

STRATEGIC DECISION MAKING FOR RESILIENT URBAN LOGISTICS

(DİRENÇLİ KENTSEL LOJİSTİK İÇİN STRATEJİK KARAR VERME)

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LIST OF SYMBOLS

ADFBK	: Aralık Değerli Fermatean Bulanık Kümeleri
AHP	: Analytical Hierarchy Process
AHS	: Analitik Hiyerarşi Süreci
ANP	: Analytic Network Process
AOs	: Aggregation Operators
ARAS	: Additive Ratio Assessment
BRAW	: Block-wise Rating the Attribute Weights
BWM	: Best Worst Method
CoCoSo	: Combined Compromise Solution
CODAS	: Combinative Distance Based Assessment
COPRAS	: Complex Proportional Assessment
CRITIC	: Criteria Importance Through Intercriteria Correlation
CRs	: Customer Requirements
ÇKKV	: Çok Kriterli Karar Verme
DEA	: Data Envelopment Analysis
DEMATEL	: Decision Making Trial and Evaluation Laboratory
DMs	: Decision Makers
DRs	: Design Requirements
EDAS	: Evaluation based on Distance from Average Solution
ELECTRE	: Elimination Et Choix Traduisant la Realité
FFS	: Fermatean Fuzzy Sets
FUCOM	: Full Consistency Method
GDM	: Group Decision Making
HOQ	: House of Quality
ICT	: Information and Communication Technologies
IFS	: Intuitionistic Fuzzy Sets

IMM	: Istanbul Metropolitan Municipality
IoT	: Internet of Things
ISM	: Interpretive Structural Modelling
ITARA	: Indifference Threshold-based Attribute Ratio Analysis
IVFF	: Interval Valued Fermatean Fuzzy Sets
IVFFDWA	: Interval-Valued Fermatean Fuzzy Dombi Weighted Average
IVFFWA	: Interval-Valued Fermatean Fuzzy Weighted Average
KFG	: Kalite Fonksiyon Göçerimi
LOPCOW	: Logarithmic Percentage Change-Driven Objective Weighting
MABAC	: Multi-Attributive Border Approximation Area Comparison
MADM	: Multiple Attribute Decision-Making
MARCOS	: Measurement of Alternatives and Ranking according to Compromise Solution
MCDM	: Multi-Criteria Decision Making
MEREC	: Method based on the Removal Effects of Criteria
MULTIMOORA	: The Multi-Objective Optimization by Ratio Analysis
NIS	: Negative Ideal Solution
PFS	: Pythagorean Fuzzy Sets
PIS	: Positive Ideal Solution
QFD	: Quality Function Deployment
RUL	: Resilient Urban Logistics
RQs	: Research Questions
SAW	: Simple Additive Weighting
SD Model	: System Dynamics Model
SWARA	: Stepwise Weight Assessment Ratio Analysis
SWOT	: Strengths, Weaknesses, Opportunities, Threats
TODIM	: Iterative Multi-Criteria Decision Making
TOPSIS	: Technique For Order Preference By Similarity To An Ideal Solution
UR	: Urban Resilience
VIKOR	: VIseKriterijumsa Optimizacija I Kompromisno Resenje
YYM	: Yorumlayıcı Yapısal Modelleme
WASPAS	: Weighted Aggregated Sum Product Assessment

WoS : Web of Science
WSM : Weighted Sum Method



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ABSTRACT

As urban populations continue to expand, with accelerated urbanization, the significance of urban logistics has grown exponentially. Urban logistics, an essential concept for quality of life and sustainability in cities, aims to define and analyze logistical challenges within urban areas, develop effective solutions, and create models. The integration of city logistics activities with technology gives rise to the concept of “smart urban logistics”. This approach underscores the utilization of technology to optimize and enhance the efficiency of city logistics systems. However, with climate change and disasters increasingly affecting urban areas, it is important for urban logistics to anticipate such events and maintain operational continuity during crises. Hence, considering resilience principles before integrating smart technologies will be an effective strategy for urban logistics. Resilient Urban Logistics (RUL) emerges as a critical concept within this framework, stressing the need for urban logistics systems to withstand unforeseen disruptions. A detailed examination of urban resilience literature reveals a lack of studies directly focusing on RUL. This thesis aims to fill this gap by focusing on strategic aspects that directly impact RUL and proposing integrated approaches for its implementation. The study unfolds across four stages: proposing the RUL strategy evaluation model, analyzing critical success factors for RUL, planning RUL technological infrastructure, and identifying technological service providers using integrated Multi-Criteria Decision Making (MCDM) approaches. The analytical dimension of the proposed methodologies is addressed using the Interval-Valued Fermatean Fuzzy Sets (IVFFS) approach.

In the first stage, the thesis introduces a framework based on SWOT-integrated IVFF-AHP and IVFF-VIKOR methodologies. This framework helps in identifying RUL implementation strategies and selecting the most suitable approach. The subsequent stage employs the IVFF Interpretive Structural Modelling (ISM) approach to pinpoint critical success factors crucial for the successful implementation of RUL. The third phase contributes to planning the technological infrastructure by prioritizing RUL components

through the IVFF Quality Function Deployment approach (QFD). The final stage proposes a framework, consisting of IVFF-AHP and IVFF-VIKOR methodologies, to select the best technology provider.

The proposed approaches were applied to Istanbul based on assessments from industry experts. The results emphasize the importance of integrating urban logistics activities coherently with city planning decisions. Additionally, an integrated control center facilitating faster decision-making through technology integration and providing real-time visibility would be a significant strategy. The success of RUL is underscored by emphasizing multi-stakeholder collaboration, increased awareness of resilience, and effective technology integration. Another significant outcome highlighted in the thesis is the critical role of the Internet of Things (IoT) technology for RUL. The integration of IoT will strengthen the robustness of logistics operations in dynamic urban environments by offering advantages such as continuous monitoring, instant intervention, predictive maintenance, and enhanced transparency through real-time data.

This thesis contributes to the successful implementation of RUL by providing effective decision-making tools in urban logistics. The results offer a roadmap guiding researchers and practitioners in this field.

ÖZET

Gün geçtikçe kentsel nüfusun artması ve kentleşmenin hızlanmasıyla kentsel lojistiğin önemi katlanarak artmaktadır. Günümüzde şehirlerde yaşam kalitesi ve sürdürülebilirlik için önemli bir kavram olan kentsel lojistik, şehirlerdeki lojistik zorlukları tanımlamak ve analiz etmek, etkili çözümler ve modeller geliştirmek amacıyla ortaya çıkmıştır. Şehirlerdeki lojistik faaliyetlerin teknolojiyle entegrasyonu “akıllı kent lojistiği” kavramını doğurmaktadır. Bu yaklaşım, şehir lojistik sistemlerinin verimliliğini optimize etmek ve geliştirmek için teknolojinin kullanılmasının altını çizmektedir. Ancak iklim değişikliği ve felaketlerin kentsel alanları giderek daha fazla etkilediği düşünüldüğünde, kentsel lojistiğin bu tür olaylara hazırlıklı olması ve kriz zamanlarında operasyonel sürekliliği devam ettirebilmesi hayati önem taşımaktadır. Bu nedenle kentsel lojistik süreçlerinde akıllı teknolojileri entegre etmeden önce dirençlilik ilkelerine öncelik vermek etkili bir strateji olacaktır. Dirençli Kentsel Lojistik (DKL), bu çerçevede kentsel lojistiğin öngörülemeyen olaylara dayanabilmesi gerekliliğinin altını çizen bir kavram olarak ortaya çıkmıştır. Kentsel dirençlilik literatürünün ayrıntılı bir incelemesi, doğrudan DKL’i ele alan çalışmaların eksikliğini ortaya koymuştur. Bu tez, DKL’i doğrudan etkileyen stratejik konulara odaklanarak ve DKL’in başarıyla uygulanması için entegre yaklaşımlar önererek bu boşluğu doldurmayı amaçlamaktadır. Çalışma dört aşamadan oluşmaktadır: DKL strateji değerlendirme modelinin önerilmesi, DKL için kritik başarı faktörlerinin analiz edilmesi, DKL teknolojik altyapısının planlanması ve bütünlük Çok Kriterli Karar Verme (ÇKKV) yaklaşımlarını kullanarak teknolojik hizmet sağlayıcıların belirlenmesi. Önerilen metodolojilerin analitik boyutu Aralık Değerli Fermatean Bulanık Kümeleri (ADFBK) yaklaşımı ile ele alınmıştır.

Tezin ilk aşamasında, SWOT temelli bütünlük ADFBK-Analitik Hiyerarşi Süreci (AHS) ve ADFBK-VIKOR metodolojilerine dayanan bir çerçeve sunulmaktadır. Bu çerçeve, DKL uygulama stratejilerinin belirlenmesine ve en uygun yaklaşımın seçilmesine yardımcı olmaktadır. Sonraki aşamada, DKL’in başarılı bir şekilde

uygulanması için önem taşıyan kritik başarı faktörlerini belirlemek amacıyla ADFBK Yorumlayıcı Yapısal Modelleme (YYM) yaklaşımı kullanılmaktadır. Üçüncü aşama, ADFBK-Kalite Fonksiyon Göçerimi yaklaşımı (KFG) aracılığıyla DKL bileşenlerini önceliklendirerek teknolojik altyapının planlanmasına katkıda bulunmaktadır. Son aşamada, en iyi teknoloji sağlayıcıyı seçmek için ADFBK-AHS ve ADFBK-VIKOR metodolojilerinden oluşan bir çerçeve önerilmektedir.

Önerilen yaklaşımlar, endüstriyel uzmanların değerlendirmeleri alınarak İstanbul için uygulanmıştır. Elde edilen sonuçlar, kentsel lojistik faaliyetlerinin şehir planlama kararlarıyla bütünlük içinde ele alınmasının önemini vurgulamaktadır. Aynı zamanda, teknoloji entegrasyonunu sağlayarak hızlı karar almayı kolaylaştıran ve gerçek zamanlı görünürlük sunan entegre bir kontrol merkezinin önemli bir strateji olacağı belirtilmektedir. DKL başarısının çok paydaşlı iş birliği, dirençliliğe olan farkındalığın artırılması ve etkili teknoloji entegrasyonu ile elde edilebileceği vurgulanmaktadır. Tezin ortaya koyduğu bir diğer önemli sonuç, Nesnelerin İnterneti teknolojisinin DKL için kritik bir araç olduğudur. Bu teknolojinin entegrasyonu, sürekli izleme, anlık müdahale, öngörücü bakım ve gelişmiş şeffaflık gibi avantajlar sunarak gerçek zamanlı veri sağlayacak ve dinamik kentsel ortamlarda lojistik operasyonlarının sağlamlığını güçlendirecektir.

Bu tez, kentsel lojistikte etkin karar verme araçları sunarak, DKL'in başarılı bir şekilde hayata geçirilmesine katkı sağlamaktadır. Elde edilen sonuçlar, araştırmacılara ve uygulayıcılara rehberlik eden bir yol haritası sunmaktadır.

1. INTRODUCTION

1.1. Smart Cities

Cities are dynamic and constantly evolving hubs of life, innovation, and development. However, challenges such as population shifts, migration, climate change, rapid and uncontrolled urbanization can lead to transportation, health, education, energy, water, waste, and environmental management issues, creating bottlenecks that need to be addressed. In such situations, cities need to make the most efficient use of their limited resources (Deloitte, 2015). To overcome these challenges and to make cities more advanced, the concept of the “smart city” has emerged, encouraging cities to become smarter and more efficient. Below are some of the definitions found in literature.

The concept of smart city is extremely wide and complex, and there are many different definitions in the literature since there is no single definition which is generally accepted. Some of these definitions are given below.

- Harrison et al. (2010) describes smart city as: *“an instrumented, interconnected, and intelligent city.”*
- Caragliu et al. (2011) describes as: *“a city that invests in human and social capital and traditional and modern communication infrastructure, has sustainable economic growth and a high quality of life, and manages natural resources, through participatory governance.”*
- Javidroozi et al. (2014) defines it as: *“an integration of the systems within a city and change their business processes in order to provide access to real time information and knowledge by all sectors and enhance communication between them.”*

- Urban sustainability directors network (2017) defines smart city as: *“collecting advanced information and communication technologies, communicating, and analyzing data to improve the design and operations of a city’s core systems and programs, as well as citizen engagement for greater efficiency, thus improving the city’s sustainability, resilience, bottom line and quality of life.”*
- Pieroni et al. (2018) describes it as: *“an integrated system in which human and social capital heavily interact, using technology-based solutions.”*
- (Gracias et al., 2023) defines as: *“Smart cities use digital technologies, communication technologies, and data analytics to create an efficient and effective service environment that improves urban quality of life and promotes sustainability.”*

As it can be seen, there are several types of definitions for “smart city” in the literature. When the definitions are analyzed, we can say that the basis of smart cities is focused on being more livable cities for people. These are the cities that increase the quality of life through the use of intelligent technologies and data and provides solutions for sustainability in environmental, social, and economic terms by using resources more efficiently. Smart cities occur with a combination of multiple factors. When the literature is examined, six basic components for smart cities are discussed (Deloitte-Vodafone, 2015). These components are shown in Figure 1.1 (Deloitte-Vodafone, 2015). For each component specified in the cities, the Internet of Things (IoT) and the advanced Information and Communication Technologies (ICT) are used to be smart and to provide development. The IoT collects real-time information by sensors from citizens and devices in cities to ensure more efficient use of resources and infrastructure through the processing of data. Besides, big data, blockchain technology, cloud technology, drones, 3d printing, robots, driverless vehicles, Geographic Information System, Wireless Internet Infrastructure, and etc. technologies are also known as smart city technologies (Deloitte-Vodafone, 2015). While smart cities offer many solutions with the help of technology in each component, it is important that the focus of smart cities is not on technology, but on people. All of these technologies are tools that should be used to improve the quality of life in cities and to provide success in smart city applications.

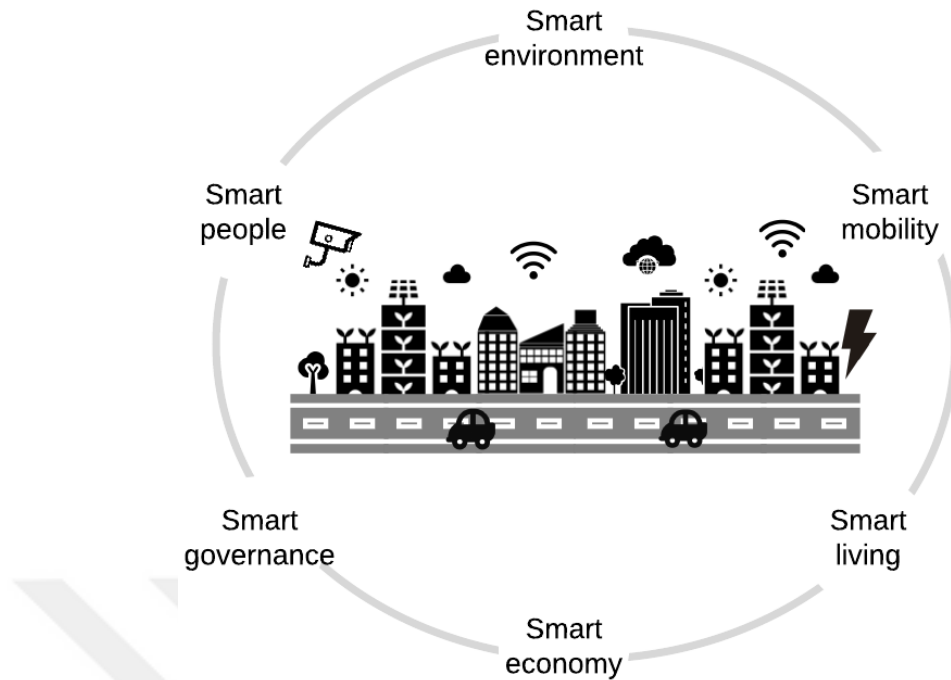


Figure 1.1: Basic components of smart cities

For smart cities, it is important that all components shown in Figure 1.1 should perform well in a forward-looking manner and especially, it will be important to focus on transportation/mobility in cities. Because the increasing population in cities not only increases the number of people living in the city but also increases the transportation of goods in the city. Considering that quality life and sustainability are the main objectives of smart cities, fewer trucks, less pollution, and less congestion should be provided in cities. In this context, urban logistics plays a vital role in the process of overcoming the mobility challenges of today's and future cities.

1.2. Urban Logistics

Logistics, refers to all processes of planning, implementation, transportation, storage, packaging, distribution of a product/service from the first producer to the end-consumer. The main objective in logistics is to provide the right product at the right place, at the right time, in the right amount, and in the right quality, to the end user at optimum cost (Nowicka, 2014). All these logistics activities are not only concerning the production and logistics sector but also concerns the city itself. The increasing share of the population living in urban areas also increases the urban mobility problems proportionally. The increasing population brings many mobility problems in cities such as traffic congestion, increasing urban freight transportation, increasing energy consumption, pollution, etc. In

order to address these problems and solve them, the concept of “Urban Logistics” has emerged (İnaç, 2012). Urban Logistics is the optimization of logistics services carried out by different companies by taking into consideration the traffic conditions, environmental impacts and energy consumption within the city, making them more efficient (Aydın, 2017). Urban logistics is crucial for the quality of life of citizens, for increasing urban competitiveness and for sustainable economic development. It plays an important economic role that provides significant benefits to multiple stakeholders across complex and dynamic supply chains (Sousa, 2015).

There are four basic principles that guide the implementation of urban logistics: mobility, sustainability, livability, and resilience (Rose et al., 2017). The principle of resilience is particularly important in ensuring that services are not disrupted in the event of a possible disaster. With the current pandemic and the increasing frequency of natural disasters, the importance of this principle has become even more apparent. By building a more resilient logistics infrastructure, cities can better protect their citizens and ensure that critical goods and services continue to flow even in challenging situations. This can help mitigate the impact of disasters and ensure that urban communities can quickly recover and rebuild.

1.3. Urban Resilience (UR) and Resilient Urban Logistics (RUL)

The concept of resilience initially originated as a means of addressing risks within ecological systems and developing strategies to cope with the impacts resulting from change (Holling, 1973).

Resilience can be defined as a system's capacity to address unforeseen events, risks, and alterations either by mitigating the impact of such events or by responding in a manner that minimizes their effects. Simultaneously, this concept carries diverse definitions across numerous fields within the literature. In addition to ecology, it found extensive research areas on topics such as supply chain management (Sheffi, 2008), psychology (Powley, 2009), and security management (Erik Hollnagel et al., 2006). The transformations experienced by cities are explored in conjunction with the concept of urban resilience. UR, as a concept, centers on cities developing the ability to withstand potential future shocks, safeguarding the social structure, economy, technical systems,

and infrastructures against these potential shocks, and sustaining their core functions (ARUP, 2014).

The notion of UR is subject to distinct interpretations in the literature presented by various organizations and authors. Henstra (2012), characterizes it as a climate-resilient city capable of responding to the adverse impacts of climate change. The Rockefeller Foundation (2020) articulates UR as the capacity of all systems and society to adapt and thrive in the face of disasters within cities. According to Lu and Stead (2013), a resilient city is one that can absorb the negative consequences of abrupt events while safeguarding the city's functionality and structure.

The primary objectives of UR encompass managing change during challenging circumstances and empowering communities to adapt and thrive while avoiding unforeseen stresses. Resilient cities are imperative, particularly for those at elevated risk, as swift recuperation, restructuring, and revival following destructive events contribute to both societal and systemic well-being.

