources recovery	(0.49, 0.57, 0.69)	(0.57,0.66, 0.78)	(0.48, 0.59, 0.74)	(0.52, 0.66, 0.84)	(1.00,1.00,1.00)

To obtain the fuzzy synthetic extent value of a criterion, the vector obtained by the sum of the vectors in the row belonging to the relevant criterion and the inverse of the vector, which is the sum of all row sums, are multiplied:

$S_{less\ atmospheric\ emissions}$ = (6.57, 7.98, 9.63) $\otimes$ (0.03, 0.04, 0.04) = (0.20, 0.29, 0.41)

$S_{less\ soil\ pollution}$ = (5.22, 6.19, 7.32) $\otimes$(0.03, 0.04, 0.04) = (0.16, 0.22, 0.31)

$S_{less\ surface\ water\ pollution}$ = (4.97, 6.05, 7.36) $\otimes$(0.03, 0.04, 0.04) = (0.15, 0.22, 0.32)

$S_{energy\ recovery}$ = (3.44, 4.10, 4.95) $\otimes$(0.03, 0.04, 0.04) = (0.10, 0.15, 0.21)

$S_{natural\ resources\ recovery}$ = (3.06, 3.48, 4.05) $\otimes$(0.03, 0.04, 0.04) = (0.09, 0.13, 0.17)

Using these vectors, the values of $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$ are calculated according to the Equation (1.8) as follows:

$V(S_{less\ atmospheric\ emissions} \geq S_{less\ soil\ pollution}) = 1.00$

$V(S_{less\ atmospheric\ emissions} \geq S_{less\ surface\ water\ pollution}) = 1.00$

$V(S_{less\ atmospheric\ emissions} \geq S_{energy\ recovery}) = 1.00$

$V(S_{less\ atmospheric\ emissions} \geq S_{natural\ resources\ recovery}) = 1.00$

$V(S_{less\ soil\ pollution} \geq S_{less\ atmospheric\ emissions}) = 0.65$

$V(S_{less\ soil\ pollution} \geq S_{less\ surface\ water\ pollution}) = 1.00$

$V(S_{less\ soil\ pollution} \geq S_{energy\ recovery}) = 1.00$

$V(S_{less\ soil\ pollution} \geq S_{natural\ resources\ recovery}) = 1.00$

$V(S_{less\ surface\ water\ pollution} \geq S_{less\ atmospheric\ emissions}) = 0.63$

$V(S_{less\ surface\ water\ pollution} \geq S_{less\ soil\ pollution}) = 1.00$

$V(S_{less\ surface\ water\ pollution} \geq S_{energy\ recovery}) = 1.00$

$V(S_{less\ surface\ water\ pollution} \geq S_{natural\ resources\ recovery}) = 1.00$

$V(S_{energy\ recovery} \geq S_{less\ atmospheric\ emissions}) = 0.10$

$V(S_{energy\ recovery} \geq S_{less\ soil\ pollution}) = 0.43$

$V(S_{energy\ recovery} \geq S_{natural\ resources\ recovery}) = 0.48$

$V(S_{energy\ recovery} \geq S_{natural\ resources\ recovery}) = 1.00$

$V(S_{natural\ resources\ recovery} \geq S_{less\ atmospheric\ emissions}) = 0.00$

$V(S_{natural\ resources\ recovery} \geq S_{less\ soil\ pollution}) = 0.15$

$V(S_{natural\ resources\ recovery} \geq S_{less\ surface\ water\ pollution}) = 0.21$

$V(S_{natural\ resources\ recovery} \geq S_{energy\ recovery}) = 0.76$

Thus, the weight vector for the environmental criteria are calculated as:

$W_{environmental\ criteria} = (0.42, 0.27, 0.27, 0.04, 0.00)$

The results show that less atmospheric emissions is the most important criterion among the environmental criteria. The criterion of less soil pollution and less surface water pollution is equally important. The criterion of energy recovery is of much lower importance than all these criteria. The weighting value for the criterion of natural resources was given as 0, which means that the mentioned criterion is not important at all compared to the other environmental criteria.

Table 4.2 shows the pairwise comparison matrix obtained for technical criteria:

Table 4.2 Pairwise comparison matrix for technical criteria

Technical Criteria	Operational feasibility	Innovativeness	Need for qualified personnel
Operational feasibility	(1.00, 1.00, 1.00)	(1.59, 2.08, 2.63)	(1.34, 1.62, 1.93)
Innovativeness	(0.38, 0.48, 0.63)	(1.00, 1.00, 1.00)	(1.52, 2.00, 2.56)
Need for qualified personnel	(0.52, 0.62, 0.75)	(0.39, 0.50, 0.66)	(1.00, 1.00, 1.00)

The fuzzy synthetic extent values obtained accordingly:

$S_{Operational\ feasibility} = (3.93, 4.71, 5.55) \otimes (0.08, 0.10, 0.11) = (0.32, 0.46, 0.64)$

$S_{Innovativeness} = (2.90, 3.48, 4.19) \otimes (0.08, 0.10, 0.11) = (0.24, 0.34, 0.48)$

$S_{Need\ for\ qualified\ personnel} = (1.91, 2.12, 2.41) \otimes (0.08, 0.10, 0.11) = (0.16, 0.21, 0.28)$

Using these vectors, the values of $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$ are calculated as follows:

$V(S_{Operational\ feasibility} \geq S_{Innovativeness}) = 1.00$

$V(S_{Operational\ feasibility} \geq S_{Need\ for\ qualified\ personnel}) = 1.00$

$V(S_{Innovativeness} \geq S_{Operational\ feasibility}) = 0.57$

$V(S_{Innovativeness} \geq S_{Need\ for\ qualified\ personnel}) = 1.00$

$V(S_{Need\ for\ qualified\ personnel} \geq S_{Operational\ feasibility}) = 0.00$

$V(S_{Need\ for\ qualified\ personnel} \geq S_{Innovativeness}) = 0.22$

Thus, the weight vector for the technical criteria are calculated as:

$W_{technical\ criteria} = (1.00, 0.57, 0.00)$

The results show operational feasibility is the most important criterion among the technical criteria. The criterion of innovativeness has lower importance compared to the criterion of operational feasibility. However, the weighting value for the criterion of need for qualified personnel was given as 0, which means that the mentioned criterion is not important at all compared to the other technical criteria.

Table 4.3 shows the pairwise comparison matrix obtained for economic criteria:

Table 4.3 Pairwise comparison matrix for economic criteria

Economic Criteria	Initial invesment costs	Operational costs	Maintenance costs	Transportation costs
Initial invesment costs	(1.00, 1.00, 1.00)	(1.37, 1.64, 1.96)	(1.25, 1.58, 1.97)	(1.53, 1.94, 2.41)
Operational costs	(0.51, 0.61, 0.73)	(1.00, 1.00, 1.00)	(1.35, 1.58, 1.82)	(1.25, 1.47, 1.73)
Maintenance costs	(0.51, 0.63, 0.80)	(0.55, 0.63, 0.74)	(1.00, 1.00, 1.00)	(1.25, 1.58, 1.97)
Transportation costs	(0.41, 0.51, 0.65)	(0.58, 0.68, 0.80)	(0.51, 0.63, 0.80)	(1.00, 1.00, 1.00)

The fuzzy synthetic extent values obtained accordingly:

$S_{Initial\ investment\ costs} = (5.15, 6.17, 7.35) \otimes (0.05, 0.06, 0.07) = (0.25, 0.35, 0.49)$

$S_{Operational\ costs} = (4.11, 4.66, 5.28) \otimes (0.05, 0.06, 0.07) = (0.20, 0.27, 0.35)$

$S_{Maintenance\ costs} = (3.30, 3.85, 4.52) \otimes (0.05, 0.06, 0.07) = (0.16, 0.22, 0.30)$

$S_{Transportation\ costs} = (2.50, 2.83, 3.26) \otimes (0.05, 0.06, 0.07) = (0.12, 0.16, 0.22)$

Using these vectors, the values of $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$ are calculated as follows:

$V(S_{Initial\ investment\ costs} \geq S_{Operational\ costs}) = 1.00$

$V(S_{Initial\ investment\ costs} \geq S_{Maintenance\ costs}) = 1.00$

$V(S_{Initial\ investment\ costs} \geq S_{Transportation\ costs}) = 1.00$

$V(S_{Operational\ costs} \geq S_{Initial\ investment\ costs}) = 0.53$

$V(S_{Operational\ costs} \geq S_{Maintenance\ costs}) = 1.00$

$V(S_{Operational\ costs} \geq S_{Transportation\ costs}) = 1.00$

$V(S_{Maintenance\ costs} \geq S_{Initial\ investment\ costs}) = 0.26$

$V(S_{\text{Maintenance costs}} \geq S_{\text{Operational costs}}) = 0.68$

$V(S_{Maintenance\ costs} \geq S_{Transportation\ costs}) = 1.00$

$V(S_{Transportation\ costs} \geq S_{Initial\ investment\ costs}) = 0.00$

$V(S_{Transportation\ costs} \geq S_{Operational\ costs}) = 0.12$

$V(S_{Transportation\ costs} \geq S_{Maintenance\ costs}) = 0.48$

Thus, the weight vector for the economic criteria are calculated as:

$W_{economic\ criteria} = (1.00, 0.53, 0.26, 0.00)$

The results revealed that the initial investment costs criterion is very important compared to other economic criteria. This criterion is followed by the operational costs criterion. The criterion of maintenance costs is insignificant compared to these two criteria. The criterion of transportation costs, on the other hand, has no meaning compared to other economic criteria. Table 4.4 shows the pairwise comparison matrix obtained for social criteria:

Table 4.4 Pairwise comparison matrix for social criteria

Social Criteria	Increased awareness on sustainable cities	Increased quality of life in the city	New employment opportunities
Increased awareness on sustainable cities	(1.00, 1.00, 1.00)	(1.48, 1.89, 2.35)	(1.10, 1.47, 1.95)
Increased quality of life in the city	(0.42, 1.00, 0.67)	(1.00, 1.00, 1.00)	(1.54, 2.02, 2.58)

Table 4.4 Pairwise comparison matrix for social criteria (continued)

New employment opportunities	(0.51, 0.68, 0.91)	(0.39, 0.49, 0.65)	(1.00, 1.00, 1.00)

The fuzzy synthetic extent values obtained accordingly:

$S_{Increased\ awareness\ on\ sustainable\ cities} = (3.59, 4.36, 5.31) \otimes (0.08, 0.09, 0.12) = (0.30, 0.41, 0.63)$

$S_{Increased\ quality\ of\ life\ in\ the\ city} = (2.97, 4.02, 4.26) \otimes (0.08, 0.09, 0.12) = (0.24, 0.38, 0.50)$

$S_{New\ employment\ opportunities} = (1.90, 2.17, 2.55) \otimes (0.08, 0.09, 0.12) = (0.16, 0.21, 0.30)$

Using these vectors, the values of $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$ are calculated as follows:

$V(S_{Increased\ awareness\ on\ sustainable\ cities} \geq S_{Increased\ quality\ of\ life\ in\ the\ city}) = 1.00$

$V(S_{\text{Increased awareness on sustainable cities}} \geq S_{\text{New employment opportunities}}) = 1.00$

$V(S_{Increased\ quality\ of\ life\ in\ the\ city} \geq S_{Increased\ awareness\ on\ sustainable\ cities}) = 0.87$

$V(S_{Increased\ quality\ of\ life\ in\ the\ city} \geq S_{New\ employment\ opportunities}) = 1.00$

$V(S_{New\ employment\ opportunities} \geq S_{Increased\ awareness\ on\ sustainable\ cities}) = 0.03$

$V(S_{New\ employment\ opportunities} \geq S_{Increased\ quality\ of\ life\ in\ the\ city}) = 0.25$

Thus, the weight vector for the social criteria are calculated as:

$W_{social\ criteria} = (1.00, 0.87, 0.03)$

Although the two criteria are very close, it appears that the criterion of increased awareness of sustainable cities is somewhat more important than the criterion of increased quality of life in the city. The criterion of new employment opportunities is rather insignificant compared to the other two criteria.

4.2 Ranking of the Strategy Alternatives According to the Weighted Criteria

In this part of the study, the performance ranking of the strategy alternatives is performed using the fuzzy TOPSIS method. For this purpose, the criteria weighted with the fuzzy AHP method from the previous section are used. Expert opinions that evaluate the performance of each proposed strategy alternative according to each sub-criterion using the linguistic terms in Table 1.6 were first taken. Since there were ten experts in the group of decision makers, the arithmetic mean of the triple fuzzy number equivalents of the

linguistic terms was taken to reduce the result to one. Accordingly, the obtained fuzzy decision matrix is as in Table 4.5:

Table 4.5 Fuzzy decision matrix

C2			C3				C4		
C2.1	C2.2	C2.3	C3.1	C3.2	C3.3	C3.4	C4.1	C4.2	C4.3
(6.80, 8.30, 9.10)	(7.00, 8.40, 9.20)	(6.50, 8.00, 8.90)	(5.80, 7.60, 8.90)	(6.40, 8.10, 9.10)	(5.80, 7.60, 8.80)	(6.40, 8.10, 9.30)	(5.80, 7.50, 8.70)	(6.50, 7.90, 8.70)	(6.80, 8.40, 9.30)
(7.00, 8.60, 9.40)	(6.80, 8.40, 9.40)	(6.80, 8.60, 9.60)	(6.60, 8.30, 9.40)	(7.00, 8.70, 9.60)	(6.60, 8.40, 9.40)	(6.80, 8.40, 9.40)	(8.20, 9.50, 9.90)	(7.60, 9.10, 9.70)	(6.40, 8.10, 9.30)
(6.00, 7. 70, 9.00)	(6.80, 8.50, 9.60)	(6.20, 8.00, 9.30)	(6.00, 7.80, 9.20)	(7.00, 8.70, 9.60)	(6.80, 8.50, 9.40)	(5.80, 7.60, 8.90)	(7.40, 9.00, 9.80)	(7.00, 8.70, 9.70)	(6.40, 8.10, 9.30)
(5.80, 7.60, 9.00)	(6.80, 8.50, 9.60)	(6.40, 8.30, 9.50)	(6.60, 8.50, 9.70)	(6.60, 8.50, 9.60)	(6.60, 8.40, 9.40)	(6.50, 7.50, 8.90)	(6.80, 8.50, 9.50)	(7.60, 9.10, 9.80)	(6.20, 8.00, 9.20)

Table 4.5 Fuzzy decision matrix (continued)

C1	C1.1	C1.2	C1.3	C1.4	C1.5
	A1	(5.30, 6.80, 7.90)	(5.90, 7.50, 8.60)	(5.50, 7.10, 8.30)	(4.90, 6.50, 7.90)	(6.80, 8.30, 9.20)
	A2	(5.90, 7.30, 8.30)	(6.10, 7.60, 8.70)	(5.70, 7.20, 8.30)	(5.50, 7.00, 8.20)	(7.00, 8.60, 9.60)
	A3	(6.30, 7.80, 8.80)	(6.50, 7.90, 8.70)	(6.10, 7.60, 8.60)	(5.30, 6.90, 8.20)	(7.40, 8.90, 9.70)
	A4	(5.30, 6.80, 8.10)	(6.30, 7.90, 8.90)	(6.90, 8.20, 8.90)	(4.50, 6.20, 7.70)	(5.60, 7.40, 8.80)

Equations (1.15) and (1.16) are used to obtain a normalized fuzzy decision matrix. The normalization is performed differently depending on whether the criterion is a benefit criterion or a cost criterion. For example, since C1.3 is a benefit criterion, normalization of the corresponding vector to the second alternative (A2) ((5.70, 7.20, 8.30)) is performed by dividing the vector elements by 8.90, which is the third largest element in the vectors in the relevant column and the new vector is obtained as (5.70/8.90, 7.20/8.90, 8.30/8.90) = (0.64, 0.81, 0.93).