Over the past decade, a growing body of research has focused on UR, spanning a wide array of topics. UR as a research domain encompasses diverse subtopics, ranging from climate change and food management to disaster management and urban planning.

Evaluating resilience is crucial, particularly in the context of urban logistics activities. The recent pandemic disaster has underscored the necessity for urban logistics to anticipate such events and highlighted the paramount importance of maintaining operational continuity during disasters. RUL can be defined as follows:

“RUL is a concept that encompasses all the works that strengthen the urban logistics infrastructures so that cities can establish and adapt their defense mechanisms against all kinds of negative situations, and that logistic systems become stronger by including smart technologies/processes. Urban logistics should include the goals of sustainability, livability, and mobility in cities as well as resilience.”

1.4. Research Framework

Cities need to be proactive and prepared to handle unexpected events that may arise in terms of their economic development, sustainability, and livability. The concept of RUL plays a crucial role in this regard. By implementing strategies that promote efficient and adaptable logistics systems, cities can better withstand disruptions caused by natural disasters, economic downturns, and other unforeseeable events. This not only helps to ensure the continued functioning of critical supply chains but also contributes to the overall resilience and well-being of urban areas. City planners and policymakers need to prioritize RUL initiatives as a means of building strong, sustainable, and livable cities for generations to come. However, it is noteworthy that there are very few studies available related to RUL evaluation (Büyükoğkan et al., 2022). To fill this gap, this thesis focuses on the strategic management, successful implementation, and technological infrastructure of RUL, to promote a more comprehensive understanding of its potential benefits. The following statements provide a summary of the thesis:

- Although urban logistics support cities to be better quality, liveable, and sustainable, cities will be vulnerable to ordinary disasters unless resilience can be achieved. Resilience will also play an essential role in supporting smart cities and smart urban logistics. Because of the increasing climate change and disasters, it is not enough for cities to be smart today, they must also be resilient and adapt to disasters. Therefore, it will be important to examine and understand UR, one of the important activities of cities, to support smart and resilient cities. When the literature was examined, it was observed that there is a research gap in the field of RUL. Since there are not a lot of publications on this subject, UR has been researched in this thesis and a detailed literature review is presented.
- Fuzzy sets have been widely used in various fields, especially in decision-making problems, since their emergence. However, in recent years, new extensions of fuzzy sets like Intuitionistic Fuzzy Sets (IFS), Pythagorean Fuzzy Sets (PFS), and Fermatean Fuzzy Sets (FFS) have been proposed to capture various aspects of uncertainty. To manage uncertainty with a broader scope, Interval-Valued Fermatean Fuzzy Sets (IVFFS) have been introduced as a generalization of

interval-valued fuzzy sets and FFS. In this thesis study, decision-making models based on IVFFS are proposed to capture and process uncertainties that exist in the RUL field.

- There is no study in the literature that evaluates the factors and strategies of RUL using an analytical approach. Therefore, the aim of this thesis study is to identify the important strategies of RUL using the SWOT integrated IVFF-Analytical Hierarchy Process (AHP) and IVFF-VIseKriterijumsa Optimizacija I Kompromisno Resenje (VIKOR) methodology.
- Successful planning and implementation of RUL are essential to mitigate unforeseen circumstances. This thesis study aims to identify and evaluate the success factors associated with the successful implementation of RUL using the IVFF-Interpretive Structural Modeling (ISM) approach.
- Technological planning aims to integrate innovative and smart solutions to optimize, accelerate, and realize RUL operations. This thesis study aims to evaluate the planning of RUL technological infrastructure using the IVFF-Quality Function Deployment (QFD) approach.
- Another critical issue is the identification of RUL technology providers. This thesis study aims to select the best technology provider for the most important technology in RUL with the IVFF-AHP and IVFF-VIKOR integrated Multi-Criteria Decision-Making (MCDM) approach.
- This thesis study was applied to Istanbul. The decision-making problems in the thesis study have been meticulously verified through expert opinions, ensuring their practical applicability and compatibility with real-world RUL scenarios.

Based on the previously mentioned highlights, the scope of the thesis study has been identified. The content of the thesis is divided into eight chapters. Chapter 2 comprehensively examines the place of RUL in the literature, by presenting detailed analyses of the UR literature. In Chapter 3, the applied methods are presented, along with

an overview of their theoretical background. Chapter 4 covers the strategic analysis of RUL, while chapter 5 discusses critical factors for the successful implementation of RUL. In Chapter 6, the technological requirements for RUL are determined, and technology prioritization is made in line with these requirements. Chapter 7 focuses on the selection of technology providers. Finally, Chapter 8 presents conclusions and future suggestions.

The research model of the thesis study has been presented in Figure 1.2.

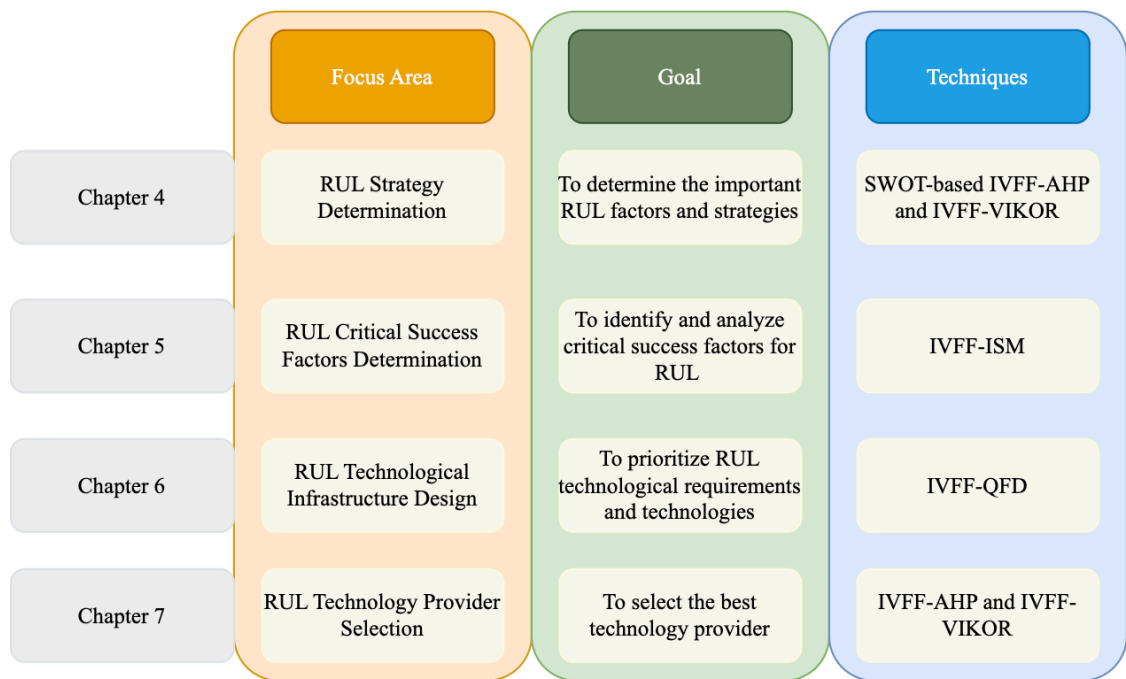


Figure 1.2: The research model of the thesis

2. LITERATURE REVIEW OF UR

The objective of this section in the thesis is to offer a comprehensive overview of the topic by conducting a thorough review of both academic and industrial literature on UR. This involves categorizing publications, scrutinizing significant trends, and identifying gaps, while also proposing recommendations for future research. The analysis encompasses a review of 178 journal articles and 11 industrial reports spanning the period from 2013 to the conclusion of 2023. The journal articles are systematically categorized into literature reviews, conceptual models, and analytical models. Additionally, the review explores the various approaches and analytical techniques discussed within the field (Büyüközkan et al., 2022). An exhaustive examination of both academic and industrial literature on UR spanning from 2013 to the close of 2023 was conducted to address the research question: “What are the potential research directions of UR?” In alignment with this research question, the following objectives were delineated:

- Objective 1: Identify the principal topics discussed in UR papers.
- Objective 2: Illuminate knowledge gaps and contribute to the future research agenda for UR.

In the pursuit of answering these questions, a thorough exploration of previous literature review studies was conducted to provide a comprehensive view of the subject. While recognizing the significance of prior studies, it is crucial to scrutinize both UR articles proposing conceptual frameworks and methodological ones that encompass analytical approaches. Conceptual frameworks aim to enhance the analysis of various dimensions of UR, delineating its advantages and challenges. Analytical approaches encompass quantitative methods such as statistical analyses, MCDM techniques, and mathematical modeling. The categorization of journal articles in this review distinguishes between “conceptual” and “analytical” articles.

This categorization provided a detailed examination of the discussed articles with the techniques they contain. Afterwards, industrial reports that are important in this field are examined and the main talking points, research gaps and future trends of UR is proposed.

The conducted analysis comprises three stages: (1) gathering data from online databases, (2) categorizing publications for data analysis, and (3) pinpointing primary themes and gaps in the literature. The research methodology is elucidated in Figure 2.1.

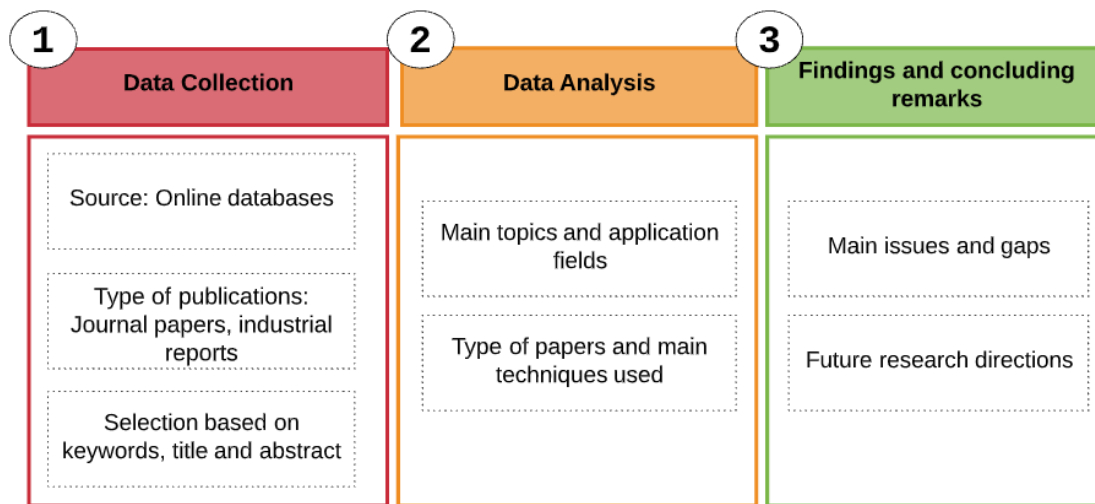


Figure 2.1: Research methodology of the literature review

2.1. Data Collection

In this review, the selection of publications was conducted through the Web of Science (WoS), Scopus, and Google databases. Publications from other databases were intentionally omitted. The WoS and Scopus databases were specifically utilized for researching journal articles, while the Google search engine was employed to examine industrial reports from organizations notable for their applications in UR.

The research process involved the use of keywords such as “urban resilience”, “city resilience”, “resilient city”, and “resilient cities”. The literature review encompassed publications in the English language, including studies published from 2013 to the end of 2023. In the investigation carried out on the WoS and Scopus databases, only article and review document types were considered, with all other document types being excluded.

In the initial search for journal articles, scrutiny was applied to titles, keywords, and abstracts of all studies, eliminating those unrelated to UR. This involved excluding UR studies with a focus on psychology and studies that, while incorporating the concept of UR in their content or summary, did not directly address the subject. Subsequently, a comprehensive screening process was conducted for the remaining studies, resulting in a total of 178 academic studies, comprising 158 articles and 20 literature review articles.

Concerning industrial reports, efforts were made to gather studies from organizations pertaining to UR measurement, planning, and design. A meticulous screening process was applied to 17 reports identified in the Google database, with 11 ultimately included in the study.

The publication selection process is detailed in Figure 2.2.

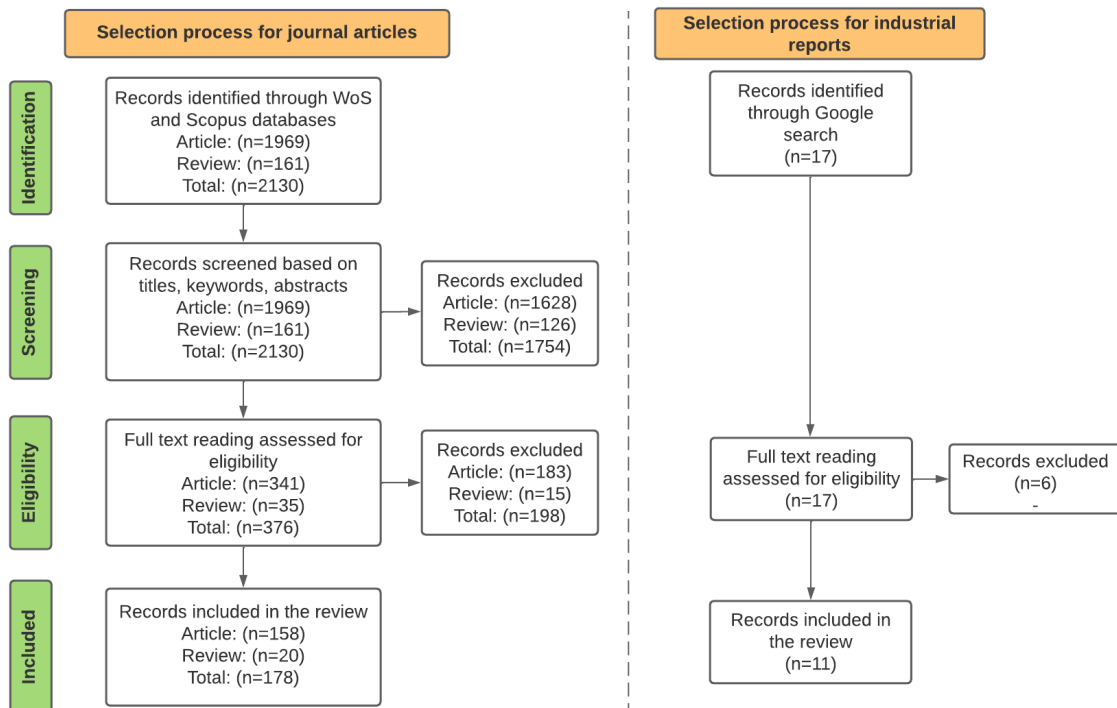


Figure 2.2: Flow diagram of publication selection process based on Prisma model

The publications are classified and detailed in the following sections.

2.2. Data Analysis

Following the collection of studies, a categorization was conducted into two parts—journal articles and industrial reports—with comprehensive analyses incorporated.

2.2.1. Journal Articles on UR

As a concept of significant relevance in the modern world, UR is pervasive across a broad spectrum of scientific investigations. It is noteworthy that numerous studies within the field of UR not only concentrate directly on the subject but also delve into related sub-topics such as flood resilience, climate change, and sustainability.

In light of this, Figure 2.3 provides an overview of paper distribution by type, Figure 2.4 highlights the most discussed topics through keyword analysis, and Figure 2.5 presents an analysis of publication years.

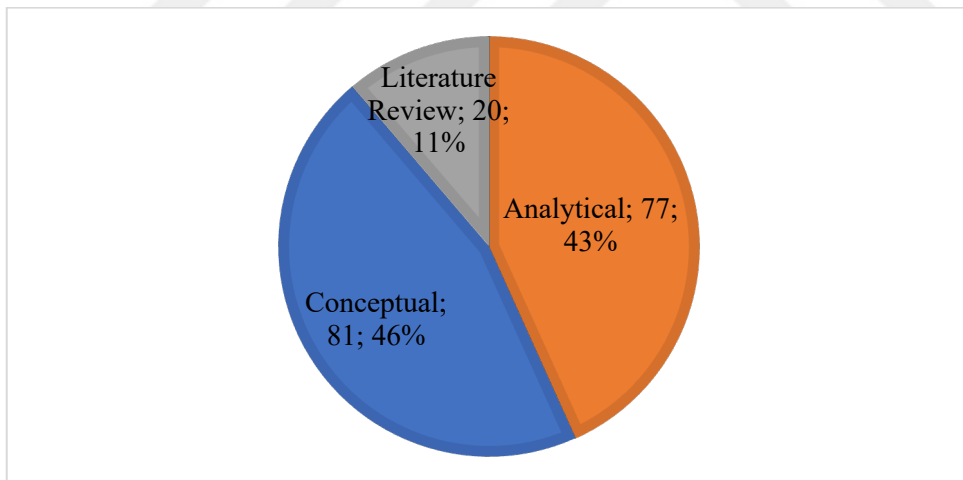


Figure 2.3: Distribution of the journal articles by type

A literature review plays a crucial role in synthesizing existing studies within a specific field. In the context of UR, it is valuable to differentiate between studies adopting a conceptual and an analytical approach. Conceptual frameworks contribute to a better understanding, classification, or explanation of UR and its implications for cities and stakeholders. On the contrary, analytical approaches encompass statistical methods, MCDM techniques, optimization, or similar quantitative methods for assessing UR.

Consequently, in addition to literature reviews, the studies discussed in journal articles are also categorized into two types based on whether they adopt a conceptual or analytical approach.

Upon analyzing Figure 2.3, it is evident that most of the examined studies conceptually explore UR. Despite the considerable attention given to this domain, UR proves to be a complex concept that resists easy definition within a singular framework. It stands as a truly multi-disciplinary field, witnessing a growing number and diversity of studies spanning various scientific areas and scopes of concern.

In this review, the VOSviewer application was employed to examine trends in prior studies within the realm of UR. VOSviewer, a scientific mapping tool crafted for visualizing bibliometric networks, encompasses various bibliometric analyses such as keyword analysis, co-authorship analysis, and the visualization of citation networks (Sharifi, 2020). Specifically, this thesis utilized it for keyword analysis, setting a minimum keyword occurrence threshold of 2, as illustrated in Figure 2.4. In this representation, the frame size corresponds to term frequency, unveiling prevalent themes and issues within the field of UR.

When the figure is examined, it is seen that there are many subtitles in UR. The most important of these are summarized below:

1. Climate change: Climate change results from both human activities and the inherent variability of the climate. Instances of related disasters include wildfires, droughts, and floods. The prevalence of these disasters in today's world emphasizes the distinctive challenges cities face in crafting resilience models (Kim & Lim, 2016).
2. Urban planning: Enhancing resilience in the realm of urban planning necessitates a holistic consideration of the entire settlement. Proactively making decisions regarding the systematic functioning and spatial arrangement of a city before the occurrence of disasters allows for the development of cities with a resilient

approach to such events. Recognizing the significance of urban planning in the field of UR is evident in this context (Yaman Galantini & Tezer, 2018).

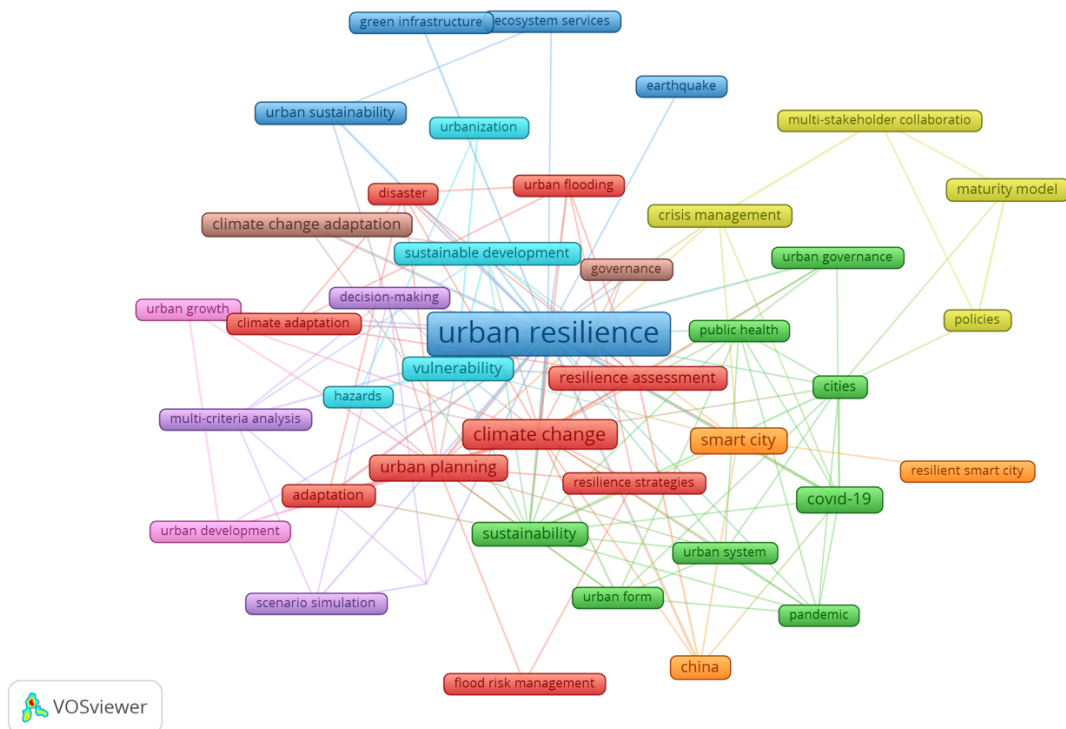


Figure 2.4: Most discussed topics under UR by keyword analysis

3. **Urban sustainability:** Urban sustainability is an idea that focuses on the goal of reducing the use of resources and solid waste of the city and increasing livability. The purpose of this is to reduce the overall ecological footprint — that is, to reduce pollution, to make an environmental and economic contribution by using the land efficiently, to recycle/convert waste to energy and to ensure the general contribution of the city in the struggle against climate change (Tabibian & Movahed, 2016).
4. **Adaptation:** Cities must be organized against external threats in terms of resilience and must have the ability to change and improve. Adaptation is about the development of the ability to prepare for a similar future shock through re-exposure to an existing shock (Kim & Lim, 2016).
5. **Urban vulnerability:** In order for cities to be prepared for the risks they face, it is necessary to reveal these vulnerabilities and develop prevention strategies.

Examples of these vulnerabilities are pandemics, floods, earthquakes, food shortages or drought (Diaz-Sarachaga & Jato-Espino, 2020).

6. Smart cities: Smart cities enhance the quality of life by integrating intelligent technologies and offer solutions in environmental, social, and economic aspects through more efficient resource utilization. In this context, smart cities contribute to UR.

The bar chart illustrated in Figure 2.5 provides a distinct overview of the increasing interest in the field of UR over the past decade. The visual representation indicates that, up to 2020, conceptual articles held the highest prominence. However, in the last three years, there has been a notable surge in analytical approaches within the UR domain.

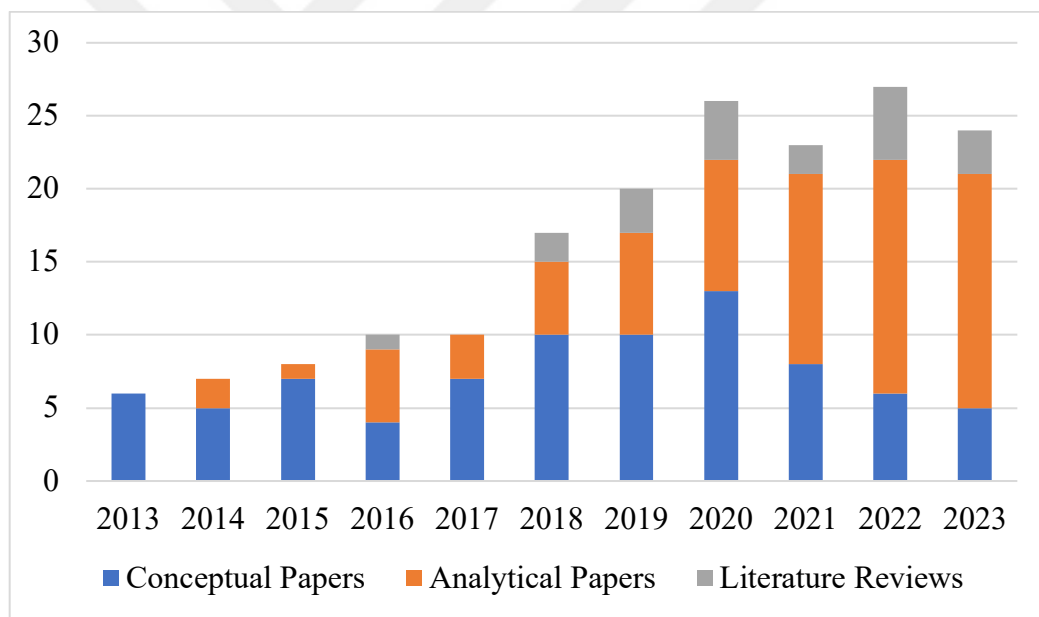


Figure 2.5: Distribution of the journal articles by publication year (2023 studies up to December 11, 2023)

2.2.2. Existing Review Studies on UR

The examination of existing review articles serves as a valuable tool for identifying primary gaps and issues within UR, shedding light on areas requiring further exploration. Recognizing a scarcity of up-to-date literature reviews in the field prompted us to consolidate these studies. Our investigation uncovered a total of 161 literature review

articles related to the subject, with a detailed examination focusing on 20 review studies. Table 1 provides a comprehensive overview of these studies, outlining their respective objectives and outcomes.

The review's timeframe spans from 2013 to the end of 2023. In addition to addressing UR within its strategic direction and factors, defining the concept, and a general exploration of UR, the studies also encompass a range of diverse areas such as disaster assessments, urban flood resilience, seismic resilience, green infrastructure, climate change, and sustainability.

Through an analysis of current literature review studies, insights emerge regarding the areas receiving more attention and those requiring further exploration. Remarkably, past literature reviews lack an examination of whether the subject is predominantly discussed conceptually or analytically, and which analytical techniques are employed. Consequently, this study aims to delve into the concepts and techniques within the realm of UR.

Table 2.1: Existing review studies of UR

Reference	Focus Area	Objective	Outcomes
(Meerow et al., 2016)	UR	To review the literature on UR.	*There is still a general lack of definition of UR.
(Gharai et al., 2018)	UR	To identify the key elements in the measurement of resilience in relation to the spatial structure of the city.	*Measuring UR in terms of its local-spatial dimension, requires more research.
(L. Wang et al., 2018)	UR	To propose an analysis of the evolution trends of UR research.	*There is still a general lack of definition of UR.

Reference	Focus Area	Objective	Outcomes
(Cariolet et al., 2019)	Disaster Mapping	To understand how UR to disasters is mapped by researchers.	*It is not possible to map the resilience of a city because of the high level of complexity. *Resilience maps do not map the capacity to adapt or convert systems. *Most of the resilience mapping methods are analytical. *The boundary between resilience and vulnerability maps is narrow.
(Masnavi et al., 2019)	Urban Planning	To introduce indices of UR to the relationship between urban form and UR.	*More research is needed for locational-spatial aspect of UR.
(Ribeiro & Pena Jardim Gonçalves, 2019)	UR	To create an opinion about UR.	*The most effective types of measures regarding the resilience of different urban systems need to be identified. *Lack of tools to assess resilience is the main gap.
(Diaz-Sarachaga & Jato-Espino, 2020)	Disaster Risks	To provide a critical analysis of the selected articles to determine their adequacy in the evaluation of urban vulnerability.	*Studies focused on multiple disasters are missing. *Studies developing risk perception and mitigation strategies are few. *A globally accepted framework that includes multiple factors in numerical methods is missing. *Studies addressing fuzzy approaches in UR are missing.
(Sharifi, 2020)	UR	To determine the state of knowledge and trends in the field of UR.	*Economic and social gaps in UR must be filled, and research on disasters other than floods is needed. *The gap regarding the application of UR tools and methods should be filled.
(Therrien et al., 2020)	UR	To examine the facilitators, barriers and trade-offs in the implementation of UR.	*Lack of governance in UR and testing in real cases. *Lack of institutional and barrier factors in UR. *The emphasis on intercity networks in UR should be increased.

Reference	Focus Area	Objective	Outcomes
(Zhu et al., 2020)	Smart Cities	To reveal the differences and relationships between smart cities and resilient cities.	*Resilient cities can have positive physical, social and environmental effects on smart cities, but the opposite can be both positive and negative. *There is a need to build resilient smart cities. *Cooperation should be made while evaluating urban problems and disasters, and more emphasis should be placed on the theoretical side for resilient cities.
(Bueno et al., 2021)	UR	To analyze the current situation and trends of UR literature.	*It has been stated that there are few studies on the COVID-19 pandemic. *Lack of studies investigating citizens' commitment to UR plans. *Lack of studies addressing how to digitally transform the UR process.
(Hassankhani et al., 2021)	Smart Cities, COVID-19	To analyze the role of technology in crisis management for dealing with the COVID-19.	*For post COVID-19 policies and strategies, the dynamics of people in metropolitan areas should be analyzed. *There is a need for further studies to find initiatives and practical solutions to address the inequality of technology distribution in rural areas.
(Canavera-Herrera et al., 2022)	Smart Cities	To analyze the literature on resilience and smart cities/smart technologies.	*It is seen that definitions of resilience exist in the smart city and smart technologies literature. *Further investigation is essential to determine the possible disturbances that smart city digital technologies could cause.
(L. Wang, 2022)	Climate Change	To analyze the current situation and trends of UR to climate change.	*Studies should focus on conducting a thorough examination of UR concerning climate change, the susceptibility of urban systems to climate change, and the impacts of multiple hazards on UR.

Reference	Focus Area	Objective	Outcomes
(Samarakody et al., 2022)	Smart Cities	To identify a set of smart characteristics/smartness criteria for making smart cities resilient.	*Smart city in defining its smartness, particularly with regard to disaster resilience, is a significant challenge that needs to be addressed.
(Wu et al., 2022)	UR	To analyze the current situation and trends of UR literature.	*Collaboration with external organizations and research institutions is insufficient in UR research. *Research efforts should emphasize topics like risk analysis in UR, the development of UR indices, and the assessment of ecosystem services.
(Y.-J. Huang et al., 2022)	Urban Community Resilience	To analyze the current situation and trends of resilient cities and communities.	*Studies that have attracted attention are on climate change, framework and UR. *It is noted that future community resilience efforts need to strengthen collaboration between industry, academia and public institutions.
(Amirzadeh et al., 2023)	COVID-19	To present a conceptual framework of principles of UR to pandemics.	*To ensure safety in public spaces and minimize health risks, it's essential to develop design principles, standards, and disaster management protocols. *Evaluating the resilience of buildings and neighborhoods against pandemics is crucial.
(Lanlan et al., 2023)	Vulnerability	To examine the concepts of vulnerability and resilience in the context of natural disasters.	*Defining climate resilience should consider the relationship between social systems' capacity and modern technology.
(Therias & Rafiee, 2023)	Smart Cities	To understand the city digital twins implementation to increase the resilience of urban communities.	*For successful implementation of digital twins, modeling hazards, collecting and managing data, and facilitating stakeholder integration are crucial.

2.2.3. Conceptual UR Papers in Literature

Conceptual frameworks serve the purpose of establishing a framework that can be utilized for the description and interpretation of data. Additionally, they function as a filtering mechanism for the identification of pertinent research questions and the selection of suitable data collection methods. These frameworks offer a structured approach to address challenges by delineating the diverse issues encountered by cities, providing a critical perspective on the matter at hand.

Research exploring the conceptual approach holds significant value, and numerous studies in this domain introduce frameworks or tools for UR. Jabareen (2013) introduced a framework for resilient city planning aimed at enhancing the resilience of cities and communities. Tabibian & Movahed (2016) presented frameworks for UR and urban sustainability, offering plans and strategies for city development. Yaman Galantini & Tezer (2018) put forward a hypothetical framework addressing the role of resilience in urban planning. In a more recent contribution, Lak et al, (2020) proposed a resilient urban design framework incorporating multiple dimensions and Wardekker et al. (2020) introduced a resilience diagnostic tool for reflecting on UR.

In relation to UR index methodologies, Suárez et al. (2016) introduced a UR index, delineating UR factors and indicators, and applied this index to 50 Spanish cities. Several studies by Gimenez et al. (2017), Labaka et al. (2019) and Hernantes et al. (2019a) have contributed to the development of UR maturity models. These models serve as guidance, offering a roadmap to determine the policies to be implemented throughout various stages of the UR process. Additional research delves into discussions centered on identifying challenges, risks, and strategic approaches applicable to UR. Banai (2020), explored the impact of the COVID-19 pandemic on UR. More recently, Zou (2023) investigate how digital technologies might impact UR. A comprehensive list of all conceptual UR papers considered in this analysis is provided in Table 2.2.

Table 2.2: Conceptual UR papers in literature

Reference	Focus Area	Approach	Reviewed city/country
(Beatley & Newman, 2013)	Sustainability	-	-
(Dieleman, 2013)	Climate Change	Action Plans Research	South Africa; Bangladesh; Nigeria; Germany; U.S. and Mexico
(Friend & Moench, 2013)	Poverty And Vulnerability	Discussion	-
(Gürevin & Seçkin, 2013)	Climate Change	Discussion	Chicago, U.S
(Jabareen, 2013)	Climate Change	Framework	-
(Wamsler et al., 2013)	Climate Change	Framework	-
(Galderisi, 2014)	Urban Planning	Discussion	-
(S. E. Chang et al., 2014)	Disaster Risks	Discussion	Vancouver, Canada
(Stead, 2014)	Climate Change	-	Rotterdam, Netherlands
(Vale, 2014)	Urban Planning	Discussion	-
(Weichselgartner & Kelman, 2014)	Urban Design	Discussion	-
(Abdrabo & Hassaan, 2015)	Climate Change	Framework	Nile Delta
(Bahadur & Thornton, 2015)	UR	Discussion	13 Asian cities
(Caputo et al., 2015)	Adaptability	Discussion	-
(Chelleri et al., 2015)	Climate Change	Discussion	Uganda; Bolivia
(Pizzo, 2015)	UR	-	-

Reference	Focus Area	Approach	Reviewed city/country
(Restemeyer et al., 2015)	Urban Flood Resilience	Framework	Hamburg, Germany
(Zhai et al., 2015)	Disaster Risks	Framework	Shenzhen, China
(Kim & Lim, 2016)	Climate Change	Framework	-
(Suárez et al., 2016)	UR	Index	Spain
(Tabibian & Movahed, 2016)	Sustainability	Framework	Mashhad, Iran
(Vona et al., 2016)	Seismic Resilience	Framework	Italy
(Crowe & Foley, 2017)	UR	Discussion	Dublin, Ireland; Edinburgh, Scotland and Philadelphia, U.S
(Delgado-Ramos & Guibrunet, 2017)	Sustainability	Framework	Mexico City, Mexico
(Gimenez et al., 2017)	Multi-Stakeholder Collaboration	Maturity Model	UK; Norway; Italy; Spain; Denmark
(Hudec, 2017)	UR	-	-
(Kita, 2017)	Disaster Risks, Climate Change	Pressure And Release (PAR) Model	Mzuzu city, Malawi
(Sharifi et al., 2017)	UR	Structured Interview Matrix (SIM) process	-
(Su, 2017)	Urban Flood Resilience	Geographic Information System (GIS)-based simulations	Taipei, Taiwan

Reference	Focus Area	Approach	Reviewed city/country
(Cobbinah & Poku-Boansi, 2018)	Urban Planning	Discussion	Accra and Kumasi, Ghana
(Gimenez et al., 2018)	Multi-Stakeholder Collaboration	Maturity Model	UK; Norway; Italy; Spain; Denmark
(Gordon et al., 2018)	Green Infrastructure	Framework	U.S
(Marana et al., 2018)	Multi-Stakeholder Collaboration	Framework	-
(Mierzejewska & Wdowicka, 2018)	UR	Document Analysis	-
(Moraci et al., 2018)	UR	Action Plans Research	Rotterdam, Netherlands
(Serre & Heinzl, 2018)	Urban Flood Resilience	Spatial Decision Support System (DS3) Model	Hamburg and Avignon
(T. L. T. Du et al., 2018)	Water Management	Framework	Da Nang, Vietnam
(X. Zhang & Li, 2018)	Sustainability	Framework	-
(Yaman Galantini & Tezer, 2018)	Urban Planning	Framework	Istanbul, Turkey
(Adedeji et al., 2019)	Urban Flood Resilience	Document Analysis	Birmingham, UK
(Aguilar-Barajas et al., 2019)	Urban Flood Resilience	Framework	Monterrey Metropolitan Area, Mexico
(Ahmed Elewa, 2019)	Public Spaces	Discussion	Rotterdam, Netherlands; Berlin, Germany
(Borie et al., 2019)	UR	Framework	Manila, Nairobi, and Cape Town

Reference	Focus Area	Approach	Reviewed city/country
(Bush & Doyon, 2019)	Nature-Based Solutions	Framework	-
(Choi & Seo, 2019)	UR	Framework	Seoul, Korea
(Gaber et al., 2019)	UR	Index	-
(Hernantes et al., 2019)	UR	Maturity Model	-
(Labaka et al., 2019)	Policymaking	Maturity Model	Different European Cities
(Ramsey et al., 2019)	Urban Flood Resilience	Framework	San Juan, Puerto Rico
(Admiraal & Cornaro, 2020)	Urban Planning	Discussion	-
(Babí Almenar et al., 2021)	Nature-Based Solutions	Framework	-
(Banai, 2020)	Pandemics	Discussion	-
(Cardoso et al., 2020)	Climate Change	Action Plans/Projects Research	Barcelona, Spain; Bristol, UK; and Lisbon, Portugal
(C. Chen et al., 2020)	Adaptability	UR Model	Taiwan; China
(Feng et al., 2020)	Urban Landscapes	Framework, Index	Shenyang, China
(Heinzlef et al., 2020)	Climate Change	Framework	France; Canada
(Lak et al., 2020)	Urban Design	Framework	-
(Maraña et al., 2020)	Multi-Stakeholder Collaboration	Framework	UK; Norway; Italy; Spain; Denmark
(McGill, 2020)	Urban Development	Action Plans Research	Kenya

Reference	Focus Area	Approach	Reviewed city/country
(M. Zhang et al., 2020)	Climate Change	Framework, index	Beijing, Chongqing and Yiwu, China
(Shamsuddin, 2020)	Policymaking	Framework	-
(Snep et al., 2020)	Nature-Based Solutions	Discussion	Amsterdam, Netherlands
(Wardekker et al., 2020)	Policymaking	Framework	Rotterdam, Netherlands
(Bixler et al., 2021)	Urban Community Resilience	Framework	Austin, Texas, USA
(Chu et al., 2021)	COVID-19, Smart Cities, Urban Governance	Framework	China
(J. Ruan et al., 2021)	Urban Flood Resilience	Framework	Guangzhou, China
(McCartney et al., 2021)	COVID-19	Discussion	Macao, China
(S.-C. Liu et al., 2021)	Urban Underground Space	Index	Shanghai, China
(Shamout et al., 2021)	Sustainability	Discussion	Jordan
(Wardekker, 2021)	Climate Change	Framework	-
(Amirzadeh et al., 2022)	UR	Discussion	-
(Dianat et al., 2022)	UR	Action Plans Research, Index	Auckland, New Zealand
(Khatibi et al., 2022)	Smart Cities	Framework	-
(Qiu et al., 2022)	Digital Platforms, COVID-19	Framework	China and Singapore

Reference	Focus Area	Approach	Reviewed city/country
(Rodríguez-Izquierdo et al., 2022)	UR	Discussion	Mexico City, Mexico
(X. Zeng et al., 2022)	Sustainability	Discussion	
(Datola, 2023)	Urban Planning	Framework	-
(Samarakkody et al., 2023)	Smart Cities	Discussion	-
(Serbanica & Constantin, 2023)	Sustainability	Discussion	-
(X. Zhang et al., 2023)	Urban Flood Resilience	Framework	Shenzhen, China
(Zou, 2023)	COVID-19, Digital Technologies	Framework	Hangzhou, China

The reviewed conceptual frameworks delve into studies that elucidate the UR concept, with a particular emphasis on defining risks and disasters. These frameworks also propose strategies, concentrating on the realms of urban design, planning, and urban management, each explored through distinct conceptual models. These models yield valuable insights, including the definition of UR, key issues, and recommended strategies. Employing analytical techniques when approaching these models enhances the consistency of results.