Let's take the C3.1 criterion. Since the criterion is a cost criterion, the first vector element with the smallest value in the column is determined. This value is 5.80. Accordingly, the normalization of the vector (6.60, 8.30, 9.40) corresponding to the second alternative (A2) of this criterion is calculated as (5.80/9.40, 5.80/8.30, 5.80/6.60) = (0.62, 0.70, 0.88)

The normalized fuzzy decision matrix obtained is as in Table 4.6:

Table 4.6 Normalized fuzzy decision matrix

	C2			C3				C4		
C1.5	C2.1	C2.2	C2.3	C3.1	C3.2	C3.3	C3.4	C4.1	C4.2	C4.3
(0.70, 0.86, 0.95)	(0.72, 0.88, 0.97)	(0.73, 0.88, 0.96)	(6.50, 8.00, 8.90)	(0.65, 0.76, 1.00)	(0.70, 0.79, 1.00)	(0.66, 0.76, 1.00)	(0.60, 0.69, 0.88)	(0.59, 0.76, 0.88)	(0.66, 0.81, 0.89)	(0.73, 0.90, 1.00)
(0.72, 0.89, 0.99)	(0.74, 0.91, 1.00)	(0.71, 0.88, 0.98)	(6.80, 8.60, 9.60)	(0.62, 0.70, 0.88)	(0.67, 0.74, 0.91)	(0.62, 0.69, 0.88)	(0.60, 0.67, 0.82)	(0.83, 0.96, 1.00)	(0.78, 0.93, 0.99)	(0.69, 0.87, 1.00)
(0.76, 0.92, 1.00)	(0.64, 0.82, 0.96)	(0.71, 0.89, 1.00)	(6.20, 8.00, 9.30)	(0.63, 0.74, 0.97)	(0.67, 0.74, 0.91)	(0.62, 0.68, 0.85)	(0.63, 0.74, 0.97)	(0.75, 0.91, 0.99)	(0.71, 0.89, 0.99)	(0.69, 0.87, 1.00)
(0.58, 0.76, 0.91)	(0.62, 0.81, 0.96)	(0.71, 0.89, 1.00)	(6.40, 8.30, 9.50)	(0.60, 0.68, 0.88)	(0.67, 0.75, 0.97)	(0.62, 0.69, 0.88)	(0.63, 0.75, 1.00)	(0.69, 0.86, 0.96)	(0.78, 0.93, 1.00)	(0.67, 0.86, 0.99)

Table 4.6 Normalized fuzzy decision matrix (continued)

C1	C1.1	C1.2	C1.3	C1.4
A1	(0.60, 0.77, 0.90)	(0.66, 0.84, 0.97)	(0.62, 0.80, 0.93)	(0.60, 0.79, 0.96)
A2	(0.67, 0.83, 0.94)	(0.69, 0.85, 0.98)	(0.64, 0.81, 0.93)	(0.67, 0.85, 1.00)
A3	(0.72, 0.89, 1.00)	(0.73, 0.89, 0.98)	(0.69, 0.85, 0.97)	(0.65, 0.84, 1.00)
A4	(0.60, 0.77, 0.92)	(0.71, 0.89, 1.00)	(0.78, 0.92, 1.00)	(0.55, 0.76, 0.94)

To obtain the weighted normalized fuzzy decision matrix, the matrix elements are multiplied by the sub-criteria weights obtained by the fuzzy AHP method in the previous section.

The weighted normalized fuzzy decision matrix obtained by multiplying the vectors in the column of each criterion by the weight of relevant criterion is shown in Table 4.7:

Table 4.7 Weighted normalized fuzzy decision matrix

C3	C4	C4.1	C4.2	C4.3
C3.4	(0.00, 0.00, 0.00)	(0.311, 0.402, 0.466)	(0.305, 0.371, 0.408)	(0.015, 0.018, 0.020)
	(0.00, 0.00, 0.00)	(0.439, 0.509, 0.530)	(0.357, 0.427, 0.455)	(0.014, 0.017, 0.020)
	(0.00, 0.00, 0.00)	(0.396, 0.482, 0.525)	(0.329, 0.408, 0.455)	(0.014, 0.017, 0.020)
	(0.00, 0.00, 0.00)	(0.364, 0.455, 0.509)	(0.357, 0.427, 0.460)	(0.013, 0.017, 0.020)

Table 4.7 Weighted normalized fuzzy decision matrix (continued)

C1					C2			C3		
C1.1	C1.2	C1.3	C1.4	C1.5	C2.1	C2.2	C2.3	C3.1	C3.2	C3.3
(0.253, 0.325, 0.377)	(0.180, 0.229, 0.262)	(0.164, 0.212, 0.248)	(0.025, 0.034, 0.041)	(0.00, 0.00, 0.00)	(0.462, 0.563, 0.618)	(0.264, 0.317, 0.347)	(0.00, 0.00, 0.00)	(0.362, 0.424, 0.556)	(0.209, 0.235, 0.297)	(0.097, 0.112, 0.147)
(0.282, 0.349, 0.396)	(0.186, 0.232, 0.266)	(0.170, 0.215, 0.248)	(0.028, 0.036, 0.042)	(0.00, 0.00, 0.00)	(0.475, 0.584, 0.638)	(0.256, 0.317, 0.354)	(0.00, 0.00, 0.00)	(0.343, 0.389, 0.489)	(0.198, 0.218, 0.271)	(0.091, 0.102, 0.129)
(0.301, 0.372, 0.420)	(0.198, 0.241, 0.266)	(0.182, 0.227, 0.257)	(0.027, 0.036, 0.042)	(0.00, 0.00, 0.00)	(0.407, 0.523, 0.611)	(0.256, 0.320, 0.362)	(0.00, 0.00, 0.00)	(0.351, 0.414, 0.538)	(0.198, 0.218, 0.271)	(0.091, 0.100, 0.125)
(0.253, 0.325, 0.387)	(0.192, 0.241, 0.272)	(0.206, 0.245, 0.266)	(0.023, 0.032, 0.040)	(0.00, 0.00, 0.00)	(0.394, 0.516, 0.611)	(0.256, 0.320, 0362)	(0.00, 0.00, 0.00)	(0.333, 0.379, 0.489)	(0.198, 0.223, 0.288)	(0.091, 0.102, 0.129)

Table 4.7 Weighted normalized fuzzy decision matrix (continued)

	A1	A2	A2	A4

When determining the FPIS values, the vector elements are assigned a value of 1 if the criterion in question is a benefit criterion and 0 if it is a cost criterion. The opposite is true when determining the FNIS values. The FPIS and FNIS values are determined using the weighted fuzzy decision matrix as follows:

A^* = [(1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (0, 0 ,0), (0, 0 ,0), (0, 0 ,0), (0, 0 ,0), (0, 0 ,0), (1, 1, 1), 1, 1, 1), 1, 1, 1)]

A^- = [(0, 0 ,0), (0, 0 ,0), (0, 0 ,0), (0, 0 ,0), (0, 0 ,0), (0, 0 ,0), (0, 0 ,0), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (0, 0, 0), (0, 0, 0), (0, 0, 0))]

The distance of the alternatives from A^* and A^- are calculated using the Equation (1.20) and the Equation (1.21) respectively. The distance of the alternatives from A^*(d^*) according to each criterion is shown in Table 4.8:

Table 4.8 Distance of the alternatives from A^* (d^*)

C4	C4.3	0.982	0.983	0.983	0.983
	C4.2	0.640	0.588	0.605	0.587
	C4.1	0.611	0.509	0.535	0.561
C3	C3.4	0.000	0.000	0.000	0.000
	C3.3	0.121	0.108	0.107	0.108
	C3.2	0.249	0.231	0.231	0.239
	C3.1	0.455	0.411	0.411	0.406

Table 4.8 Distance of the alternatives from A^* (d^*) (continued)

		A1	A2	A3	A4
C1	C1.1	0.684	0.659	0.637	0.681
	C1.2	0.777	0.773	0.765	0.766
	C1.3	0.793	0.790	0.779	0.761
	C1.4	0.967	0.964	0.965	0.968
	C1.5	1.000	1.000	1.000	1.000
C2	C2.1	0.457	0.440	0.493	0.501
	C2.2	0.692	0.692	0.688	0.688
	C2.3	0.000	0.000	0.000	0.000

The distance of the alternatives from A^- (d^-) according to each criterion is shown in Table 4.9:

Table 4.9 Distance of the alternatives from A^- (d^-)

C3	C3.3	0.882	0.893	0.895	0.893
	C3.4	1.000	1.000	1.000	1.000
C4	C4.1	0.398	0.494	0.471	0.447
	C4.2	0.364	0.415	0.401	0.417
	C4.3	0.018	0.017	0.017	0.017

Table 4.9 Distance of the alternatives from A^- (d^-) (continued)

C3	C3.2	0.754	0.771	0.771	0.765
	C3.1	0.558	0.596	0.571	0.603
C2	C2.3	1.000	1.000	1.000	1.000
	C2.2	0.311	0.312	0.316	0.316
	C2.1	0.551	0.570	0.520	0.515
C1	C1.5	0.000	0.000	0.000	0.000
	C1.4	0.034	0.036	0.036	0.032
	C1.3	0.211	0.213	0.224	0.240
	C1.2	0.226	0.230	0.237	0.237
	C1.1	0.322	0.345	0.368	0.326
		A1	A2	A3	A4

Accordingly, the total d^* and d^- values of the alternatives will be as in Table 4.10:

Table 4.10 Total d^* and d^- values of the alternatives

Alternative	d^*	d^-
A1	8.427	6.629
A2	8.149	6.894
A3	8.230	6.827
A4	8.250	6.808

Based on the above values, the closeness coefficient (CC_i) and the ranking of the alternatives is determined using the Equation (1.22) as shown in Table 4.11:

Table 4.11 The closeness coefficient (CC_i) and the ranking of the alternatives

Alternative	Closeness Coefficient (CC_i)	Rank
A1	0.440	4
A2	0.458	1
A3	0.453	2
A4	0.452	3

The ranking of the proposed smart waste management strategy alternatives according to the above closeness coefficients is A2 > A3 > A4 > A1.