2.2.4. Analytical UR Papers in Literature

While the emphasis in the domain of UR may appear to lean towards conceptual models, a literature review reveals a noticeable increase in both output and diversity of analytical methods in UR since 2014. These methods serve the purpose of quantitatively assessing existing conceptual frameworks or stand as models with their own conceptual foundations. The adoption of analytical methods proves advantageous in UR, offering benefits in terms of comparison, decision-making, and performance evaluation. A detailed list of all analytical UR papers incorporated in this analysis is provided in Table 2.3.

Upon reviewing the analytical methodologies applied in the field of UR, it is evident that a range of techniques such as statistical methods, modeling approaches, and MCDM methods are prevalent. A noteworthy trend in recent years is the widespread use of the AHP in UR studies. Some researchers have enhanced AHP by incorporating fuzzy set theory or integrating different MCDM approaches. For instance, Romero-Lankao et al. (2016) introduced a livelihoods framework to characterize urban households and later applied the fuzzy AHP method to investigate the impact of wealth, poverty, and exposure on vulnerability to climatic risks. Zhu et al. (2019) and Moghadas et al. (2019) employed AHP with TOPSIS in their studies on smart cities and urban flood resilience, respectively. Other studies leveraging MCDM techniques utilized tools such as Fuzzy Cognitive Maps, Decision Making Trial and Evaluation Laboratory (DEMATEL), Analytical Network Process (ANP), and VIKOR. The literature review suggests an advancement in the sophistication of these techniques over time. For example, Z. Li et al. (2019) developed an urban flood resilience evaluation system using the hesitant fuzzy VIKOR technique. M. Yang et al. (2022) applied the entropy TOPSIS method for the UR evaluation of the Chengdu-Chongqing Economic Circle, and Mabrouk & Haoying (2023) utilized MCDM techniques for predicting and analyzing urban flood-risk areas.

In addition to MCDM techniques, data analysis and statistical methods are commonly employed. Statistical approaches play a crucial role in summarizing data derived from quantitative research and identifying potential relationships between variables.

Our examination reveals that statistical methods employed in the literature on UR include factor analysis, descriptive analysis, correlation analysis, principal component analysis, ANOVA, cluster analysis, sampling methods, and regression analysis. These methodologies are predominantly utilized through the administration of questionnaires or interviews.

Table 2.3: Analytical UR papers in literature

Reference	Focus Area	Approach	Technique	City/country
(Barroca et al., 2015)	Disaster Risks	Modelling	Block Maxima Approach, Extreme-Value Theory, Peaks Over Threshold Approach	-
(Berte & Panagopoulos, 2014)	Green Infrastructure	MCDM	SWOT Analysis	Faro, Portugal
(Ozuduru et al., 2014)	Shopping Centers/Streets Resilience	Statistics	Simple Random Sampling Method	Ankara, Turkey
(Bastaminia et al., 2016)	Seismic Resilience	Statistics	One Sample T Test, Friedman Test, Kendalls Tau	Dehdasht City, Iran
(Grinberger & Felsenstein, 2016)	Welfare Effects	Modelling	Dynamic Agent Based Modeling	Jerusalem, Israel
(Olazabal & Pascual, 2016)	Urban Energy Resilience	MCDM	Fuzzy Cognitive Maps	Bilbao, Spain
(Romero-Lankao et al., 2016)	Urban Households	MCDM	Fuzzy AHP	Mumbai, India
(Tabibian & Rezapour, 2016)	UR	Statistics	Regression Analysis, Factor Analysis	Tehran City, Iran
(Banica et al., 2017)	Seismic Resilience	MCDM, Statistics	Principal Components Analysis (PCA), Z Score, AHP	Iasi City, Romania
(Boschetti et al., 2017)	UR	Statistics	Correlations, Factor Analysis	Sydney, Melbourne and Perth, Australia

Reference	Focus Area	Approach	Technique	City/country
(H. Xu & Xue, 2017)	Public Spaces	MCDM	AHP	-
(Borsekova et al., 2018)	Disaster Risks	Statistics	Pearson Correlation Coefficient, Correlation Matrix, Poisson Regression	-
(Darkwah et al., 2018)	Climate Change	Statistics	Multi-Stage Sampling Approach, Descriptive Statistics	Kumasi, Ghana
(Kim & Song, 2018)	Climate Change	Statistics	Confirmatory Factor Analysis, Cluster Analysis, ANOVA	Korean Cities
(Moghadas et al., 2019)	Urban Flood Resilience	MCDM	AHP, TOPSIS	Tehran, Iran
(Molavi, 2018)	Disaster Risks	Statistics	Sample T-Test, Delphi Method	Lahijan city, Iran
(Zheng et al., 2018)	Climate Change	Statistics	Factor Analysis, Principal Component Analysis and Cluster Analysis	Beijing, China
(Brunetta & Salata, 2019)	Disaster Risks	Statistics	Clustering Analysis	Turin, Italy
(da Silva et al., 2019)	Sustainability	Statistics	Descriptive Analysis	São Paulo, Brazil
(Iturriza et al., 2019)	UR	Modelling	Delphi method, SD model	Norway, Spain, UK
(X. Zhang et al., 2019)	Disaster Risks	MCDM	Delphi Method, AHP	Shenzhen, China
(Zhu et al., 2019)	Smart Cities	MCDM	AHP, TOPSIS, Regression Analysis	China
(Z. Li et al., 2019)	Urban Flood Resilience	MCDM	Hesitant Fuzzy VIKOR	China

Reference	Focus Area	Approach	Technique	City/country
(Bottero et al., 2020)	UR	Modelling, MCDM	SD model, ANP	Turin, Italy
(Datola et al., 2021)	UR Capacities	Modelling, MCDM	SD model, ANP	-
(Dong et al., 2020)	Smart Cities	Statistics	Entropy Evaluation Method, Regression Model	China
(Ghouchani et al., 2020)	UR	Statistics	Exploratory Factor Analysis	-
(G. Li et al., 2020)	Policymaking	Modelling	SD Model, Simulation	Beijing, China
(H. Xu et al., 2020)	Public Spaces	MCDM	ANP, DEMATEL	China
(Iturriza et al., 2020)	Climate Change	Modelling	Delphi, SD model, Pilot Test, Simulation	Kristiansand, Norway
(L. Li et al., 2020)	Green Infrastructure	MCDM	AHP	Ghent, Belgium
(Xun & Yuan, 2020)	UR	MCDM	Intuitionistic Trapezoidal Fuzzy Numbers, TOPSIS	Dalian city, China
(Yao & Wang, 2020)	Smart Cities	Statistics	Variational Bayes, Latent Dirichlet allocation	Texas
(AbouKorin et al., 2021)	COVID-19	Statistics	Kruskal-Wallis H-Test, ANOVA, Regression Analysis, Correlations	England, Germany and Italy
(Bellini et al., 2021)	Smart Cities	Modelling, MCDM	Functional Resonance Analysis Method, AHP	-
(Feofilovs & Romagnoli, 2021)	UR	Modelling	SD model, Monte Carlo simulation	-

Reference	Focus Area	Approach	Technique	City/country
(G. Huang et al., 2021)	UR	MCDM	DEMATEL, ISM	-
(J. Chen et al., 2021)	COVID-19	Statistics	Descriptive Analysis, Regression Analysis	China
(J. Wang & Foley, 2021)	Urban Open Spaces	MCDM	AHP, WSM	Dublin, Ireland
(Lak et al., 2021)	COVID-19	Statistics	Factor Analysis	Tehran City, Iran
(Q. Zhou et al., 2021)	Smart Cities	Statistics	Descriptive Analysis	China
(Sajjad et al., 2021)	Disaster Risks	Statistics	ANOVA, Spatial Analysis	Hong Kong
(X. Liu et al., 2021)	UR	Statistics	Cluster Analysis	China
(X. Fu et al., 2021)	Green Infrastructure	MCDM	AHP-Fuzzy Comprehensive Evaluation	Ohio, USA
(Y. Chen et al., 2021)	COVID-19	Statistics	Exploratory Spatial Data Analysis, Multi-scale Geographical Weighted Regression Model	China
(Anelli et al., 2022)	Disaster Risks	MCDM	AHP	Rome, Italy
(A. Ding et al., 2022)	Public Spaces, COVID-19	Statistics	Spatial Analysis, Kernel Density Analysis, Pearson Correlation	China
(Bunmi Mudashiru et al., 2022)	Urban Flood Resilience	MCDM	AHP, Fuzzy AHP	Penang, Malaysia
(Datola et al., 2022)	UR	Modelling	SD Model	-

Reference	Focus Area	Approach	Technique	City/country
(Ekmekcioğlu et al., 2022)	Urban Water Scarcity	MCDM	Fuzzy AHP, Fuzzy TOPSIS	-
(Gafer et al., 2022)	COVID-19	Statistics	Descriptive Analysis	Eilat, Israel
(Kutty et al., 2022)	Smart Cities	Modelling	Metric Distance-Based Multivariate Analysis and Machine Learning Models	European Cities
(L. Liu et al., 2022)	Climate Change	Statistics	Data Analysis	Beijing-Tianjin-Hebei region, China
(Majewska et al., 2022)	COVID-19	Statistics	Data Analysis	Polish Cities
(Mouratidis, 2022)	COVID-19	Statistics	Paired t-tests and Wilcoxon Signed-Rank Tests, Regression Analysis	Oslo and Viken, Norway
(M. Yang et al., 2022)	UR	MCDM	Entropy weight-TOPSIS	Chengdu-Chongqing, China
(Rezvani et al., 2022)	UR	MCDM	AHP-based ARCDM (Automated rational and consistent decision making)	-
(R. Zhao et al., 2022)	UR	Statistics	Spatial Analysis	Chinese Cities
(Shi et al., 2022)	Climate Change	Statistics	Spatial Analysis	Chinese Cities
(Xia & Zhai, 2022)	UR	Modelling, MCDM	Particle Swarm Optimization, TOPSIS, AHP	Yangtze River Delta, China
(Z. Liu et al., 2022)	Public Health Disaster	MCDM	Rough AHP	Jiangsu, China

Reference	Focus Area	Approach	Technique	City/country
(H. Fu et al., 2023)	COVID-19	Statistics	Geographically Weighted Regression Model	China
(H. Wang et al., 2023)	UR	Statistics	Exploratory Spatial Data Analysis	Chinese Cities
(Jamali et al., 2023)	UR	MCDM	Delphi, DEMATEL, ANP	Tehran City, Iran
(J. Li et al., 2023)	Sponge City Resilience	MCDM	AHP-Entropy Method, GRA	Shaanxi Province, China
(X. Wang et al., 2023)	UR	Statistics	Spatial Analysis, Kernel Density Analysis	Jinan City, China
(J. Zhang et al., 2023)	UR	MCDM	Entropy weight-CRITIC	Northeast China
(J. Zhang & Wang, 2023)	COVID-19	Modelling	SD Model	Wuhan and Nanjing, China
(Kutty et al., 2023)	Smart Cities, Sustainability, Resilience and Livability	MCDM	Spherical Fuzzy AHP, EDAS, Fuzzy C-means Clustering	European Cities
(K.-L. Wang et al., 2023)	High-Speed Railway	Modelling	Time-Varying DID Model	Chinese Cities
(Mabrouk & Haoying, 2023)	Urban Flood Resilience	MCDM	Fuzzy AHP, VIKOR, WSM, and TOPSIS	Alexandria, Egypt
(Mao et al., 2023)	COVID-19, Public Spaces, Technology	Statistics	Data Analysis	Dongsheng, China
(Rezaei et al., 2023)	Disaster Risks	MCDM	AHP, ordered weighted average (OWA) method	Tehran City, Iran

Reference	Focus Area	Approach	Technique	City/country
(X. Chen et al., 2023)	UR	Modelling	Dynamic Bayesian Network	Fujian Province, China
(Y. Liu et al., 2023)	COVID-19	Statistics	Moran's I Statistics	Beijing, Shanghai, and Tianjin, China
(Yuan & Hu, 2023)	COVID-19	Statistics	Data Analysis	Chinese Cities
(Z. Wang et al., 2023)	Sustainable Development Transformation	MCDM	Entropy weight-TOPSIS	Chinese Cities

Zheng et al. (2018) sought to investigate the correlation between resilience and development, focusing on the city of Beijing. Their methodology involved the creation of a framework incorporating UR indicators. Subsequently, factor analysis was applied to rank the UR index. Boschetti et al. (2017) employed a questionnaire to gauge public understanding of UR and utilized factor analysis to analyze the questionnaire results. Studies centered on seismic resilience, exemplified by Banica et al. (2017) adopted statistical approaches for assessing seismic vulnerabilities. These investigations also integrated MCDM techniques with statistical analysis. Kim & Song (2018) applied factor analysis and cluster analysis in their research to quantify UR, taking climate change into account. Ghouchani et al. (2020) determined the priorities of resilience criteria through exploratory factor analysis. Mao et al. (2023) concentrated on a central public open space in Xinxiang, China, analyzing it as a microcosm of urban dynamics during COVID-19 through data analysis.

Dong et al. (2020) employed entropy evaluation methods and regression models within the context of smart city resilience. In a similar domain, Oke et al. (2020) introduced an alternative statistical model based on one-way ANOVA. The analysis conducted by Da Silva et al. (2019) focused on UR (UR) capacity and its correlation with economic, social, and environmental well-being in smart cities, utilizing descriptive statistics and examining smart cities in the state of São Paulo. Borsekova et al. (2018) presented

evidence on the resilience of urban systems following an external shock, relying on statistical analysis, comparison, and evaluation of extensive datasets.

In addition to studies involving MCDM and statistical techniques, research extends to modeling and optimization, covering areas such as location-allocation problems, mathematical modeling, dynamic agent-based modeling, and system dynamics. For instance, Zhang & Wang (2023) introduced a dynamic UR evaluation model and System Dynamics (SD) approach to simulate UR changes during the COVID-19 pandemic. Li et al. (2020) explored a comprehensive UR concept encompassing governance resilience, material and energy resilience, socio-economic resilience, and infrastructure resilience, using an SD model to illustrate the dynamic UR process. Grinberger & Felsenstein (2016) proposed a dynamic agent-based model to assess the welfare impacts of urban disasters. Cheung et al. (2015) conducted a case study in the Greater London Area, demonstrating the application of location optimization techniques for the deployment of police facilities.

Our investigation reveals the widespread use of various techniques within the domain of UR, and analytical approaches are rapidly advancing. The reviewed articles indicate that the reinforcement of analytical methods is evident through diverse approaches and the utilization of more sophisticated tools.

2.2.5. Industrial Reports on UR

Diverse industrial reports related to UR were compiled through the Google database. The imperative for city municipalities and other organizations to establish strategies for identifying and mitigating vulnerabilities in the rapidly evolving urban landscape is underscored in numerous reports. United Nations Office for Disaster Risk Reduction (2013) aimed to provide critical insights, trends, and implications for building UR. ARUP & The Rockefeller Foundation (2015) presented a framework outlining 12 goals, 52 indicators, and 156 variables categorized under leadership & strategy, health & wellbeing, infrastructure & ecosystems, and economy & society. The Rockefeller Foundation (2019) sought to guide UR efforts, emphasizing integration, risk sensitivity, and long-term planning. Zimmermann et al. (2019) reported on the definition and development of UR, addressing milestones, stakeholder collaborations, financial aspects, sustainability

relationships, and benefits. The report stressed the need for city governance to assess resilience considering multiple risks, advocate for increased public awareness, and leverage digitalization for enhanced information-sharing and robust structures against unforeseen shocks. National Institute of Urban Affairs & The Energy and Resources Institute (2020) proposed a policy brief focusing on promoting and strengthening UR, highlighting significant challenges and enablers for Indian cities. Greater London Authority (2020) conducted a study on the resilience of London, identifying potential shocks and stresses impacting the city's well-being and reviewing UR projects and their implementation. UN-Habitat (2021) aimed to propose a diagnostic and planning tool for UR for managing COVID-19 response and recovery. United Nations Development Programme (2022) presented on building resilience with the UR project after COVID-19 in Yangon region Myanmar. Deloitte (2022) surveyed 200 city leaders and 2000 citizens to explore which cities are becoming resilient and building capacity for change. UN-Habitat (2022) offers suggestions on how cities can create new UR by also addressing smart technologies. Economist Impact (2023) aimed to present a report that will measure the resilience of cities, identify challenges and provide insight into opportunities.

These reports delineate strategic approaches within UR, highlighting crucial features and subtopics of the field. Furthermore, they provide a roadmap for enhancing resilience and detail responses to various disruptive events.

2.3. Findings and Discussion

Objective 1- Identify the principal topics discussed in UR papers:

The initial research objective in this review study aimed to delineate the primary themes within the domain of UR. Based on the analyses conducted in preceding sections, in conjunction with studies exploring UR holistically, the principal research areas within UR encompass: 1) climate change, 2) urban planning, 3) urban hazards and disaster risks, 4) urban sustainability and green infrastructure, 5) the adaptation of UR, and 6) UR and smart cities. These thematic areas are succinctly summarized below.

- **Climate change:** The literature reveals that resilience was initially synonymous with climate resilience. Presently, the imminent risks posed by climate change, such as floods, fires, and drought, have become a global reality. These risks are notably concentrated in urban areas, disproportionately affecting vulnerable populations. The enhancement of integrated UR systems emerges as a crucial strategy for cities to withstand unforeseen stresses arising from climate change. Researchers have directed their focus toward evaluating the impact and awareness of climate change on UR, representing a pivotal area of development. Studies encompassing strategy assessment, awareness building, adaptation, and urban planning play a critical role in addressing the challenges posed by climate change. Ribeiro & Pena Jardim Gonçalves (2019) and L. Wang et al. (2018), highlight climate change as one of the predominant issues explored in the field. Given its status as a fundamental challenge amidst urbanization and population growth, climate change is poised to remain a top priority in the field for the foreseeable future.
- **Urban planning:** Urban planning studies have gained significant importance since the early 2000s, with the integration of resilience emerging as a relatively recent but rapidly growing trend in the UR literature. The concept of resilience in urban planning is regarded as a solution to escalating socio-economic challenges and other risks faced by cities. Despite increased attention in this field, its impact on spatial planning remains underdeveloped. There is a noted absence of a multidimensional and comprehensive approach to UR and urban planning, leading to potential vulnerabilities in cities due to complex land use and insufficient spatial planning (Masnavi et al., 2019). The ongoing COVID-19 pandemic has further prompted a reevaluation of urban services planning, such as transportation, infrastructure, and residential usage based on human proximity (Megahed & Ghoneim, 2020). This shift in understanding is expected to have a profound and transformative impact on future urban planning studies.
- **Urban hazards and disaster risks:** Beyond investigations into climate change, heightened focus in the field of UR research addresses issues related to urban hazards and disaster risks. Researchers and practitioners engage in studies

examining both natural and man-made disasters within urban contexts. These inquiries aim to identify risks in the realm of UR, devise strategies to mitigate them, and explore recovery processes post-disaster. Notably, literature predominantly scrutinizes flood-related disasters, succeeded by earthquakes and landslides. However, there is a recognized need for further research evaluating UR against other critical disaster scenarios such as droughts.

- **Urban sustainability and green infrastructure:** UR plays a pivotal role in enhancing the sustainability of cities, with UR and urban sustainability being intricately connected concepts. In the context of significant changes, adaptability, recovery capabilities, and resilience become imperative for the establishment of a sustainable city. Instances like deforestation near urban areas, for instance, can trigger sudden floods or landslides. Conversely, safeguarding and cultivating the green system are crucial for both resilience and sustainability. Within UR literature, the emerging concept of green infrastructure is notable. For example, L. Li et al. (2020) aimed to identify areas for green infrastructure planning, enhancing urban sustainability and resilience against surface water flood risks. Their study underscores the significance of urban green infrastructure as a pivotal strategy, contributing significantly to mitigating rainwater flow and ensuring city sustainability. Green infrastructure plays a critical role in bolstering city safety, human health, well-being, and resilience to extreme climatic conditions. Despite the wealth of existing studies, future research should delve more deeply into the multifaceted role of green infrastructure in UR and sustainability (Titz & Chiotha, 2019).
- **The adaptation of UR:** In the present day, cities confront a multitude of challenges arising from climate change-induced disasters and unforeseen events in our industrial and technological world. To mitigate these challenges with minimal impact, both practitioners and scholars are compelled to delve into the study of adaptation, transforming it into a crucial research domain. Diaz-Sarachaga and Jato-Espino's literature review (Diaz-Sarachaga & Jato-Espino, 2020), underscores that the urban disadvantaged groups emerge as the most vulnerable to these events, accentuating the significance of adaptation studies, particularly in

cities where they are prevalent. The ongoing COVID-19 pandemic has further underscored the necessity for proactive preparation, comprehension of priorities, risk assessments, and the identification of critical elements for adaptation. The lessons learned from this crisis should undoubtedly heighten awareness and contribute to the establishment of more resilient cities.

- **UR and smart cities:** The exploration of smart cities has gained considerable attention from both practitioners and scholars in recent years, aiming to enhance the quality of life and provide advanced solutions through the integration of smart technologies and data. Resilience has emerged as a pivotal element in this context, with digitalization holding the potential to uniquely support resilience and contribute to improved urban development (Arafah et al., 2018). Particularly in the context of the ongoing COVID-19 pandemic, one of the most pressing challenges affecting UR, the utilization of smart city applications and emerging technologies becomes imperative (S. Yang & Chong, 2021). An analysis of the literature reveals a notable increase in the presentation of integrated smart and resilient city models over the past five years. Both conceptual and analytical models have been put forth to assess the resilience of smart cities. For instance, Zhu et al. (2019) employ MCDM approaches to evaluate smart cities in China. In their literature study on the subject, Zhu et al. (2020) stated that resilient cities have positive effects on smart cities. In addition, they emphasized that both smart cities and resilient cities are crucial for urban planning, stressing the goal of building “resilient smart cities”. While interest in smart and resilient cities is growing, it remains a subject that warrants continued exploration in future research endeavors.

Objective 2- Illuminate knowledge gaps and contribute to the future research agenda for UR:

Aligned with the second research objective, the literature review revealed gaps in the field of UR, prompting the identification of future research directions. These include 1) analytical methods and fuzzy approaches, 2) UR practices, 3) vulnerability analysis with

multiple factors, 4) urban supply chain and logistics, and 5) UR technology applications. The summary of these research gaps is presented below.

- **Analytical methods and fuzzy approaches:** The existing literature on UR reveals a research gap pertaining to analytical methods and fuzzy approaches. While various analytical strategies have been employed, there is a prevalent dominance of conceptual models. This study advocates a shift towards emphasizing analytical methods, suggesting that commencing with a conceptual understanding before proceeding to quantitative assessments could yield more effective results for UR. It is recommended that future research places emphasis on diverse MCDM techniques, extending beyond statistical methods. Additionally, there is a notable absence of approaches accommodating the evaluation of multiple decision-makers, and addressing this gap can contribute to more objective evaluations in decision-making processes. Furthermore, the incorporation of fuzzy methods in applications is proposed for generating realistic outcomes that account for uncertainties. Subsequent studies could explore approaches integrating various fuzzy group decision-making methods.
- **UR practices:** The existing gap in the literature pertains to UR practices. The literature review process has unveiled numerous UR frameworks proposed in both academic studies and industrial reports, with one notable example being from ARUP (2014). This study delineates the primary goals, indicators, and qualities of resilient cities, offering clarity on the areas that cities need to develop within the resilience scope, such as infrastructure, economy, workforce, and security. While several UR frameworks have emerged, scholarly efforts have predominantly focused on defining the concept or characteristics of UR rather than outlining practical policy implementation for UR promotion. A significant global initiative addressing this gap is the "100 Resilient Cities" project by the Rockefeller Foundation (2020). This project aims to formulate resilience development strategies covering institutional, economic, social, and environmental dimensions for one hundred cities worldwide. The project underscores that a city's resilience strategy must be reflective, resourceful, inclusive, integrated, robust, redundant, and flexible for effective implementation.

Evaluating the strategies applied in UR, understanding how and under what conditions these applications impact cities, will enhance the effectiveness of proposed frameworks. This analysis provides crucial opportunities for practitioners to learn from each other and guide decision-makers.

- **Vulnerability analysis with multiple factors:** The third identified gap in the existing literature pertains to vulnerability analysis that considers multiple factors. In the course of the literature review, it became evident that prior studies in the field of UR predominantly focused on assessing risks associated with individual disasters, as highlighted in the preceding section. Notably, a common limitation among these studies is their concentration on a singular type of disaster, such as floods, landslides, or fires. Diaz-Sarachaga & Jato-Espino (2020) also underscore this deficiency in their literature review. Consequently, the findings underscore the necessity of developing an updated framework capable of addressing vulnerabilities related to multiple hazards worldwide, aiming to fill the identified research gaps. Such a framework would not only address these gaps but also contribute to the literature by establishing a globally accepted model for UR.
- **Urban supply chain and logistics:** The most recent gap identified in the UR literature pertains to urban supply chains and logistics. Disasters impact cities differently, necessitating a thorough examination of how supply chain and logistics systems function during disasters, determining trustworthy cities, and planning the logistics network routes (Therrien et al., 2020). The profound impact of disasters and global crises on people and cities underscores the growing urgency for studies aimed at enhancing logistics and supply chain activities both pre and post-disasters. Particularly in the current context of the ongoing COVID-19 pandemic, logistics and supply chains have experienced significant disruptions, revealing the inadequacy of many existing resilience strategies. This situation prompts critical discussions on the significance of UR and warrants further assessment in the future. Subsequent research endeavors can address this gap by concentrating on resilience in urban logistics and urban supply chains.

- UR technology applications: Emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI), digital twins, and big data have the potential to significantly enhance UR, enabling cities to better withstand and recover from disruptions. By leveraging these technologies, city planners can improve operational efficiency, anticipate disaster scenarios, and enhance critical infrastructure to create a more robust and adaptable urban ecosystem (Therias & Rafiee, 2023). Further research is needed to determine the optimal ways and areas to integrate these technologies into UR infrastructure, and it is essential to collaborate with sector experts to ensure that best practices are followed.

As a result of conducting a thorough literature review on UR, the section has identified the main issues and research gaps in this field. It is noteworthy that urban logistics is one of the most crucial functions of cities, yet there is a lack of a comprehensive study addressing resilience in this domain, indicating a research gap in the literature. Hence, this thesis aims to bridge this gap by discussing the issue of RUL and presenting a development framework that could serve as a road map for future research in this area.

3. THEORETICAL BACKGROUND

3.1. Overview of Fermatean Fuzzy Sets (FFSs)

Fuzzy set theory was first introduced by Zadeh (1965). The fuzzy set is an extension of the characteristic function in classical sets and is characterized by a belonging function. Here, the Decision-Makers (DMs) can determine the membership degree in the range of $[0, 1]$. Elements have a certain degree of membership in that set. It has a definition that enables the inclusion of variable real-life judgments into calculations. The interest in fuzzy logic is growing gradually (Entemann, 2002; Jana & Mahanta, 2023; J.-S. Pan et al., 2023).

After fuzzy sets were defined, Intuitionistic Fuzzy Sets (IFS) were introduced by K.T. Atanassov (1986) as a generalization of fuzzy sets. While classical fuzzy sets are represented by membership degree only, IFSs are characterized by membership and non-membership degrees of all objects in the universe, and their sum is always in the range of $[0, 1]$ (Atanassov, 2012). IFS cannot be defined when the sum of the membership and non-membership grades is greater than 1. Therefore, to address this deficiency, the Pythagorean Fuzzy Set (PFS) was developed by Yager (2013) to generalize the IFS concept. While the sum of membership degrees in IFS is in the range of $[0, 1]$, in PFS, the sum of the squares of the degrees of membership and non-membership falls into the range of $[0, 1]$. This shows that PFS includes IFS (X. Zhang & Xu, 2014).

They are both commonly used in decision-making applications, yet they have some differences in their definition and properties. PFSs are defined based on the Pythagorean theorem, which allows the representation of uncertainty in terms of distance. PFS has attracted the attention of many experts and researchers in a short time and has been applied to decision-making problems in many different fields (Joshi, 2019; Y. Liu et al., 2020), such as technological innovation risk evaluation (Liang et al., 2015), investment

decision (Aghamohagheghi et al., 2019), assessment on emergency response capabilities (Y. Du et al., 2017), transportation problem applications (Saikia et al., 2023), renewable energy resource evaluation (Geetha et al., 2022) and technology provider selection (F. Zhou & Chen, 2022). It has been observed that there are cases where the square sum of membership and non-membership degrees is greater than 1. IFS or PFS could not explain and solve these problems (F. Zhou & Chen, 2022). Senapati and Yager (2020) proposed the FFSs in this direction. Senapati and Yager (2020) conducted an analysis of the interrelationships among FFS, IFS, and PFS. They observed that IFS is a specific instance or special case within the broader framework of PFS, and, conversely, FFS is an extension or generalization of PFS. The limit of squares sums of the membership and non-membership degrees determined by the PFS has been expanded by defining the FFS Senapati and Yager (2020). In FFS, the cubic sum of membership and non-membership values of an object are in the range of $[0, 1]$ (Akram, Ali, et al., 2022). FFS theory plays an important role in various fields, as it is an advantageous and powerful concept for dealing with uncertain information (D. Liu, Liu, & Chen, 2019). In this section, some basic explanations of FFSs are introduced that are frequently used in the subsequent sections of the thesis (Alkan & Kahraman, 2022; Bouraima et al., 2023; Jeevaraj, 2021; Seikh & Mandal, 2023; Senapati & Yager, 2019a; Shit & Ghorai, 2021).

Let X be a universe of discourse. An FFS F in X is defined as,

$$F = \{\langle x, \mu_F(x), \nu_F(x) \rangle : x \in X\} \quad (3.1.1)$$

where

$$\begin{aligned} \mu_F(x) &: X \rightarrow [0,1] \\ \nu_F(x) &: X \rightarrow [0,1] \end{aligned}$$

denotes degree of membership and non-membership of each element $x \in X$ to the set F , respectively. Also,

$$0 \leq \mu_F(x)^3 + \nu_F(x)^3 \leq 1 \quad (3.1.2)$$

for all $x \in X$. The degree of hesitancy is defined as follows:

$$\pi_F(x) = \sqrt[3]{1 - \mu_F(x)^3 - \nu_F(x)^3} \quad (3.1.3)$$

Let $F = (\mu_F, \nu_F)$, $F_1 = (\mu_{F_1}, \nu_{F_1})$ and $F_2 = (\mu_{F_2}, \nu_{F_2})$ be the FFSs, their operations are defined as follows:

$$F_1 \cap F_2 = (\min \{\mu_{F_1}, \mu_{F_2}\}, \max \{\nu_{F_1}, \nu_{F_2}\}) \quad (3.1.4)$$

$$F_1 \cup F_2 = (\max \{\mu_{F_1}, \mu_{F_2}\}, \min \{\nu_{F_1}, \nu_{F_2}\}) \quad (3.1.5)$$

$$F^c = (\nu_F, \mu_F) \quad (3.1.6)$$

Let $F = (\mu_F, \nu_F)$, $F_1 = (\mu_{F_1}, \nu_{F_1})$ and $F_2 = (\mu_{F_2}, \nu_{F_2})$ be the FFSs and $\lambda > 0$, their operations are defined as follows:

$$F_1 \boxplus F_2 = \left(\sqrt[3]{\mu_{F_1}^3 + \mu_{F_2}^3 - \mu_{F_1}^3 \mu_{F_2}^3}, \nu_{F_1} \nu_{F_2} \right) \quad (3.1.7)$$

$$F_1 \boxtimes F_2 = \left(\mu_{F_1} \mu_{F_2}, \sqrt[3]{\nu_{F_1}^3 + \nu_{F_2}^3 - \nu_{F_1}^3 \nu_{F_2}^3} \right) \quad (3.1.8)$$

$$\lambda F = \left(\sqrt[3]{1 - (1 - \mu_F^3)^\lambda}, \nu_F^\lambda \right) \quad (3.1.9)$$

$$F^\lambda = \left(\mu_F^\lambda, \sqrt[3]{1 - (1 - \nu_F^3)^\lambda} \right) \quad (3.1.10)$$

Let $F = (\mu_F, \nu_F)$ be the FFSs then the score and accuracy functions are defined as follows:

$$Score(F) = \mu_F^3 - \nu_F^3 \quad (3.1.11)$$

$$acc(F) = \mu_F^3 + \nu_F^3 \quad (3.1.12)$$

Let $F_i = (\mu_{F_i}, \nu_{F_i})$, $(i = 1, 2, \dots, n)$ be the FFSs and $w = (w_1, w_2, \dots, w_n)^T$ be the weight vector of F_i with $\sum_{i=1}^n w_i = 1$, then a Fermatean Fuzzy Weighted Average (FFWA) operator is a function $FFWA : F^n \rightarrow F$, where

$$FFWA(F_1, F_2, F_3, \dots, F_n) = (\sum_{i=1}^n w_i \mu_{F_i}, \sum_{i=1}^n w_i \nu_{F_i}) \quad (3.1.13)$$

For any two real numbers (a, b) and for $\beta \geq 1$, the Dombi triangular norm $D(a, b)$ and co-norm $S(a, b)$ are defined as follows:

$$T(a, b) = \frac{1}{1 + \left\{ \left(\frac{1-a}{a} \right)^\beta + \left(\frac{1-b}{b} \right)^\beta \right\}^{1/\beta}} \quad (3.1.14)$$

$$S(a, b) = 1 - \frac{1}{1 + \left\{ \left(\frac{1-a}{a} \right)^\beta + \left(\frac{1-b}{b} \right)^\beta \right\}^{1/\beta}} \quad (3.1.15)$$

where $(a, b) \in (0, 1) \times (0, 1)$.

Let $F_i = (\mu_{F_i}, \nu_{F_i})$ be the FFSs and $w = (w_1, w_2, \dots, w_n)^T$ be a weight vector of F_i and $\sum_{i=1}^n w_i = 1$, $w_i > 0$. The Fermatean Fuzzy Dombi Weighted Average (FFDWA) operator is given as follows:

$$FFDWA(F_1, F_2, \dots, F_n) =$$

$$\left(\sqrt[3]{1 - \frac{1}{1 + \left\{ \sum_{i=1}^n w_i \left(\frac{\mu_{F_i}^3}{1 - \mu_{F_i}^3} \right)^\beta \right\}^{1/\beta}}}}, \sqrt[3]{\frac{1}{1 + \left\{ \sum_{i=1}^n w_i \left(\frac{\nu_{F_i}^3}{1 - \nu_{F_i}^3} \right)^\beta \right\}^{1/\beta}}} \right) \quad (3.1.16)$$

Let X be a non-empty set. An IVFFS $\tilde{F}$ in X is defined as follows:

$$\tilde{F} = \{ \langle x, \mu_F(x), \nu_F(x) \rangle : x \in X \}$$

where

$$\begin{aligned} \mu_{\tilde{F}}(x) : X &\rightarrow [0,1] \\ \nu_{\tilde{F}}(x) : X &\rightarrow [0,1] \end{aligned}$$

(3.1.17)

denotes the degree of membership and non-membership of each element $x \in X$ to the set $\tilde{F}$.