The results show that considering the selected criteria, the application PAYT, which uses blockchain technology, has the best performance among the proposed smart sustainable waste management strategies. Among the two strategies with very close CC_i values, IoT-based community composting is slightly ahead of IoT-based illegal sewage discharge prevention by only 0.001 difference. The strategy of integrating illegal waste collection workers into a formal smart system came in last with the lowest CC_i value compared to others.

4.3 Sensitivity Analysis

In multi-criteria decision-making, sensitivity analysis is used to test the consistency of the ranking obtained and to be sure of the result obtained. In studies where hybrid MCDM is used, researchers usually perform sensitivity analysis using scenarios in which the original criteria weights are changed to varying degrees [124].

In this study, a sensitivity analysis is performed with eighteen different scenarios in which the weighting of the criteria is changed. In the first ten scenarios, the weight of each of the ten benefit criteria is increased by 25%. In Scenarios 11 - 15, the weight of each of the five cost criteria is increased by 25%. In Scenario 16, the weight of the criterion with the highest weight in each main criteria group is reduced by 50%. In Scenario 17, the weight of the criterion with the highest weight in each main criterion group is assumed to be 1 and all other criterion weights are assumed to be 0. Finally, in Scenario 18, the weights of the criteria are chosen to be the same in each main criteria group. Accordingly,

the new closeness coefficient values (CC_i) of the alternatives after the sensitivity analysis are obtained as in Table 4.12:

Table 4.12 The new closeness coefficient values (CC_i) of the alternatives

Scenario	C_I(A1)	C_I(A2)	C_I(A3)	C_I(A4)
1	0.440	0.458	0.454	0.451
2	0.441	0.458	0.453	0.452
3	0.440	0.458	0.453	0.452
4	0.441	0.459	0.455	0.453
5	0.440	0.458	0.453	0.452
6	0.440	0.458	0.453	0.451
7	0.440	0.458	0.454	0.453
8	0.439	0.458	0.453	0.451
9	0.440	0.457	0.453	0.452
10	0.440	0.458	0.453	0.452
11	0.440	0.458	0.453	0.452
12	0.440	0.458	0.453	0.452
13	0.440	0.458	0.454	0.452
14	0.440	0.458	0.453	0.452
15	0.440	0.458	0.453	0.452
16	0.410	0.423	0.419	0.417
17	0.437	0.458	0.450	0.443
18	0.408	0.422	0.417	0.413

The results of the sensitivity analysis show that the ranking of the alternatives obtained with the fuzzy AHP- fuzzy TOPSIS hybrid approach remain unchanged when the criteria weights are varied. This can be illustrated in the radar chart in Figure 4.1, which shows the very small difference in the closeness coefficient values of the alternatives when the sensitivity analysis is performed:

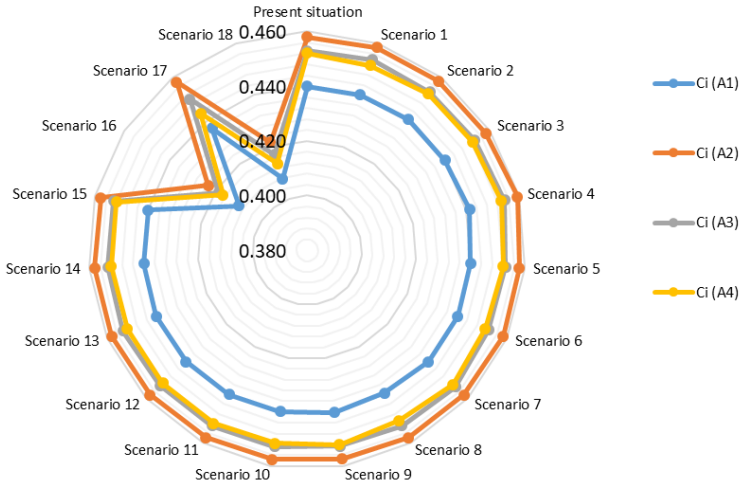


Figure 4.1 The change in the CC_i values of the alternatives

In all eighteen scenarios, the application PAYT which uses blockchain technology (A1) took first place in the ranking of alternatives with the highest closeness coefficient value. IoT-based community composting (A2) follows. Although they have very close CC_i values as in the present results, preventing illegal sewage discharge by utilizing IoT (A3) performed slightly better than integrating informal recyclable waste collection into an Iot-based formal system (A4). Although no significant change in the closeness coefficients occurred in the first sixteen scenarios in which the criterion weights were increased or decreased at specific rates, it was found that the weights changed in the 16th scenario, in which the criterion weights were assigned values of 1 and 0, and in the 17th scenario, in which the criterion weights were assigned values of 1 and 0. However, this situation did not affect the ranking of the alternatives. This confirms the reliability and the stability of the results obtained from the hybrit fuzzy AHP-TOPSIS approach.

4.4 Implications for Smart Sustainable Waste Management

To contribute to filling the knowledge gap in determining smart sustainable waste management strategies using fuzzy multi-criteria decision-making methods, four different smart sustainable waste management strategies were evaluated with a hybrid fuzzy AHP-TOPSIS approach. After identifying the alternatives that include smart sustainable waste management strategies, fifteen sub-criteria related to the main environmental, technical, economic and social criteria groups to be considered in the evaluation of the strategies in the study were selected from the literature, and their weights

were assigned using fuzzy AHP in accordance with subjective expert opinions. Less atmospheric emissions, operational feasibility, initial investment costs, and increased awareness on sustainable cities were the most important criteria in their groups. The fact that operational feasibility and initial investment costs are the most important technical and economic criteria, respectively, according to the expert evaluations confirms that smart sustainable waste management strategies require very careful and detailed planning before they are implemented.

After weighting the criteria, the fuzzy TOPSIS method was used to rank the performance of the proposed strategies in the presence of the mentioned criteria, again in accordance with the subjective expert opinions. A Pay as You Throw Application Leveraging Blockchain Technology (A2) took the first place with the highest closeness coefficient (CC_i). The long-term success and acceptance of such a waste management strategy is directly related to the conditions and needs of the region in which it is implemented. The main disadvantage of the system can be the illegal dumping of waste, depending on the level of development of the place where the system is introduced. Therefore, this strategy also results in the need for preventive legal regulations and strict controls. The strategy proposed in the study was designed to be the subject of a pilot study. In this way, the applicability of the system and its acceptance by the residents of the city will be tested.

The second-ranked IoT-based Community Composting (A3) has a CC_i value that is only 0.001 higher than the third-ranked Preventing Illegal Sewage Discharge by Utilizing IoT (A4) In such cases, where the two alternatives have such close CC_i values, a multi-tiered approach in decision-making can be carried out by applying a Life Cycle Analysis (LCA) and/or SWOT Analysis in parallel with the hybrid fuzzy MCDM application to support the result obtained.

To observe whether different criterion weights change the performance rankings of the alternatives, a sensitivity analysis was performed with eighteen different scenarios in which criterion weights were increased or decreased to varying degrees. After the analysis, the change in the values of the closeness coefficients (CC_i) of the alternatives was very small and the initial ranking did not change in any of the scenarios. In this way, the robustness of the results obtained in the study was confirmed.

4.5 Final Outcomes and Limitation of the Study

The long-term success of smart sustainable waste management strategies depends on the extent to which they meet the needs and expectations of the city in which they are implemented and how compatible they are with the sustainability goals of local governments. This makes these strategies multivariate, multi-restrictive, and multi-stakeholder, which complicates the determination processes. In this study, it was shown that decision-makers can benefit from a hybrid fuzzy AHP-TOPSIS approach when determining sustainable waste management strategies in smart cities. The present study also revealed that authorities should give due consideration to operational feasibility and initial investment costs before implementing such strategies. In future studies, piloting the proposed smart waste management strategies will allow decision-makers to make more concrete assessments by identifying the strengths and weaknesses of the strategies and testing their applicability. Furthermore, decision-making processes can be more strongly supported in this way by applying an LCA or SWOT analysis in parallel with a hybrid fuzzy AHP-TOPSIS approach.

Although the smart sustainable waste management strategies proposed in the study are comprehensive and multi-level, no specific city, residential area, or pilot region was chosen as the application site for the strategies. For this reason, the proposed strategies were determined to encompass more general approaches without sharp boundaries. However, the needs and expectations of city residents, as well as local government plans and goals for a sustainable environment and economy, require that these strategies be implemented at different scales and with different adaptations.

Since the proposed strategies in the study were handled in a more general way, the evaluations of the decision makers were also made in this way. But take, for example, the inclusion of illegal waste collection workers in a formal smart system. Since the human factor is involved here, the data obtained through preliminary interviews with potential workers to be included in the system will help make the expert evaluations in the decision-making processes healthier. Or consider the PAYT application based on Blockchain. Before implementing this strategy, knowing the main goals of the authorities (e.g., reducing the amount of household waste generated annually, increasing the amount of waste recycled annually, etc.) could put the decision makers' assessments on a more realistic footing in terms of costs, operational feasibility, and acceptance.

Local governments are primarily responsible for ensuring environmental and economic sustainability in cities. In addition, most waste management services are provided by municipalities. This makes them one of the most important stakeholder groups in the integration of smart city technologies into sustainable waste management. In forming the decision-making group in the study, experts working in the smart city departments of various municipalities were reached, but although some of the experts provided positive feedback, they did not participate in the mailed questionnaires. For this reason, in the part of the study where the criteria and alternatives are evaluated verbally, there is no opinion of a smart city expert working in the public sector.

REFERENCES

[1] United Nations Department of Economic and Social Affairs, Population Division (2019). World Urbanization Prospects 2018: Highlights (ST/ESA/SER.A/421).

[2] Our World in Data, https://ourworldindata.org/urbanization#what-share-of-people-will-live-in-urban-areas-in-the-future, 27.01.2023.

[3] United Nations Human Settlements Programme (UN-Habitat), World Cities Report 2020: The Value of Sustainable Urbanization, 2020.

[4] United Nations Environment Programme, Emissions Gap Report 2019, 2019.

[5] United Nations, https://www.unwater.org/app/uploads/2018/10/WaterFacts_water_and_urbanization_sep2018.pdf, 31.10.2020.

[6] A. Camero, E. Alba, "Smart City and information technology: A review", Cities, vol. 93, pp. 89–94, 2019.

[7] R.E. Hall, B. Bowerman, J. Braverman, J. Taylor, H. Todosow and U. Von Wimmersperg, "The vision of a smart city", Brookhaven National Lab, vol. 1, 2000.

[8] C. Harrison, B. Eckman, R. Hamilton, P. Hartswick, J. Kalagnanam, J. Paraszczak and P. Williams, "Foundations for smarter cities", IBM Journal of research and development, vol. 54, pp. 1-16, 2010.

[9] A. Caragliu, C. Del Bo and P. Nijkamp, "Smart cities in Europe. Journal of urban technology", vol. 18, pp. 65-82, 2011.

[10] C. Manville, G. Cochrane, J. Cave, , J. Millard, J.K. Pederson, R.K. Thaarup, A. Liebe, M. Wissner and R. Massink, "Mapping smart cities in the EU", EPRS: European Parliamentary Research Service, 2014.

[11] R.P. Dameri, "Searching for Smart City definition: a comprehensive proposal", nternational Journal of Computers & Technology, vol. 11, pp. 2544–2551, 2013.

[12] M. Eremia, L. Toma, and M. Sanduleac, "The Smart City Concept in the 21st Century", Procedia Engineering, vol. 181, pp. 12–19, 2017.

[13] A.S Syed, D. Sierra-Sosa, A. Kumar, and A. Elmaghraby, "IoT in Smart Cities: A Survey of Technologies, Practices and Challenges", Smart Cities, vol. 4, pp. 429–475, 2021.

[14] S. Chatterjee, A.K. Kar, and M.P. Gupta, "Success of IoT in smart cities of India: An empirical analysis", Government Information Quarterly, vol. 35, pp. 349–361, 2018.

[15] P. Mell, T. Grance, "The NIST Definition of Cloud Computing", Special Publication (NIST SP), vol. 800–145, 2011.

[16] E. Giovannoni, G. Fabietti, "What Is Sustainability? A Review of the Concept and Its Applications", Integrated Reporting, pp. 21–40, 2013.

[17] T. Kuhlman and J. Farrington, "What is sustainability?", Sustainability, vol. 2, pp. 3436–3448, 2010.

[18] R. Goodland, “The Concept of Environmental Sustainability”, Annual Review of Ecology and Systematics, vol. 26, pp. 1–2, 1995.

[19] R. Morelli, “Environmental Sustainability: A Definition for Environmental Professionals”, Journal of Environmental Sustainability, vol. 1, pp. 1–9, 2011.

[20] J.K. Seadon, “Sustainable waste management systems”, Journal of Cleaner Production, vol. 18, pp. 1639–1651, 2010.

[21] J. Petts, “Municipal waste management: inequities and the role of deliberation”, Risk Analysis, vol. 20(6), pp. 821–832, 2000.

[22] J. Nilsson-Djerf, F. McDougall, “Social factors in sustainable waste management”, Warmer Bulletin, vol. 73, pp. 18–20, 2000.

[23] B. Esmaeilian, B. Wang, K. Lewis, F. Duarte, C. Ratti, and S. Behdad, “The future of waste management in smart and sustainable cities: A review and concept paper”, Waste Management, vol. 81, pp. 177–195, 2018.

[24] M.A Hannan, M.D.A. Al Mamuna, A. Hussain, H. Basri, and R.A Begum, “A review on technologies and their usage in solid waste monitoring and manage-ment systems: Issues and challenges”, Waste Management, vol. 43, pp. 509–523, 2015.

[24] O.M Johannson, “The effect of dynamic scheduling and routing in a solid waste management system”, Waste Management, vol. 26, pp 875–885, 2006.

[26] S. Sener, E. Sener, B. Nas, and R. Karaguzel, “Combining AHP with GIS for landfill site selection: Acase study in the Lake Beysehir catchment area (Konya, Turkey)”, Waste Management, vol. 30, pp. 2037–2046, 2010.

[27] M.A Hannan, M. Arebey, R.A Begum, and H. Basri,“Radio Frequency Identification (RFID) and communication Technologies for solid waste bin and truck monitoring system”, Waste Management, vol. 31, pp. 2406–2413, 2011.

[28] Y. Glouche, P. Couderc, “A Smart Waste Management with Self-Describing objects”, The Second International Conference on Smart Systems, Devices and Technologies (SMART’13), IARIA, 2013, pp. 62–70.

[29] T.T Anagnostopoulos, Z. Zaslavsky, and A. Medyedev, “Robust Waste Collection exploiting Cost Efficiency of IoT potentiality in Smart Cities”, 1st IEEE International Conference on Recent Advances in Internet of Things, RIoT 2015, 2015, pp. 1–6.

[30] Z. Wena, S. Hua, D. De Clercq, M.B Beck, H. Zhang, , F. Fei, and J. Liu, “Design, implementation, and evaluation of an Internet of Things (IoT) network system for restaurant food waste management”, Waste Management, vol. 73, pp. 26–38, 2017.

[31] K.D Kang, H. Kang, I.M.S.K. Ilankoon, and C.Y Chong, “Electronic waste collection systems using Internet of Things (IoT): Household electronic waste management in Malaysia”, Journal of Cleaner Production, vol. 252, 119801, 2020.

[32] P. Jiang, Y. Van Fan, J. Zhou, M. Zheng, X. Liu, and J.J. Klemeš, “Data-driven analytical framework for waste-dumping behaviour analysis to facilitate policy regulations”, Waste Management, vol. 103, pp. 285–295, 2020.

[33] S. Gopikumar, S. Raja, Y.H Robinson, V. Shanmuganathan, and S. Rho, “A Method of Landfill Leachate management using Internet of Things for Sustainable Smart city development”, Sustainable Cities and Society, vol. 66, 2020.

[34] R. Senthilkumar, P. Venkatakrishnan, and N. Balaji, “Intelligent Based Novel Embedded System Based IoT Enabled Air Pollution Monitoring System”, Microprocessors and Microsystems, vol. 77, 2020.

[35] T.A Khoa, C.H Phuc, P.D Lam, L.M.B. Nhu, N.M Trong, N.T.H Phuong, N.V Dung, N. Tan-Y, H.N Nguyen, and D.N.M Duc, "Waste Management System Using IoT-Based Machine Learning in University", Wireless Communications and Mobile Computing, vol. 2020, 2020.