For each $x \in X$, $\mu_{\tilde{F}}(x)$ and $\nu_{\tilde{F}}(x)$ are immediate intervals and their lower and upper bounds are denoted by $\mu_{\tilde{F}}^L(x)$, $\mu_{\tilde{F}}^U(x)$, $\nu_{\tilde{F}}^L(x)$, $\nu_{\tilde{F}}^U(x)$. Therefore, $\tilde{F}$ can be expressed as follows:

$$\begin{aligned} \mu_{\tilde{F}}(x) &= [\mu_{\tilde{F}}^L(x), \mu_{\tilde{F}}^U(x)] \subseteq [0,1], \nu_{\tilde{F}}(x) = [\nu_{\tilde{F}}^L(x), \nu_{\tilde{F}}^U(x)] \subseteq [0,1] \\ \text{where } 0 &\leq \mu_{\tilde{F}}^U(x)^3 + \nu_{\tilde{F}}^U(x)^3 \leq 1 \end{aligned} \quad (3.1.18)$$

For all $x \in X$, the degree of hesitancy is defined as follows:

$$\pi_{\tilde{F}}(x) = [\pi_{\tilde{F}}^L(x), \pi_{\tilde{F}}^U(x)] = \left[\sqrt[3]{1 - (\mu_{\tilde{F}}^U(x))^3 - (\nu_{\tilde{F}}^U(x))^3}, \sqrt[3]{1 - (\mu_{\tilde{F}}^L(x))^3 - (\nu_{\tilde{F}}^L(x))^3} \right] \quad (3.1.19)$$

Let $\tilde{F} = ([\mu_{\tilde{F}}^L, \mu_{\tilde{F}}^U], [\nu_{\tilde{F}}^L, \nu_{\tilde{F}}^U])$, $\tilde{F}_1 = ([\mu_{\tilde{F}_1}^L, \mu_{\tilde{F}_1}^U], [\nu_{\tilde{F}_1}^L, \nu_{\tilde{F}_1}^U])$ and $\tilde{F}_2 = ([\mu_{\tilde{F}_2}^L, \mu_{\tilde{F}_2}^U], [\nu_{\tilde{F}_2}^L, \nu_{\tilde{F}_2}^U])$ be the IVFFSs and $\lambda > 0$, their operations are described as follows:

$$\tilde{F}_1 \oplus \tilde{F}_2 = \left(\left[\sqrt[3]{(\mu_{\tilde{F}_1}^L)^3 + (\mu_{\tilde{F}_2}^L)^3 - (\mu_{\tilde{F}_1}^L)^3 (\mu_{\tilde{F}_2}^L)^3}, \sqrt[3]{(\mu_{\tilde{F}_1}^U)^3 + (\mu_{\tilde{F}_2}^U)^3 - (\mu_{\tilde{F}_1}^U)^3 (\mu_{\tilde{F}_2}^U)^3} \right], [\nu_{\tilde{F}_1}^L \nu_{\tilde{F}_2}^L, \nu_{\tilde{F}_1}^U \nu_{\tilde{F}_2}^U] \right) \quad (3.1.20)$$

$$\tilde{F}_1 \otimes \tilde{F}_2 = \left([\mu_{\tilde{F}_1}^L \mu_{\tilde{F}_2}^L, \mu_{\tilde{F}_1}^U \mu_{\tilde{F}_2}^U], \left[\sqrt[3]{(\nu_{\tilde{F}_1}^L)^3 + (\nu_{\tilde{F}_2}^L)^3 - (\nu_{\tilde{F}_1}^L)^3 (\nu_{\tilde{F}_2}^L)^3}, \sqrt[3]{(\nu_{\tilde{F}_1}^U)^3 + (\nu_{\tilde{F}_2}^U)^3 - (\nu_{\tilde{F}_1}^U)^3 (\nu_{\tilde{F}_2}^U)^3} \right] \right) \quad (3.1.21)$$

$$\lambda \tilde{F} = \left(\left[\sqrt[3]{1 - \left(1 - (\mu_{\tilde{F}}^L)^3\right)^\lambda}, \sqrt[3]{1 - \left(1 - (\mu_{\tilde{F}}^U)^3\right)^\lambda} \right], \left[(v_{\tilde{F}}^L)^\lambda, (v_{\tilde{F}}^U)^\lambda \right] \right) \quad (3.1.22)$$

$$\tilde{F}^\lambda = \left(\left[(\mu_{\tilde{F}}^L)^\lambda, (\mu_{\tilde{F}}^U)^\lambda \right], \left[\sqrt[3]{1 - \left(1 - (v_{\tilde{F}}^L)^3\right)^\lambda}, \sqrt[3]{1 - \left(1 - (v_{\tilde{F}}^U)^3\right)^\lambda} \right] \right) \quad (3.1.23)$$

Let $\tilde{F} = ([\mu_{\tilde{F}}^L, \mu_{\tilde{F}}^U], [v_{\tilde{F}}^L, v_{\tilde{F}}^U])$ be an IVFFS. The score function of $\tilde{F}$ is explained as follows:

$$S(\tilde{F}) = \frac{(\mu_{\tilde{F}}^L)^3 + (\mu_{\tilde{F}}^U)^3 - (v_{\tilde{F}}^L)^3 - (v_{\tilde{F}}^U)^3}{2} \quad (3.1.24)$$

Let $\tilde{F}_1 = ([\mu_{\tilde{F}_1}^L, \mu_{\tilde{F}_1}^U], [v_{\tilde{F}_1}^L, v_{\tilde{F}_1}^U])$ and $\tilde{F}_2 = ([\mu_{\tilde{F}_2}^L, \mu_{\tilde{F}_2}^U], [v_{\tilde{F}_2}^L, v_{\tilde{F}_2}^U])$ be the IVFFSs. The Euclidean distance between $\tilde{F}_1$ and $\tilde{F}_2$ is as follows:

$$D_E(\tilde{F}_1, \tilde{F}_2) = \frac{\sqrt{D_\mu + D_\nu + D_{\pi l} + D_{\pi u}}}{6} = \frac{\sqrt{\left(\mu_{\tilde{F}_1}^3 - \mu_{\tilde{F}_2}^3\right)^2 + \left(\mu_{\tilde{F}_1}^3 - \mu_{\tilde{F}_2}^3\right)^2 + \left(v_{\tilde{F}_1}^3 - v_{\tilde{F}_2}^3\right)^2 + \left(v_{\tilde{F}_1}^3 - v_{\tilde{F}_2}^3\right)^2 + \left((1 - \mu_{\tilde{F}_1}^3 - v_{\tilde{F}_1}^3) - (1 - \mu_{\tilde{F}_2}^3 - v_{\tilde{F}_2}^3)\right)^2 + \left((1 - \mu_{\tilde{F}_1}^3 - v_{\tilde{F}_1}^3) - (1 - \mu_{\tilde{F}_2}^3 - v_{\tilde{F}_2}^3)\right)^2}}{6} \quad (3.1.25)$$

Let $\tilde{F}_i = ([\mu_{\tilde{F}_i}^L, \mu_{\tilde{F}_i}^U], [v_{\tilde{F}_i}^L, v_{\tilde{F}_i}^U]), (i = 1, 2, \dots, n)$ be a set of IVFFSs and $w = (w_1, w_2, \dots, w_n)^T$ be a weight vector of $\tilde{F}_i$ and $\sum_{i=1}^n w_i = 1$, then an Interval-Valued Fermatean Fuzzy Weighted Average (IVFFWA) operator, IVFFWA: $\tilde{F}^n \rightarrow \tilde{F}$, is as follows:

$$IVFFWA = (\tilde{F}_1, \tilde{F}_2, \dots, \tilde{F}_n) = \left(\left[\sqrt[3]{\left(1 - \prod_{i=1}^n \left(1 - (\mu_{\tilde{F}_i}^L)^3\right)^{w_i}\right)}, \sqrt[3]{\left(1 - \prod_{i=1}^n \left(1 - (\mu_{\tilde{F}_i}^U)^3\right)^{w_i}\right)} \right], \left[\prod_{i=1}^n (v_{\tilde{F}_i}^L)^{w_i}, \prod_{i=1}^n (v_{\tilde{F}_i}^U)^{w_i} \right] \right) \quad (3.1.26)$$

Let $\tilde{F}_i = ([\mu_{\tilde{F}_i}^L, \mu_{\tilde{F}_i}^U], [v_{\tilde{F}_i}^L, v_{\tilde{F}_i}^U]), (i = 1, 2, \dots, n)$ be a set of IVFFSs. Then the Interval-Valued Fermatean Fuzzy Dombi Weighted Average (IVFFDWA) operator is a function IVFFDWA: $\tilde{F}^n \rightarrow \tilde{F}$, where $w = (w_1, w_2, \dots, w_n)^T$ be a weight vector of $\tilde{F}_i$ and $\sum_{i=1}^n w_i = 1, w_i > 0$.

$$IVFFDWA = (\tilde{F}_1, \tilde{F}_2, \dots, \tilde{F}_n) =$$

$$\left[\sqrt[3]{1 - \frac{1}{1 + \left\{ \sum_{i=1}^n w_i \left(\frac{(\mu_{F_i}^l)^3}{1 - (\mu_{F_i}^l)^3} \right)^\beta \right\}^{\frac{1}{\beta}}}}, \sqrt[3]{\frac{1}{1 + \left\{ \sum_{i=1}^n w_i \left(\frac{(\mu_{F_i}^u)^3}{1 - (\mu_{F_i}^u)^3} \right)^\beta \right\}^{\frac{1}{\beta}}}}}, \right. \\ \left. \sqrt[3]{1 - \frac{1}{1 + \left\{ \sum_{i=1}^n w_i \left(\frac{(\nu_{F_i}^l)^3}{1 - (\nu_{F_i}^l)^3} \right)^\beta \right\}^{\frac{1}{\beta}}}}, \sqrt[3]{\frac{1}{1 + \left\{ \sum_{i=1}^n w_i \left(\frac{(\nu_{F_i}^u)^3}{1 - (\nu_{F_i}^u)^3} \right)^\beta \right\}^{\frac{1}{\beta}}}}}, \right] \quad (3.1.27)$$

Despite the pivotal role and significant advantages that FFS holds in handling uncertain information, the current literature lacks a thorough analysis of key areas and applications. This deficiency extends to research gaps and outcomes, hindering a nuanced understanding of FFS. This gap in comprehensive analysis impedes the full realization of FFS's potential and calls for a more robust exploration of its foundational aspects and practical applications. Addressing this gap is crucial for advancing the theoretical foundation and facilitating future advancements in the field. In light of this deficiency, a detailed literature review of FFSs is given in the following section.

3.1.1. Literature Review of FFSs

Through the literature review, some shortcomings of the FFS literature can be highlighted, and new research directions can be discussed. The number of studies on FFS in the literature is limited because it is a relatively new field. As a basis for the literature review on FFSs, "Fermatean Fuzzy Set" selection criteria were searched as keywords in Web of Science (WoS) and Scopus databases, and 470 documents obtained.

Specifically, the selection of source type "journal," document type "article," and language "English" was chosen. This meticulous curation process resulted in the selection of source type "journal" and document type "article", yielding a refined pool of 421 documents. Notably, 49 documents, spanning conference proceedings, books, editorials, and notes,

were excluded from the original 470, streamlining the corpus. The rationale behind selecting "journal" as the source type is rooted in the preference for peer-reviewed scholarly works, ensuring a higher level of scrutiny and quality in the included literature (R. Kumar et al., 2022; S. Kumar et al., 2022). Similarly, the choice of document type "article" further refines the selection, prioritizing in-depth research contributions over other document types such as conference proceedings, books, editorials, and notes.

Subsequently, a language filter was applied. This additional refinement led to a final selection of 420 documents, with only one document not in the English language.

The subsequent phase is contingent on the systematic elimination of duplicated documents identified in both Scopus and WoS. After that, a judicious decision was made to exclusively include journals assessed within the esteemed Q1 and Q2 lists of Scopus and WoS (Kocak et al., 2023; Mohammadi & Sakhteh, 2023). Initially, the removal of duplicate works resulted in a refined corpus comprising 265 documents. The removal of duplicates in both databases resulted in the exclusion of 155 documents from the initial pool of 420, thereby streamlining the corpus. Subsequently, an additional curation step involved the exclusion of Q3 and Q4 journals, leading to a further reduction to 152 documents. In the final purification step, a meticulous process of abstract reading and keyword verification was undertaken following the four-eye principle, culminating in the ultimate refinement of the corpus to a robust selection of 135 documents.

During the four-eye principle reading process, the following criteria are utilized:

- Generic articles not having any Fermatean Fuzzy Number (FFN) sets, operations, or operators.
- Articles do not address any specific use of FFS operations and extensions.

In conducting the descriptive analysis to capture the trend in FFS publications, the initial focal point is the presentation of Figure 3.2, illustrating the distribution of articles on a yearly basis. Notably, the inclusion of Early Access articles from 2024 has been omitted from the figure, strategically opted to foster a clearer representation of the increasing trend in FFS publications.

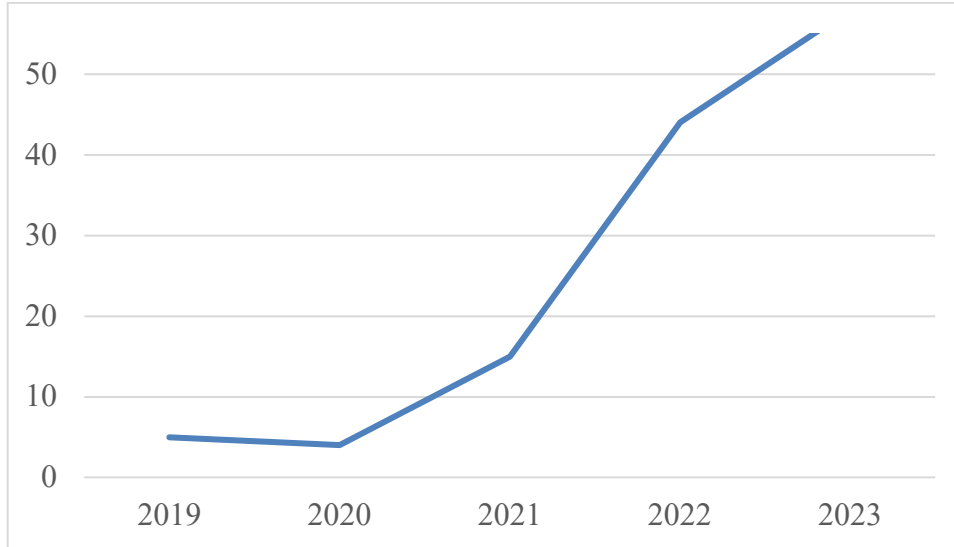


Figure 3.1: Year wise distribution of the FFSs studies (2023 studies up to November 27, 2023)

The evolving interest in FFSs is vividly reflected in the dynamic publication trends observed over recent years. Beginning with a modest representation in 2019 and 2020, the subsequent years, particularly 2022 and 2023, witnessed a substantial surge in scholarly contributions. This escalating trajectory not only underscores the growing significance of FFS but also signifies a heightened interest and engagement within the academic community. It's worth mentioning that the inclusion of Early Access articles from 2024 further emphasizes the ongoing momentum in FFS research, despite the year being incomplete at the time of this analysis. This escalating trajectory underscores the growing significance and scholarly activity surrounding FFSs.

FFS theory introduces a new approach to uncertainty in decision-making. Currently, researchers are exploring the potential of FFS and applying it to various decision-making problems. Most of the FFS studies that have been conducted so far have focused on MCDM problems. FFSs provide a nuanced way of modeling uncertainties and imprecisions, which can be particularly useful in decision-making scenarios where precise information is hard to come by. These studies are detailed in the following sections.

3.1.1.1. MCDM Methods Used in FFSs

Table 3.1 summarizes the several MCDM methods implied in the FFS literature. This table shows that the TOPSIS method, which is one of the most popular MCDM methods, is the most frequently implied technique in the FFS studies. The FFS-TOPSIS approach measures the degree of membership and non-membership in the evaluation process, considering the uncertainties in the problem. FFS-TOPSIS can determine the distance between each evaluated item and the PIS and NIS, making it a method that attains more data than additional MCDM methods (Senapati & Yager, 2020).

The second prevalent MCDM technique in FFS literature is the CRITIC method. Using this method, it is possible to cope with the problems related to fuzzy sets and obtain more accurate results by avoiding subjectivity using the CRITIC method (Saraji et al., 2021). The third most common techniques are CODAS, COPRAS, DEMATEL and SWARA with their use in seven articles. Using the CODAS method helps to combine the two distance measures and reduce the possibility of instability in the solution by providing a more rational analysis and greater flexibility between distance-based methods (Biswas et al., 2021). COPRAS stands out with its ability to simultaneously describe the ratios to both ideal and anti-ideal solutions (Akram, Ramzan, et al., 2022). DEMATEL is particularly useful in analyzing complex systems and representing interrelationships visually, while SWARA provides a systematic and transparent approach to weight assessment, which reduces subjectivity and enables efficient decision-making (G. Gonzales et al., 2022). CoCoSo and MULTIMOORA are the fourth most used methods with their use in six articles. CoCoSo has minimal impact on the results in case the alternatives change and supports the precision of the decision-making system (Lai et al., 2022). MULTIMOORA is a powerful tool that evaluates all objectives, considers all interactions between alternatives and objectives simultaneously (Rani & Mishra, 2021).

Table 3.1: MCDM methods used in FFS studies

MCDM Method	References	Application Areas
TOPSIS	(Akram, Shahzadi, et al., 2022; Alahmadi et al., 2023; Amman et al., 2023; Aydoğan & Ozkir, 2024; Bouraima et al., 2023; Fahmi, 2023; Fahmi et al., 2023; Golui et al., 2024; Hooshangi et al., 2023; Karuppiah & Sankaranarayanan, 2023; Kirişci & Simsek, 2023; D. Liu, Liu, & Chen, 2019; Qi et al., 2024; Senapati & Yager, 2019a, 2020; Shahzadi et al., 2023; S. Yang et al., 2022; S. Zeng, Gu, et al., 2023)	Health, Logistics and Supply Chain Management, Finance, Agriculture, Project Investment, Risk Management, Construction, Sustainable Development, Energy, Construction
CRITIC	(Aro et al., 2022; Erdogan & Ayyildiz, 2022; R. Gonzales et al., 2022; Hezam, Mishra, et al., 2023; A. Mishra, Bullet, et al., 2022; A. R. Mishra, Chen, et al., 2023; A. R. Mishra, Rani, et al., 2023; Qin et al., 2023; Rani, Mishra, Deveci, et al., 2022; Saraji et al., 2021; Tan et al., 2022)	Logistics and Supply Chain Management, Health, Sustainable Development, Education, Risk Management, Finance, Transportation
COPRAS	(Akram, Ramzan, et al., 2022; Görçün, Aytekin, et al., 2023; Korucuk et al., 2022; P. Liu et al., 2022; A. Mishra, Rani, Saha, Senapati, et al., 2022; Rani, Mishra, Deveci, et al., 2022; Saraji et al., 2021)	Sustainable Development, Manufacturing, Energy, Industry 4.0 adoption
CODAS	(Akram, Niaz, et al., 2022; Aro et al., 2022; Biswas et al., 2021; Erdogan & Ayyildiz, 2022; Farid et al., 2023; R. Gonzales et al., 2022; Simic, Gokasar, et al., 2022)	Logistics and Supply Chain Management, Construction, Health, Education, Technology, Transportation
DEMATEL	(G. Gonzales et al., 2022; Kao et al., 2022; Karuppiah et al., 2022, 2023; Karuppiah & Sankaranarayanan, 2023; Moktadir & Ren, 2023b; Y. Yang et al., 2024)	Economy, Sustainable Development, Education, Energy, Waste Management

MCDM Method	References	Application Areas
SWARA	(Aydoğan & Ozkir, 2024; Ayyildiz, 2022; Deveci, Varouchakis, et al., 2023; Görçün, Aytekin, et al., 2023; Hezam, Mishra, et al., 2023; Korucuk et al., 2022; Seikh & Mandal, 2023)	Energy, Risk Management, Waste Management
CoCoSo	(Q. Chen et al., 2022; Hezam, Rani, et al., 2023; Lai et al., 2022; A. Mishra, Rani, Saha, Hezam, et al., 2022; Simic, Ivanovic, et al., 2022; D. Wei et al., 2022)	Risk Management, Logistics and Supply Chain Management, Blockchain, Waste Management, Urban Planning, Manufacturing
MULTIMOORA	(Akram & Bibi, 2023; Deveci, Gokasar, et al., 2023; Luo & Liu, 2022; Narayanamoorthy et al., 2022; Rani & Mishra, 2021; Y. Yang et al., 2024)	Energy, Sustainable Development, Transportation, Urban Planning
WASPAS	(Çolak & Lezki, 2023; Keshavarz-Ghorabae et al., 2020; A. Mishra & Rani, 2021; Rani & Mishra, 2022; Rao & Sujatha, 2023)	Waste Management, Logistics and Supply Chain Management
AHP	(Alkan & Kahraman, 2022; Bouraima et al., 2023; Karuppiah et al., 2023; Karuppiah & Sankaranarayanan, 2023; S. Zeng et al., 2022)	Education, Logistics and Supply Chain Management, Waste Management, Construction
BWM	(Gao et al., 2024; Gul & Ak, 2022; D. Wei et al., 2022; S. Zeng, Chen, et al., 2023)	Aviation, Logistics and Supply Chain Management, Waste Management
ELECTRE	(Akram, Bibi, et al., 2023; Kirisci et al., 2022; L.-P. Zhou et al., 2021)	Health, Technology
EDAS	(A. Mishra, Bullet, et al., 2022; Niu et al., 2022; S. Zeng, Chen, et al., 2023)	Urban Planning, Logistics and Supply Chain Management

MCDM Method	References	Application Areas
TODIM	(D. Liu, Liu, & Wang, 2019; Muktadir & Ren, 2023a; Y. Pan et al., 2023)	Construction, Logistics and Supply Chain Management, Waste Management
ARAS	(Gül, 2021; Rani, Mishra, Saha, et al., 2022)	Waste Management, Health
MABAC	(Biswas et al., 2023; Tan et al., 2022)	Risk Management, Technology
FUCOM	(Biswas et al., 2021; Görçün, Pamucar, et al., 2023)	Technology
PROMETHEE	(Akram & Bibi, 2023; Seikh & Mandal, 2023)	Finance, Waste Management
VIKOR	(Gao et al., 2024; Gül, 2021)	Health, Waste Management
WPM	(Senapati & Yager, 2019b)	Construction
SMART	(Keshavarz-Ghorabae et al., 2020)	Logistics and Supply Chain Management
SAW	(Gül, 2021)	Health
DEA	(Akram, Shah, et al., 2022a)	Transportation
BRAW	(Q. Chen et al., 2022)	Risk Management
LOPCOW	(Niu et al., 2022)	Urban Planning
ITARA	(Simic, Torkayesh, et al., 2022)	Waste Management
QFD	(Seker & Aydin, 2023)	Transportation
MAIRCA	(Görçün, Pamucar, et al., 2023)	Technology
WINGS	(Muktadir & Ren, 2023a)	Waste Management

When the fifth most common MCDM methods in FFS studies are examined, the methods appeared as WASPAS and AHP. It has been observed that the use of AHP increased in 2023. AHP is a method used by practitioners in various fields in the literature due to its compatibility with hierarchical decision structures and its ability to make precise pairwise

comparisons effectively. On the other hand, while ANP offers advantages in addressing interdependencies and feedback loops, it has not yet been used with FFSs. ANP's emphasis on network structures may be overly complex for decision scenarios where hierarchical representation is sufficient. The inherent adaptability and simplicity of AHP, together with its compatibility with FFSs, make it a well-suited method for decision modeling in scenarios where a more complex network structure is not a prerequisite.