[36] T. J. Sheng, M.S Islam, N. Misran, M.H. Baharuddin, H. Arshad, M.D.R. Islam, M.E. H. Chowdhury, H. Rmili, and M.T Islam, "An Internet of Things Based Smart Waste Management System Using LoRa and Tensorflow Deep Learning Model," IEEE Access, vol. 8, pp. 148793-148811, 2020.

[37] T.D. Mastos, A. Nizamis, T. Vafeiadis, N. Alexopoulos, C. Ntinas, D. Gkortzis, A. Papadopoulos, D. Ioannidis, and D. Tzovaras, “Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution”, Journal of Cleaner Production, vol. 269,122377, 2020.

[38] M. Kassou, S. Bourekkadi, S. Khoulji, K. Slimani, H. Chikri, and M.L. Kerkeb, “Blockchain-based medical and water waste management conception”, E3S web of conferences, EDP Sciences, 2021, p. 00070.

[39] Y.S. Gupta, S. Mukherjee, R. Dutta, and S. Bhattacharya, “A blockchain-based approach using smart contracts to develop a smart waste management system”, Int. J. Environ. Sci. Technol, vol.19, pp. 7833–785, 2022.

[40] C. Kahraman, Ed., Fuzzy multi-criteria decision making: theory and applications with recent developments, New York, NY, US: Springer Science & Business Media, 2008.

[41] T. Aouam, S.I. Chang, S and E.S. Lee, “Fuzzy MADM: An outranking method. European Journal of Operational Research”, vol. 145, pp. 317-328, 2003.

[42] X. Jin, “Approaching sustainability in engineering design with multiple criteria decision analysis”, Doctoral dissertation, Oklahama State University, 1996.

[43] R. Lahdelma, P. Salminen, and J. Hokkanen, “Using Multicriteria Methods in Environmental Planning and Management”, Environmental Management, vol. 26, pp. 595–605, 2000.

[44] E. Triantaphyllou, Multi-Criteria Decision Making Methods: A Comparative Study. Kluwer Academic Publishers, 2000.

[45] M. Bogurcu, Investigation Of Sectoral Priorities For Cleaner (Sustainable) Production At Regional And National Level, Master’s thesis, The Graduate School Of Natural And Applied Sciences, Middle East Technical University, Ankara, 2012.

[46] A. Taskin Gumus, “Evaluation of hazardous waste transportation firms by using a two step fuzzy-AHP and TOPSIS methodology”, Expert Systems with Applications, vol. 36, pp. 4067–4074, 2009.

[47] R.E. Bellman and L.A. Zadeh, “Decision making in a fuzzy environment”, Management Science, vol. 17, pp. 141–164, 1970.

[48] H.J. Zimmermann, “Fuzzy programming and linear programming with several objective functions”, Fuzzy Sets and Systems, vol. 1, 45–55,1978.

[49] M. Dursun and E.E. Karsak, "A fuzzy MCDM approach for personnel selection", Expert Systems with Applications, vol. 37, pp. 4324-4330, 2010.

[50] H.M. Wang Chen, S.Y. Chou, Q.D. Luu, and T.H.K. Yu, "A fuzzy MCDM approach for green supplier selection from the economic and environmental aspects" Mathematical Problems in Engineering, 2016.

[51] M. Kabak, S. Burmaoğlu and Y. Kazançoğlu, "A fuzzy hybrid MCDM approach for professional selection", Expert Systems with Applications, vol. 39, pp. 3516–3525, 2012.

[52] P.J.M. Van Laarhoven and W. Pedrycz, "A fuzzy extension of Saaty's priority theory, Fuzzy Sets and Systems", vol. 11, pp. 229–241, 1983.

[53] Da-Yong. C, "Applications of the extent analysis method on fuzzy AHP", European journal of operational research, vol. 95, pp. 649–655, 1996.

[54] E. Dursun, "Bulanik Ahp Yöntemi ile Tedarikçi Seçimi ve Tekstil Sektöründe Bir Uygulama", Master's thesis, The Graduate School of Science Engineering and Technology, Istanbul Technical University, 2009.

[55] C. Kim and J.-S. Won, "A Fuzzy Analytic Hierarchy Process and Cooperative Game Theory Combined Multiple Mobile Robot Navigation Algorithm," Sensors, vol. 20, p. 2827, 2020.

[56] C.L. Hwang, and K. Yoon, Multiple Attribute Decision Making: Methods and Applications, Springer, Berlin, Heidelberg, New York, 1981.

[57] C-T. Chen, C-T. Lin, and S-F. Huang, "A Fuzzy Approach for Supplier Evaluation and Selection in Supply Chain Management", International Journal of Production Economics, vol. 102, pp. 289–301, 2006.

[58] N. Alptekin, E. Eroglu Hall and N. Sevim, "Evaluation of Websites Quality Using Fuzzy TOPSIS Method", International Journal of Academic Research in Business and Social Sciences, vol. 5, pp: 221–242, 2015.

[59] C. Achillas, N. Moussiopoulos, A. Karagiannidis, G. Banias, and G. Perkoulidis, "The use of multi-criteria decision analysis to tackle waste management problems: a literature review", Waste Management & Research, vol. 31, pp. 115–129, 2013.

[60] M.M. Sobral, K.W Hipel, and G.J. Farquhar, "A multi-criteria model for solid waste Management", Journal of Environmental Management" vol. 12, pp. 97–110, 1981.

[61] E. Erkut, S.R Moran, "Locating Obnoxious Facilities in the Public Sector: An Application of the Analytic Hierarchy Process to Municipal Landfill Siting Decisions", Socio-Economic Planning Sciences, vol. 25, pp. 89–102, 1991.

[62] R. Banai, "Fuzziness in Geographical Information Systems: contributions from the analytic hierarchy process", International Journal of Geographical Information Systems, vol. 7, pp. 315–329, 1993.

[63] K. Charnpratheep, Q. Zhou, and B.Garner, "Preliminary Landfill Site Screening Using Fuzzy Geographical Information Systems", Waste Management & Research, vol. 15, pp. 197–215, 1997.

[64] J.P Su, P.T Chiueh, M.L Hung, and H.W Ma, "Analyzing policy impact potential for municipal solid waste management decision-making: A case study of Taiwan", Resources, Conservation and Recycling, vol. 51, pp. 418–434, 2007.

[65] S. Önüt, S. Soner, “Transshipment site selection using the AHP and TOPSIS approaches under fuzzy environment”, Waste Management, vol. 28, pp. 1552–1559, 2008.

[66] B.D. Xi, J. Su, G.H. Huang, X.S. Qin, Y.H Jiang, S.L. Huo, D.F. Ji, and B. Yao, “An integrated optimization approach and multi-criteria decision analysis for supporting the waste-management system of the City of Beijing, China”, Engineering Applications of Artificial Intelligence, vol. 23, pp. 620–631, 2010.

[67] M. Ekmekçioğlu, T. Kaya, and C. Kahraman, “Fuzzy multicriteria disposal method and site selection for municipal solid waste”,Waste Management, vol. 30, pp. 1729–1736, 2010.

[68] M. Ilangkumaran, V. Sasirekha, L. Anojkumar, G. Sakthivel, M. Boopathi Raja, T. Ruban Sundara Raj, C. Siddhartha, P. Nizamuddin and S. Praveen Kumar, "Optimization of wastewater treatment technology selection using hybrid MCDM", Management of Environmental Quality, vol. 24, pp. 619–641, 2013.

[69] A. Beskese, H.H. Demir, H.K. Ozcan and H.E. Ökten, “Landfill site selection using fuzzy AHP and fuzzy TOPSIS: a case study for Istanbul”, Environ Earth Sci, vol. 73, pp. 3513–3521, 2015.

[70] E. Arıkan, Z.T Şimşit-Kalender, Ö. Vayvay, “Solid waste disposal methodology selection using multi-criteria decision making methods and an application in Turkey”, Journal of Cleaner Production, vol. 142, pp. 403–412, 2017.

[71] S.J Kamble, A. Singh, and M.G. Kharat, “A hybrid life cycle assessment based fuzzy multi-criteria decision making approach for evaluation and selection of an appropriate municipal wastewater treatment technology”, Euro-Mediterr J Environ Integr, vol. 2, 2017.

[72] V.K Manupati, M. Ramkumar, V. Baba and A. Agarwal, “Selection of the best healthcare waste disposal techniques during and post COVID-19 pandemic era”, Journal of Cleaner Production, vol. 281, 125175, 2021.

[73] A. Gaur, H. Prakash, K. Anand, G. Kumar and A. Hussain, “Evaluation of Municipal Solid Waste Management Scenarios using Multi-Criteria Decision Making under Fuzzy Environment”, Process Integr Optim Sustain, vol. 6, pp. 307–321, 2022.

[74] Y. Ali, D.H Jokhio, A.A Dojki, O. Rehman, F. Khan, and A. Salman, “Adoption of circular economy for food waste management in the context of a developing country”, Waste Management & Research, vol. 40, pp. 676–684, 2022.

[75] N. Van Thanh, “Optimal Waste-to-Energy Strategy Assisted by Fuzzy MCDM Model for Sustainable Solid Waste Management”, Sustainability, vol. 14, 6565, 2022.

[76] K. Albayrak, “A hybrid fuzzy decision making approach for sitting a solid waste energy production plant”, Soft Comput, vol. 26, pp. 575–587, 2022.

[77] M. Topaloglu F. Yarkin and T. Kaya, “Solid waste collection system selection for smart cities based on a type-2 fuzzy multi-criteria decision technique”, Soft Computing, vol. 22, pp. 4879–4890, 2018.

[78] A. Chauhan, S.K Jakhar and C. Chauhan, “The interplay of circular economy with industry 4.0 enabled smart city drivers of healthcare waste disposal”, Journal of Cleaner Production, Volume 279, 2021.

[79] S. Seker, “IoT based sustainable smart waste management system evaluation using MCDM model under interval-valued q-rung orthopair fuzzy environment”, Technology in Society, vol. 71, 2022.

[80] M. Yörükoğlu and S. Aydın, “Assessment of Smart Waste Management Systems with Spherical AHP Method”, Artificial Intelligence for Knowledge Management, Energy, and Sustainability, AI4KMES 2021.IFIP Advances in Information and Communication Technology, 2022, vol 637.

[81] A. Scheinberg, Value Added: Modes of Sustainable Recycling in the Modernisation of Waste Management Systems, Doctor of Philosophy, Wageningen University, Wageningen, 2011.

[82] F. Fei, L. Qua, Z. Wena, Y. Xueb, and H. Zhanga, “How to integrate the informal recycling system into municipal solid waste management in developing countries: Based on a China’s case in Suzhou urban area”, Resources, Conservation and Recycling, vol. 110, pp. 74-86, 2016.

[83] M. Masood, and C.Y. Barlow, “Framework for integration of informal waste management sector with the formal sector in Pakistan”, Waste management & Research, vol. 31, pp. 93-105, 2013.

[84] A. Scheinberg, M. Simpson, and Y. Gupt, “Economic Aspects of the Informal Sector in Solid Waste Management”, GTZ and CWG, 2010.

[85] H.C. Haan, A. Coad, and I. Lardinois, Municipal waste management: Involving micro-and-small enterprises, Guidelines for municipal managers, First Edition, International Training Centre of the ILO, SKAT, WASTE, Turin, 1998.

[86] Guidelines For Integration of Informal Waste Collectors, http://mdctinet.org.mk/images/pdf/Guidelines%20for%20integration%20of%20informal%20waste%20collector.pdf, 12.06.2022.

[87] M. Medina, “The Informal Recycling Sector in Developing Countries: Organizing Waste Pickers to Enhance Their Impact”, Gridlines, vol. 44, 2008.

[88] H. Yang, M. Ma, J.R. Thompson, and R.J. Flower, R. J, “Waste management, informal recycling, environmental pollution and public health”, Journal of Epidemiology and Community Health, vol. 72, pp. 237-243, 2018.

[89] D. Offenhuber and D. Lee, “Putting the informal on the map: tools for participatory waste management”, 12th Participatory Design Conference, 2012, pp. 13–16.

[90] Integrating the informal sector for improved waste management, https://blog.private-sector-and-development.com/2012/11/12/integrating-informal-sector-for-improved-waste-management/, 22.09.2022.

[91] Eskisehir Tepebasi Municipality, Tepebasi GESIKOOP Project, https://www.tepebasi.bel.tr/hd.asp?hid=10627, 14.10.2021.

[92] Y. Xue, Z. Wen, H. Bressers, and N. Ai, “Can intelligent collection integrate informal sector for urban resource recycling in China?”, Journal of Cleaner Production, vol. 208, pp. 307-315, 2019.

[93] J. Reichenbach, “Status and prospects of pay-as-you-throw in Europe – A review of pilot research and implementation studies”, Waste Management, vol. 28, pp. 2809-2814, 2008.

[94] J.Morlok, H. Schoenberger, D. Styles, J.L. Galvez-Martos, and B.Zeschmar-Lahl, “The Impact of Pay-As-You-Throw Schemes on Municipal Solid Waste Management: The Exemplar Case of the County of Aschaffenburg, Germany”, Resources, vol. 6, p. 8, 2017.

[95] L. Alves, S. Silva, and I. Soares, “Waste management in insular areas: A Pay-As-You-Throw system in Funchal”, Energy Reports, vol. 6, pp. 31–36, 2020.

[96] B. Bilitewski, “From traditional to modern fee systems”, Waste Management, vol. 28, pp. 2760-2766, 2008.

[97] V.Elia, M. Grazia Gnoni, and F. Tornese, “Designing Pay-As-You-Throw schemes in municipal waste management services: A holistic approach”, Waste Management, vol. 44, pp. 188-195, 2015.

[98] L. Dahlén and A. Lagerkvist, “Pay as you throw: Strengths and weaknesses of weight-based billing in household waste collection systems in Sweden”, Waste Management, vol.30, pp. 23-31

[99] P. van der Werf, K. Larsen, J.A. Seabrook, and J. Gilliland, “How neighbourhood food environments and a pay-as-you-throw (PAYT) waste program impact household food waste disposal in the city of Toronto”, Sustainability, vol. 12, p. 7016, 2020.

[100] I. Hong, S. Park, B. Lee, J. Lee, D. Jeong, and S. Park, "IoT-Based Smart Garbage System for Efficient Food Waste Management", The Scientific World Journal, vol. 2014, 2014.

[101] K. Aravossis, E. Nikolaidou, and C. Fountzoula, “Solid Waste Management through a modern innovative PAYT system”, Third International Conference on Sustainable Solid Waste Management, 2015, pp. 2-4.

[102] J.L. Canterbury, Pay-As-You-Throw: Lessons Learned About Unit Pricing of Municipal Solid Waste, U.S. EPA - United States Environmental Protection Agency Office of Solid Waste, 1994.

[103] A. Ukkonen, and O. Sahimaa, “Weight-based pay-as-you-throw pricing model: Encouraging sorting in households through waste fees”, Waste Management, vol. 135, pp. 372-380, 2021.

[104] M.Vitoraki, “Implementation of pay-as-youthrow schemes in Greece: majör benefits and future potential”, DEREE – The American College of Greece 7th International Conference on Sustainable Solid Waste Management, 2019.

[105] P. Gopalakrishnan, J.F. Hall, and S. Behdad, “A Blockchain-Based Traceability System for Waste Management in Smart Cities”, ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2020.

[106] M.R Laouar, Z. Touati Hamad, and S. Eom, “Towards blockchain-based urban planning: Application for Waste Collection Management”, 9th International Conference on Information Systems and Technologies, 2019.

[107] UN: Record 193 million people faced food insecurity in 2021, https://www.aljazeera.com/news/2022/5/4/un-record-number-of-people-without-enough-to-eat-in-2021, 03.11.2022.

[108] United Nations Environment Programme (UNEP) Food Waste Index Report 2021, https://catalogue.unccd.int/1679_FoodWaste.pdf, 03.11.2022.

[109] Composting 101, https://www.nrdc.org/stories/composting-101, 04.11.2022.

[110] Food Matters in Baltimore: Reimagining Waste Into Wealth, https://www.nrdc.org/resources/food-matters-baltimore-reimagining-waste-wealth, 27.01.2023.

[111] Baltimore Food Matters Program, https://www.baltimoresustainability.org/projects/baltimore-food-matters-program/, 04.11.2022.

[112] Prescott Farmers Market Program, https://prescottfarmersmarket.org/community-compost/, 04.11.2022.

[113] Topraktan Topraga Biodegradable Waste Project https://ebrubaybarademir.com/topraktan-topraga-biyobozunur-atik-yonetim-projesi/, 04.11.2022.

[114] J. Růžičková, H. Raclavská, M. Kucbel, A. Grobelak, M. Šafář, K. Raclavský, B. Švédová, D. Juchelková and K. Moustakas, "The potential environmental risks of the utilization of composts from household food waste", Environmental Science and Pollution Research, vol. 28, pp. 24663–24679, 2021.