Each MCDM method has its advantages and disadvantages. Concerning these benefits and limitations from a single MCDM technique, most studies preferred using integrated MCDM methods to eliminate these restraints. Studies using the integrated MCDM method in FFS literature are shown in Table 3.2. The use of integrated MCDM techniques empowers decision makers to make more informed and reliable decisions by capitalizing on the strengths of multiple approaches and considering a wider range of factors, ultimately leading to enhanced decision quality and effectiveness. integrated MCDM techniques provide a means to handle the complexities and uncertainties inherent in real-world decision problems. The integration of diverse methods can enhance decision robustness and improve the accuracy of results, as it reduces the reliance on a single technique and accounts for various aspects and dimensions of the problem at hand (Lee & Chang, 2018).

Table 3.2: Integrated MCDM methods used in FFS studies

MCDM Methods	References	Application Areas
CRITIC and COPRAS	(Rani, Mishra, Deveci, et al., 2022; Saraji et al., 2021)	Sustainable Development, Technology
CRITIC and CODAS-Sort	(Aro et al., 2022; R. Gonzales et al., 2022)	Logistics and Supply Chain Management, Education
SWARA and COPRAS	(Görçün, Aytekin, et al., 2023; Korucuk et al., 2022)	Digital Marketing, Waste Management
MEREC and MULTIMOORA	(Deveci, Gokasar, et al., 2023; Narayanamoorthy et al., 2022)	Energy, Transportation
BWM and VIKOR	(Gao et al., 2024)	Waste Management
TOPSIS and SWARA	(Aydoğan & Ozkir, 2024)	Education
DEMATEL and MULTIMOORA	(Y. Yang et al., 2024)	Sustainable Development
CRITIC and SWARA	(Hezam, Mishra, et al., 2023)	Sustainable Development
DEMATEL and AHP	(Karuppiah et al., 2023)	Manufacturing
DEMATEL and WASPAS	(Çolak & Lezki, 2023)	Logistics and Supply Chain Management
AHP, DEMATEL and TOPSIS	(Karuppiah Sankaranarayanan, 2023)	& Waste Management
AHP and TOPSIS	(Bouraima et al., 2023)	Construction
WINGS and TODIM	(Moktadir & Ren, 2023a)	Waste Management
SWARA and PROMETHEE	(Seikh & Mandal, 2023)	Waste Management
CRITIC, Rank-Sum, DNMA	(A. R. Mishra, Rani, et al., 2023)	Transportation
MEREC and REGIME	(Fetanat et al., 2023)	Sustainable Development

MCDM Methods	References	Application Areas
CoCoSo and BRAW	(Q. Chen et al., 2022)	Risk Management
EDAS and LOPCOW	(Niu et al., 2022)	Urban Planning
CRITIC, TOPSIS and CODAS	(Erdogan & Ayyildiz, 2022)	Health
ITARA and MARCOS	(Simic, Torkayesh, et al., 2022)	Waste Management
BWM and CoCoSo	(D. Wei et al., 2022)	Logistics and Supply Chain Management
CoCoSo and MEREC	(Simic, Ivanovic, et al., 2022)	Urban Planning
MABAC and CRITIC	(Tan et al., 2022)	Risk Management
CRITIC and EDAS	(A. Mishra, Bullet, et al., 2022)	Logistics and Supply Chain Management
EDAS and BWM	(S. Zeng, Chen, et al., 2023)	Logistics and Supply Chain Management
MEREC and ARAS	(Rani, Mishra, Saha, et al., 2022)	Waste Management
FUCOM and CODAS	(Biswas et al., 2021)	Technology
FUCOM and MAIRCA	(Görçün, Pamucar, et al., 2023)	Technology
SAW, ARAS, and VIKOR	(Gül, 2021)	Health
WASPAS and SMART	(Keshavarz-Ghorabae et al., 2020)	Logistics and Supply Chain Management
TODIM and TOPSIS	(D. Liu, Liu, & Wang, 2019)	Construction

Taking all these factors into consideration, it has been substantiated in the academic literature that the FFS technique offers convenience and suitability in the utilization of both individual and integrated MCDM methodologies. The literature supports the notion that FFS is well-aligned with the requirements and complexities associated with decision-making processes, as it effectively accommodates the use of diverse MCDM techniques.

The comprehensive literature review of MCDM-related FFS studies highlight the pioneering integration of SWOT, AHP-VIKOR, ISM, and QFD methods within the FFS environment. This original implementation not only distinguishes the research but also establishes these methodologies as groundbreaking in the context of RUL strategic decision-making.

3.1.1.2. Application Areas in the Integrated FFS Literature

A rigorous examination of FFS-integrated methods was undertaken, culminating in the creation of a table delineating application areas and objectives. This table briefly encapsulates the focal points of FFS applications, substantiated by relevant references, thereby providing a nuanced perspective on the diverse domains where FFS demonstrates applicability.

Table 3.3: FFS integrated methodologies' application areas and their objectives

Application Areas	Objectives	References
Logistics and Supply Chain Management	Challenges characterization for circular supply chains Logistics distribution center assessment Fractional transportation problems (FTPs) Selecting appropriate logistics service providers (drug distributors) Green low-carbon port evaluation Green supplier selection Supplier selection Third-party reverse logistics provider selection Sustainable supply chain network design Supply chain digital transformation strategies evaluation Crowdsourcing logistics platform evaluation Supply chain optimization	(Akram, Shah, et al., 2022b; Alkan & Kahraman, 2022; Amman et al., 2023; Aro et al., 2022; Çolak & Lezki, 2023; Deliktaş et al., 2023; Fahmi et al., 2023; Farid et al., 2023; Mateen et al., 2023; A. Mishra, Bullet, et al., 2022; Y. Pan et al., 2023; Rong et al., 2022; Verma, 2021; D. Wei et al., 2022; S. Yang et al., 2022)
Urban Planning	Urban agglomeration Urban transport planning Urban quality of life selection	(Akram & Bibi, 2023; Niu et al., 2022; Simic, Ivanovic, et al., 2022)
Waste Management	Waste recycling partner selection Selection of optimal lithium-ion battery recycling process Location selection for hazardous waste IoT barriers for smart cities' waste operations E-waste recycling partner selection Food waste treatment technology selection Healthcare waste disposal location selection Mitigation strategy evaluation Bio-medical waste management Medical waste treatment technology selection	(Chakraborty & Saha, 2022, 2023; Gao et al., 2024; Görçün, Aytekin, et al., 2023; Karuppiah & Sankaranarayanan, 2023; Luqman & Shahzadi, 2023; A. Mishra, Rani, Saha, Hezam, et al., 2022; A. Mishra & Rani, 2021; Moktadir & Ren, 2023a; Mondal et al., 2023; Rani & Mishra, 2022; Rao & Sujatha, 2023; Seikh & Mandal, 2023; Simic, Torkayesh, et al., 2022)

Application Areas	Objectives	References
Sustainable Development	Regional green development level evaluation Sustainable CBT location selection Evaluation and ranking of the sustainable CBT location candidates Sustainable Development Evaluation Selecting desalination technology Reduce Smog from the Environment Negative emissions technologies evaluation Air quality evaluation Digital technology assessment for sustainable transportation Low-carbon cities evaluation Sustainable urban transport solutions Sustainability evaluation for urban energy internet	(Akram, Bibi, et al., 2022; Fetanat et al., 2023; Hezam, Mishra, et al., 2023; Kakati et al., 2024; Lai et al., 2022; P. Liu et al., 2022; Luo & Liu, 2022; Mondal et al., 2023; Rani, Mishra, Deveci, et al., 2022; Shahzadi et al., 2021; Y. Yang et al., 2024; S. Zeng, Gu, et al., 2023)
Health	Evaluating and Benchmarking COVID-19 Vaccines Comparison of hospital service performances Site selection Looking for the most serious case of COVID-19 Covid-19 testing laboratory selection Patient selection Surgeon robot selection and evaluation of the most affected country due to COVID-19 Residential site selection, nucleic acid testing institutions evaluation Effective sanitizer selection A lab selection for the COVID-19 test Panoramic x-ray selection	(Akram et al., 2020; G. Ali & Ansari, 2022; Deng & Wang, 2021; Erdogan & Ayyildiz, 2022; Garg et al., 2020; Gül, 2021; Ilieva & Yankova, 2022; Kirişci, 2023; Shahzadi et al., 2021; Zeb et al., 2022; L.-P. Zhou et al., 2021)
Energy	Finding a spot for a photovoltaic solar power plant Clean energy indicators prioritization Selection of the best location for a Nuclear Power Plant Renewable energy source selection Industry 4.0 implementation in new energy systems Evaluation of potential sites for solar farms	(Ayyildiz, 2022; Hooshangi et al., 2023; A. Mishra, Rani, Saha, Senapati, et al., 2022; Moktadir & Ren, 2023b; Narayanamoorthy et al., 2022)

Application Areas	Objectives	References
Construction	Best construction company selection Franchisee location selection Green construction supplier evaluation Location selection Suitable bridge construction selection Sustainable construction site	(Akram, Niaz, et al., 2022; Bouraima et al., 2023; Keshavarz-Ghorabae et al., 2020; Senapati & Yager, 2019b, 2020)
Risk Management	The occupational health and safety risk assessment model proposition for gas pipeline construction projects Risk investment assessment Construction operations risk analysis Self-service electric vehicles Mining risk assessment Disaster preparedness	(K.-H. Chang et al., 2023; Q. Chen et al., 2022; Deveci, Varouchakis, et al., 2023; Kirişci & Simsek, 2023; Tan et al., 2022; W. Wang et al., 2023)
Agriculture	Selection of the best area for agriculture	(Akram et al., 2022)
Transportation	Multi-objective transportation problem Electric vehicle charging station location selection Taxation of public transit investments Urban transport planning Urban climate change policy for transportation activities Climate change-resilient transportation evaluation Sustainable mobility hub center design Energy consumption in urban mobility	(Akram, Shah, et al., 2022a; Deveci, Gokasar, et al., 2023; A. R. Mishra, Rani, et al., 2023; Rani & Mishra, 2021; S. et al., 2023; Seker & Aydin, 2023; Simic, Gokasar, et al., 2022; Simic, Ivanovic, et al., 2022)
Finance	Internet finance soft power and sportswear brand assessment Selection of bank manager	(Akram, Shahzadi, et al., 2022; Akram & Bibi, 2023)
Economy	Evaluation of the critical factors in Green Economy practices	(Karuppiah et al., 2022)
Education	Online Teaching Quality Evaluation Barrier's prioritization to implementing Education 4.0 Turkish research universities ranking	(Aydoğan & Ozkir, 2024; R. Gonzales et al., 2022; S. Zeng et al., 2022)

Application Areas	Objectives	References
Manufacturing	Food company ranking and green supplier selection Human–robot collaboration evaluation Automotive industry warehouse site selection Assessment of autonomous smart wheelchairs	(Akram, Ramzan, et al., 2022; Hezam, Rani, et al., 2023; Karuppiah et al., 2023; Saha et al., 2023)
Emergency decision-making	Mine accidents	(Shahzadi et al., 2023)
Technology	ETL software selection Intrusion detection systems evaluation Mobile phone evaluation Blockchain technology selection Smartphone brand selection	(Akram, Bibi, et al., 2023; Albahri et al., 2023; Biswas et al., 2021, 2023; Görçün, Pamucar, et al., 2023)
Aviation	Risk assessment occupational health and safety (OHS)	(Gul & Ak, 2022)

Upon reviewing the application areas within FFS literature, it is evident that there is a noticeable absence of studies that explore the RUL structure through the integration of FFS values within a GDM environment.

3.1.1.3. The Extensions of FFSs

The FFS is also extended with existing fuzzy approaches to fortify its benefits while dealing with ambiguous information. This section provides an in-depth exploration of various extensions of FFS that have been proposed in the literature. By discussing the advantages and disadvantages of each extension, this analysis aims to shed light on how FFS can be further developed and improved to meet the needs of different applications and scenarios. The following targets are aimed to reach by having an extended FFS approach (Akram, Bibi, et al., 2022; H. Wang et al., 2019):

- Employing the FFS in qualitative environments with semantic form,
- Managing the membership and non-membership that are not fully defined but represented by interval form,

- Coping with cubic sets, bipolar fuzzy sets, or hesitant fuzzy sets,
- Handling the insufficiency of the parameterized by combining soft set,
- Managing the estimations by fusing with the rough set.

Table 3.4: Extensions of FFS

FFS Extensions	References
Interval-valued FFS	(Akram, Shah, et al., 2022b; Alkan & Kahraman, 2022; Biswas et al., 2023; Bouraima et al., 2023; Deveci, Gokasar, et al., 2023; Görçün, Aytekin, et al., 2023; Hezam, Rani, et al., 2023; Ilieva & Yankova, 2022; Jeevaraj, 2021; Kirişci, 2023; Kirişci & Simsek, 2023; Luqman & Shahzadi, 2023; A. R. Mishra, Rani, et al., 2023; Moktadir & Ren, 2023a, 2023b; Mondal et al., 2023; Qi et al., 2024; Qin et al., 2023; Rani, Mishra, Deveci, et al., 2022; Rani & Mishra, 2022; S. et al., 2023; Seikh & Mandal, 2023; Shahzadi et al., 2023)
Hesitant FFS	(Lai et al., 2022; Luo & Liu, 2022; Sha & Shao, 2023; H. Wang et al., 2019; Y. Wang et al., 2023)
2-Tuple FFS	(Akram, Bibi, et al., 2022, 2023; Akram, Niaz, et al., 2022; Akram, Ramzan, et al., 2023; Akram & Bibi, 2023)
Trapezoidal FFS	(Fahmi et al., 2023)
Triangular FFS	(Akram, Shahzadi, et al., 2023; Fahmi, 2023)
FF Linguistic Sets	(Akram, Ramzan, et al., 2022; Q. Chen et al., 2022)
FF Soft Sets	(Akram, Ali, et al., 2022; Zeb et al., 2022)
Fermatean Cubic Fuzzy Sets	(Niu et al., 2022; Rong et al., 2022)
3,4-Quasirung Fuzzy Set	(Gul & Ak, 2022)
Rough-FF	(Albahri et al., 2023; Kao et al., 2022)
FF N-Soft Sets	(Akram et al., 2022)
Interval-valued Hesitant FFS	(P. Liu et al., 2022)
FF Bipolar Soft Set	(G. Ali & Ansari, 2022)
Dempster–Shafer Theory-Based FFS	(Deng & Wang, 2021)

Table 3.4 reveals that a significant portion of the FFS literature utilizes ordinary FFS, with a considerable number of studies also integrating MCDM techniques. While these extensions have demonstrated effectiveness in tackling diverse problems, the evolving and complex nature of decision-making environments demands further considerations.

To manage uncertainty with a broader domain, the concept of IVFFSs have been introduced as a generalization of interval-valued fuzzy sets and FFS (Jeevaraj, 2021). IVFFS, the most used FFS extension in the literature, is a very useful concept for dealing with uncertainty by taking membership and non-membership scores in intervals where the cubic sum of the upper bounds of the membership and non-membership intervals is less than or equal to 1. It allows DMs to express their evaluations in a wider area and can solve and model complex decision-making problems more efficiently. In this thesis, decision-making models are employed within the IVFF environment to enhance MCDM models and provide a more meticulous characterization of problems involving incomplete and uncertain information.

3.1.1.4. Aggregation Operators of FFSs

Aggregation methods are valuable for unifying and combining the various assessments in the form of FFSs. They are useful during the decision-making processes in which DMs explicit their valuation through the FFS in decision-making problems. Many addition operators used to make decisions are founded on geometric mean, arithmetic mean, and integrals (Peng & Dai, 2020). To achieve robust and meaningful outcomes, selecting appropriate Aggregation Operators (AOs) is essential for tailoring FFSs to specific decision contexts.

- **Algebraic AOs:** In MCDM problems, aggregation issues are elucidated through scoring techniques such as the weighted addition operator. Classic weighted aggregation methods are usually known as a weighted average, weighted geometric, or simple aggregation weighting. Other common addition operators can be specified as the ordered weighted average or the ordered weighted geometric operator. Senapati and Yager (2019a) developed a series of FF AOs, such as the FF weighted average AOs and FF weighted geometric AOs and applied

them in MCDM problems. Liu et al. (2019a) proposed FFLWA, FFLWG under an FF linguistic environment. Verma (2021) also proposed FFLWA, FFLWG, the FFL-ordered weighted averaging, the FFL-ordered weighted geometric, the FFL-hybrid averaging, and the FFL-hybrid geometric operators under FF linguistic environment for a MADGM problem and aggregated four DMs evaluations. Rani and Mishra (2022) used Interval-valued FF weighted geometric AOs. FF soft AOs such as FF soft weighted averaging, FF soft ordered weighted averaging, FF soft weighted geometric and FF soft ordered weighted geometric AOs are proposed by Zeb et al. (2022). Liu et al. (2022) utilized Interval-valued Hesitant FF weighted AOs and Lai et al. (2022) Hesitant FF weighted averaging AOs for a GDM problem consisting of three DMs. To address limitations in FF weighted average and FF weighted geometric AOs, recently, Simic et al. (2023) proposed FF hybrid weighted arithmetic geometric and FF hybrid ordered weighted arithmetic geometric AOs.