[115] Y. F. Pratama, E. Ariyanto and S. A. Karimah, "Prototype of Automation of Organic Fertilizer Manufacturing Systems Based on Internet of Things", 7th International Conference on Information and Communication Technology (ICoICT), 2019, pp. 1-6.

[116] Y. Nikoloudakis, S. Panagiotakis, T. Manios, E. Markakis, and E. Pallis, "Composting as a Service: A Real-World IoT Implementation", Future Internet, vol. 10, p. 107, 2018.

[117] T. Li, M. Winnel, H. Lin, J. Panther, C. Liu, R. O'Halloran, K. Wang, T. An, P.K. Wong, S. Zhang and H. Zhao, "A reliable sewage quality abnormal event monitoring system", Water Research, vol. 121, pp. 248-257, 2017.

[118] J. Rocher, D.A. Basterrechea, M. Taha, and J. Lloret, "Water conductivity sensor based on coils to detect illegal dumpings in smart cities", Fourth International Conference on Fog and Mobile Edge Computing (FMEC), 2019, pp. 324-329.

[119] J. Rocher, M. Parra, L. Parra, S. Sendra, J. Lloret, and J. Mengual, "A Low-Cost Sensor for Detecting Illicit Discharge in Sewerage", Journal of Sensors, vol. 2021, pp. 1-16, 2021.

[120] J. Rocher, J.L. García-Navas, O. Romero, and J. Lloret, "A WSN-based Monitoring System to Control Sewerage", Sixth International Conference on Internet of Things: Systems, Management and Security (IOTSMS), 2019, pp. 277-282.

[121] F. Solano, S. Krause, and C. Wöllgens, "An Internet-of-Things Enabled Smart System for Wastewater Monitoring", IEEE Access, vol. 10, pp. 4666-4685, 2022.

[122] P. Hammond, M. Suttie, V.T. Lewis, A.P. Smith, and A.C. Singer, "Detection of untreated sewage discharges to watercourses using machine learning", npj Clean Water, vol. 4, pp. 1-10, 2021.

[123] Multi-Criteria Decision Analysis (MCDA/MCDM), https://www.1000minds.com/decision-making/what-is-mcdm-mcda, 08.01.2023.

[124] S. Goyal, D. Garg, D. and S. Luthra, "Sustainable production and consumption: analysing barriers and solutions for maintaining green tomorrow by using fuzzy-

AHP–fuzzy-TOPSIS hybrid framework", Environment, Development and Sustainability, vol. 23, pp. 16934–16980, 2021.

A
REPRESENTATIVE SECTIONS FROM THE QUESTIONNAIRE

5. **TEKNİK ALT KRİTERLERİNİN AĞIRLIKLANDIRILMASI** *

Her satırda yalnızca bir şıkkı işaretleyin.

	Tamamıyla Önemli	Çok Kuvvetli Derecede Önemli	Kuvvetli Derecede Önemli	Biraz Daha Fazla Önemli	Eşit Derecede Önemli	Biraz Daha Fazla Önemli	Kuvvetli Derecede Önemli	Çok Kuvvetli Derecede Önemli	Tamamıyla Önemli
Operasyonel fizibilite——— Yenilikçilik	◯	◯	◯	◯	◯	◯	◯	◯	◯
Operasyonel fizibilite——— Nitelikli personel ihtiyacı	◯	◯	◯	◯	◯	◯	◯	◯	◯
Yenilikçilik——— Nitelikli personel ihtiyacı	◯	◯	◯	◯	◯	◯	◯	◯	◯

Figure A.1 Evaluation of technical sub-criteria in linguistic terms

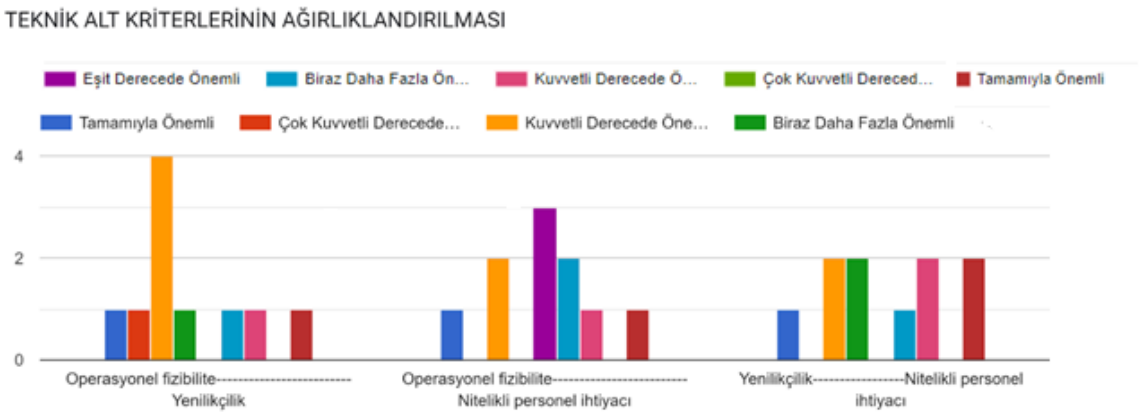


Figure A.2 Evaluation results of technical sub-criteria in linguistic terms (x-axis: number of experts)

10. **Daha az yüzey suları kirliliği** *

Her satırda yalnızca bir şıkkı işaretleyin.

	Çok İyi	İyi	Biraz İyi	Orta	Biraz Kötü	Kötü	Çok Kötü
Kayıtdışı atık toplama işçilerinin kooperatiflerin yer aldığı ve Bilgi ve İletişim Teknolojisi (BİT) araçlarının kullanıldığı kayıtlı atık toplama sistemine dahil edilmesi	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Blockchain teknolojisi ve Bilgi ve İletişim Teknolojisi (BİT) araçlarından yararlanan bir "Attığın Kadar Öde" (Pay As You Throw) uygulaması	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Toplum gönüllüleri ve yerel yönetimlerin işbirliği ile yürütülecek ve Bilgi ve İletişim Teknolojisi (BİT) araçlarından yararlanılan kompostlaştırma uygulaması	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Bilgi ve İletişim Teknolojisi (BİT) araçlarından yararlanarak kanalizasyon ve yüzey sularına vidanjörler ile yapılan kaçak atıksu deşarjlarının önüne geçen uygulama	⬭	⬭	⬭	⬭	⬭	⬭	⬭

Figure A.3 Evaluation of alternatives in linguistic terms according to less surface water pollution sub-criterion

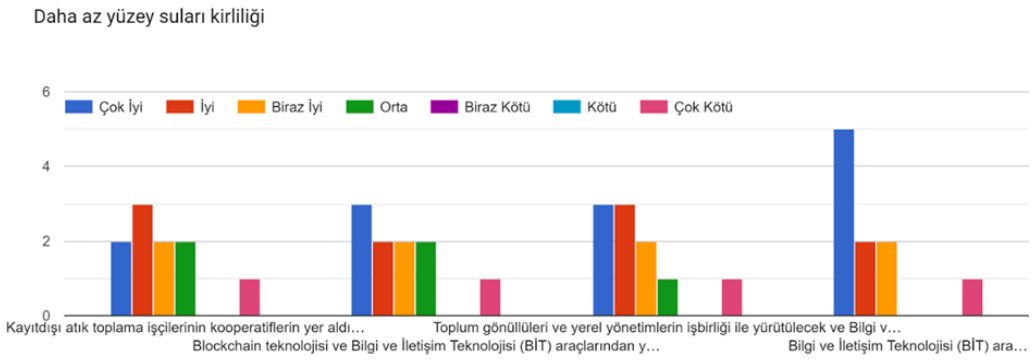


Figure A.4 Evaluation results of alternatives in linguistic terms according to less surface water pollution sub-criterion (x-axis: number of experts)

PUBLICATIONS FROM THE THESIS

Conference Papers

1. B.G. Demircan and K. Yetilmezsoy, "Akıllı Sürdürülebilir Atık Yönetimi Stratejilerinin Değerlendirilmesinde Bir Hibrit Bulanık AHP-TOPSIS Uygulaması", V. National Scientific and Vocational Studies Congress in Engineering, BILMES 2022, Session II, pp. 17-30, 16-18 December 2022, Turkey.

2. B.G. Demircan, "Determination Of Sustainable Waste Management Strategies In Smart Cities Using Fuzzy Multi Criteria Decision Making Approach", 5th Engineers of Future International Student Symposium, EFIS 2021, Session V, pp. 442-447