- Hamacher AOs: Jan et al. (2021) proposed FF Hamacher weighted average, FF Hamacher ordered weighted average, FF Hamacher hybrid weighted average AOs for MADM problems and present an application in disaster management with three DMs. Shahzadi et al. (2021a) proposed Hamacher interactive hybrid weighted averaging AOs under FF numbers. It is stated that recommended operators have inefficiency, constraint, monotony, homogeneity characteristics and shear invariance. They are flexible and powerful operators that appropriately describe imprecise information in complex situations. In real-world circumstances, DMs frequently consider diverse criteria prioritization. Then, FF Hamacher prioritized AOs are suggested by Jan et al. (2021) to cope with this situation. Niu et al. (2022) presented Fermatean Cubic Fuzzy Sets Hamacher weighted averaging AOs under a Fermatean Cubic Fuzzy Environment. Ruan and Chen (2023) proposed probabilistic interval-valued hesitant FF Hamacher weighted averaging and geometric AOs in reducing carbon emissions of manufacturers in the supply chain.
- Yager AOs: Combining the important features of FFS with the Yager operator, six new operators are proposed: FF Yager weighted average, FF Yager ordered

weighted average, FF Yager hybrid weighted average, FF Yager weighted geometric, FF Yager ordered weighted geometric and FF Yager hybrid weighted geometric AOs (Garg et al., 2020). These AOs show more accurate outcomes when they are implied in real-life FFS-integrated MCDM problems.

- **Hamy mean AOs:** The Hamy mean AOs are one of the popular operators included in IFSs (B. Xu, 2020) and PFSs (G. Wei et al., 2019) implementations. It is an adaptive and comprehensive approach to deal with complex and inconsistent data, with its main advantage being that these operators consider the interrelationships between fuzzy numbers. Therefore, it has been applied to the FFS environment (Chakraborty & Saha, 2022). It has been seen that three studies are using this operator in the FFS literature, and it is predicted that it will increase in the future.
- **Einstein AOs:** Einstein AOs are a simple and creative approach to tackling decision-making problems. In the FFS literature, some Einstein AOs have been established as an improvement of algebraic operators like FF Einstein weighted averaging, FF Einstein ordered weighted averaging, generalized FF Einstein weighted averaging, and generalized FF Einstein ordered weighted averaging operators (Akram et al., 2020).
- **Dombi AOs:** Dombi AOs, developed by Dombi (1982), provide a flexible concatenation operator thanks to its flexible parameter, which is the main advantage of these operators. It is aimed to create a more sensitive structure by using Dombi AOs on FFSs. Shit & Ghorai (2021) proposed FF Dombi weighted averaging operator, FF Dombi ordered weighted averaging operator, FF Dombi weighted geometric operator, and FF Dombi ordered weighted geometric operator.
- **Power AOs:** Power AOs use a nonlinear weighted average aggregation tool that allows the input arguments to support each other (Peng & Selvachandran, 2019). In the FFS literature, two studies proposed FF weighted power average operator and FF weighted power geometric operators with algebraic AOs (Luo and Liu 2022).

- Aczel-Alsina AOs: Rong et al. (2022) proposed cubic FF Aczel-Alsina AOs in the selection of the old chain logistics distribution center. They aimed to flexibly integrate the cubic FF information. This presented operator can directly combine cubic FF information, but it is a limitation that it does not consider how the evaluation criteria are related to each other.
- Schweizer–Sklar AOs: Schweizer–Sklar AOs are flexible operators to aggregate information. Wei et al. (2022) proposed FF Schweizer–Sklar weighted averaging operator, FF Schweizer–Sklar weighted geometric operator for green supplier selection problem based on four DMs.
- Maclaurin symmetric mean AOs: These operators can capture interrelationships between multi-input criteria via variable parameters. In this way, they make the decision-making processes more realistic. Liu et al. (2022) proposed a new FF Archimedean copula-based Maclaurin symmetric mean operator based on three DMs for renewable energy source selection.
- Frank AOs: These operators compensate for the lack of algebraic operations by providing more flexibility and robustness in the information aggregation process and can model decision-making problems more appropriately; hence they are introduced by Tan et al. (2022) for combining FF information.
- Heronian mean AOs: The Heronian mean AO is an aggregation approach developed to deal with exact numeric values and is an important operator as it can capture the correlations of the combined arguments. Rani et al. (2022b) proposed FF weighted generalized geometric Heronian mean AO and presented an application on food waste treatment technology selection. Mishra et al. (2023b) applied interval-valued FF Heronian mean AOs to evaluate urban climate change policy alternatives for transportation.
- Bonferroni mean AOs: This operator differs from other classical tools such as arithmetic, geometric, and harmonic in that it reflects the interrelationship

between any arguments. In this way, it appears as a useful operator in decision-making applications. Wang et al. (2019) and Chakraborty and Saha (2023) proposed Archimedean Bonferroni mean AOs in Hesitant FF environment.

Upon examination of the FFS literature, it becomes apparent that a diverse range of 13 different AOs are employed within the FF environment. However, it is noteworthy that these operators may overlook the flexibility of the information aggregation process. To advance the field of FFS, future studies would greatly benefit from placing increased emphasis on the development and exploration of innovative operators.

To make the aggregation process more flexible, the MCDM models in this thesis are built based on the Interval-valued Fermatean fuzzy Dombi weighted averaging operator (IVFFDWA), which is highlighted for its flexibility with general parameters.

3.1.1.5. Linguistic Sets of FFSs

Linguistic variables play a significant role in managing the complexity and difficulty of the data collection process, particularly in decision-making scenarios (Akram, Ramzan, et al., 2022). FF Linguistic Sets (FFLSs) are a recent extension of the FFSs and fuzzy linguistic approach, designed to manage comparative linguistic expressions. Figure 3.2 provides an overview of the most used FFLSs in the FFS literature, which can serve as a useful reference for researchers and practitioners seeking to leverage the power of linguistic sets in their decision-making efforts.

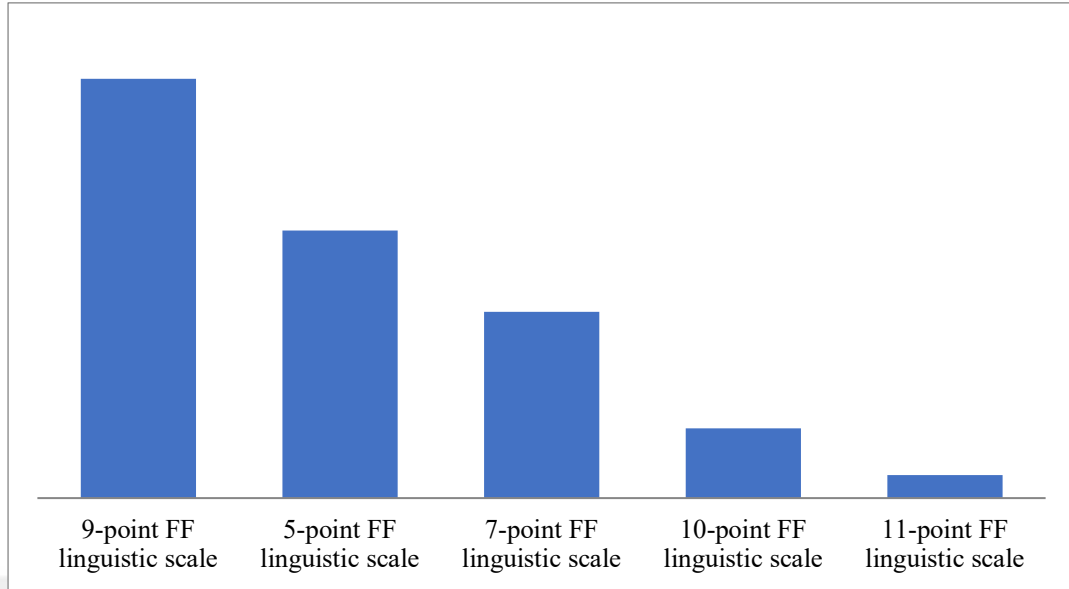


Figure 3.2: Most commonly used FFLSs

Within the literature on FFS, several researchers have proposed different linguistic scales for decision-making purposes. The most commonly employed linguistic scale is the 9-point scale, as indicated by studies (Akram, Ramzan, et al., 2022; Ayyildiz, 2022; Biswas et al., 2021; Bouraima et al., 2023; Chakraborty & Saha, 2022, 2023; Erdogan & Ayyildiz, 2022; Gao et al., 2024; Gul et al., 2021; Kao et al., 2022; Keshavarz-Ghorabae et al., 2020; Simic, Gokasar, et al., 2022; Verma, 2021; Y. Yang et al., 2024). Additionally, the 5-point linguistic scale has been utilized in various papers (Akram et al., 2020; Golui et al., 2024; G. Gonzales et al., 2022; Ilieva & Yankova, 2022; Karuppiyah et al., 2022; Karuppiyah & Sankaranarayanan, 2023; Kirisci et al., 2022; Mateen et al., 2023; Moktadir & Ren, 2023b; Simic, Ivanovic, et al., 2022; H. Wang et al., 2019). Some authors opted for a 7-point linguistic scale for FFS applications, as evidenced by studies mentioned (Akram, Bibi, et al., 2022; Aro et al., 2022; Q. Chen et al., 2022; Deveci, Varouchakis, et al., 2023; R. Gonzales et al., 2022; Görçün, Pamucar, et al., 2023; D. Liu, Liu, & Chen, 2019; D. Liu, Liu, & Wang, 2019; S. Zeng, Chen, et al., 2023). Furthermore, a 10-point linguistic scale was employed by Ruan and Chen (2023), Rao and Sujatha (2023), Chang et al. (2023), Rani et al. (2022b) and Mishra et al. (2022b), while Tan et al. (2022) and Wei et al. (2022) utilized an 11-point linguistic scale. Notably, Simic et al. (2022a) employed a combination of scales, using a 5-point scale to distinguish experts, a 7-point scale to evaluate criteria importance, and a 9-point scale to assess alternatives. Kirisci et

al. (2022) applied a 5-point scale to calculate the weights of experts and criteria, and a 10-point scale was used to evaluate alternatives. Linguistic sets play a crucial role in decision-making by providing a means to express and quantify subjective judgments and preferences. They enable DMs to describe and evaluate criteria, alternatives, and expert opinions using linguistic terms rather than precise numerical values. Linguistic sets bridge the gap between qualitative and quantitative assessments, allowing for a more intuitive and human-centric approach to decision-making (Herrera-Viedma et al., 2021). By incorporating linguistic sets, DMs can capture the nuances and uncertainties inherent in complex decision problems, leading to more accurate and meaningful results. The utilization of proposed linguistic scales in decision-making problems serves the purpose of determining expert weights, evaluating criteria, and assessing alternatives (Akram, Niaz, et al., 2022). The selection of a FF language scale depends on the specific decision-making context and the desired level of granularity for criteria evaluation. While scales such as the 9-point, 10-point, or 11-point provide greater detail and expressive capability, they can become time-consuming when dealing with a large number of criteria (Herrera-Viedma et al., 2021). On the other hand, the 5-point scale offers ease of use and is suitable for simpler decision-making scenarios, although it may lack the ability to differentiate adequately between different preference levels. In this regard, the 7-point scale strikes a balance between other scales, offering a practical compromise between detail and simplicity. The choice of an appropriate Fermatean fuzzy language scale should be based on the specific requirements of the decision-making problem at hand, taking into consideration the trade-offs between level of detail and computational complexity.

3.1.1.6. FFS comparison with IFS and PFS

In decision-making, choosing the appropriate type of fuzzy set is critical and requires careful analysis of the specific application and nature of the data. Different types of fuzzy sets, such as IFS, PFS, and FFS, offer distinct advantages and disadvantages depending on the problem at hand. Therefore, it is essential to consider the technical concepts of FFS and compare the different types of fuzzy sets to determine the most suitable one. Table 3.5 provides a comprehensive comparison of IFS, PFS, and FFS, highlighting their respective strengths and weaknesses. In the existing literature, numerous studies employing integrated FFS methods have conducted comparisons between their proposed

FFS-based approaches and the IF and PF approaches. These comparative analyses have consistently highlighted the advantages of FFS, particularly in domains characterized by significant uncertainty, such as risk assessment. Making the right choice of fuzzy set can significantly impact the accuracy and effectiveness of decision-making processes. Therefore, DMs should thoroughly evaluate their options and select the most appropriate fuzzy set for their specific needs.

Table 3.5: IFS, PFS and FFS comparison

Fuzzy Sets	Sources/Reference	Benefits	Drawbacks
IFS	(Atanassov and Vassilev 2020; Xu 2020; Dhiman et al. 2020)	Ability to express affirmation, negation, and uncertainty through membership definitions. More ideal than fuzzy sets to handle non-probabilistic uncertainty and non-determinism in the system.	Limitations related to the truth and falsity grades.
PFS	(Zhang and Xu 2014; Du et al. 2017; Liu et al. 2020; Geetha et al. 2022)	Improved accuracy in decision-making thanks to the use of distance concept. Ease of computation thanks to the distance concept.	Difficulties in determining the distance function where there is little information available.
FFS	(Keshavarz-Ghorabae et al. 2020; Verma 2021; Jan et al. 2021; Akram et al. 2022h; Rani et al. 2022b; Ayyildiz 2022; Wei et al. 2022)	Better suited to curb imprecision than IFS and PFS. Provides more precise results as compared to the existing methods.	Limited availability of software tools due to PFSs are not widely available as tools for traditional fuzzy sets.
Shared Features	(Zhang and Xu 2014; Atanassov and Vassilev 2020; Dhiman et al. 2020; Geetha et al. 2022; Kirisci et al. 2022; Ayyildiz 2022; Wei et al. 2022; Akram et al. 2022c; Chakraborty and Saha 2022)	Flexible thanks to expressing the degree of membership and non-membership. Capable of handling conflicting information with membership and non-membership functions.	Increased complexity with more than one membership function compared to traditional fuzzy sets. Limited availability of software tools.

Upon conducting a comprehensive review of the FFS literature, it was observed that there is a dearth of studies in this domain incorporating IVFF-AHP, IVFF-VIKOR integrated SWOT, IVFF-ISM, and IVFF-QFD. Additionally, in the context of RUL, there is a notable absence of FFS-integrated MCDM models. Furthermore, the integration of the IVFFDWA aggregation operator in the MCDM models presented in this thesis facilitates a more adaptable approach to modeling MCDM problems in the presence of uncertainties. The subsequent sections of this chapter delve into a detailed exploration of the methods discussed in the thesis.

3.2. Overview of SWOT Analysis

This section explains the SWOT analysis and presents a literature review synthesizing relevant research to enhance the depth and context of the thesis.

3.2.1. Definition of SWOT Analysis

Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis is a commonly used method for companies and organizations and provides them to examine their internal strengths and internal weaknesses of a product or service and defines the opportunities and threats of the external environment (Kahraman et al., 2007). It helps to define current situation and allows a long-term growth by determining the factors that will ensure growth and eliminating those that will cause failure. The main goal of the SWOT analysis is to develop strategies which will be appropriate between external and internal factors. When the RUL literature is examined, SWOT analysis studies have not been encountered. For this reason, MCDM approaches used with SWOT analysis have been examined in the following section.

3.2.2. Literature Review of SWOT Analysis

Although it is an advantageous method, the importance degrees of the factors cannot be measured quantitatively. In the literature, MCDM methods are used to evaluate SWOT analysis quantitatively. When we examined the literature, it was seen that AHP method was first used in quantitative analysis of SWOT. Although AHP-SWOT is a widely used

methodology, other methods such as ANP have been used as the pair-wise comparison matrices become more complex. In the following years, it has been observed that the fuzzy approaches have been integrated into the SWOT analysis. Table 3.6 examines some of the SWOT analysis studies including fuzzy MCDM applications in the last ten years. When Table 3.6 is examined, SWOT analysis is integrated with many different MCDM methods during the evaluation phase. Most of the SWOT analysis studies are in the form of case studies, indicating its successful application in such scenarios. A deeper analysis of these studies reveals that AHP and ANP are the commonly used methods for evaluating SWOT factors, whereas TOPSIS, VIKOR, ARAS, MARCOS, etc. are employed for assessing alternatives. Furthermore, the table indicates that SWOT has not been utilized in the IVFF environment so far.

Table 3.6: SWOT analysis studies with fuzzy MCDM applications

Reference	Integrated Method	Application Area	Type
(Kabak, 2013)	Fuzzy ANP, Fuzzy DEMATEL	Personnel Selection	Case study
(Aliakbari Nouri et al., 2015)	Fuzzy ANP, Fuzzy TOPSIS	Technology selection	Case study
(Arabzad et al., 2015)	Fuzzy TOPSIS	Supplier selection	Case study
(Dimic et al., 2016)	Fuzzy Delphi, DEMATEL, ANP	Strategy analysis	Case study
(Kabak et al., 2016)	Fuzzy ANP	Energy policy making	Case study
(Dadpour & Shakeri, 2017)	Fuzzy VIKOR, PROMETHEE	Private sector selection	Numerical example
(Ervural et al., 2018)	ANP, Fuzzy TOPSIS	Strategic energy planning	Case study
(Milenkovic et al., 2018)	Fuzzy PROMETHEE	Optimal toll collection system selection	Numerical example
(Büyükoçkan & Ilıcak, 2019)	Multiple preference relations	Social media	Case study
(Solangi et al., 2019)	AHP, Fuzzy TOPSIS	Sustainable energy planning	Case study

Reference	Integrated Method	Application Area	Type
(Barak & Javanmard, 2020)	IVF-TOPSIS, IVF-ARAS, IVF-SAW, IVF-COPRAS, QSPM	Partner selection	Case study
(Jiskani et al., 2020)	Fuzzy TOPSIS, Fuzzy AHP	Sustainable mining	Numerical example
(Mardani et al., 2020)	Hesitant Fuzzy-SWARA-WASPAS	Healthcare systems	Case study
(Y. Wang et al., 2020)	Fuzzy AHP	Renewable energy resources selection	Case study
(Buyukozkan, Mukul, et al., 2021)	Hesitant Fuzzy Linguistic AHP-MABAC	Health tourism strategy selection	Case study
(Havle et al., 2021)	Fuzzy AHP, Fuzzy MARCOS	Digital transformation	Case study
(Kaytez, 2022)	Fuzzy ANP	Power planning	Case study
(Maihemuti et al., 2022)	Fuzzy AHP, Fuzzy MARCOS	Power system operation	Case study
(Beheshtinia et al., 2023)	Fuzzy TOPSIS, Fuzzy VIKOR, Fuzzy VISIS	Energy management	Case study
(D. Wang et al., 2023)	Fuzzy AHP, Fuzzy TOPSIS	Resilient energy	Case study
(Rahimirad & Sadabadi, 2023)	AHP, Fuzzy TOPSIS, Fuzzy VIKOR	Technology policymaking	Case study

3.3. Overview of Interpretive Structural Modeling (ISM)

This section explains the ISM and gives its computational steps. Following that, a literature review of ISM is proposed.

3.3.1. Definition of ISM

ISM is a powerful tool that can help us understand complex relationships between elements related to a topic. Developed by Warfield in 1974, this interactive planning methodology can identify relationships between a set of elements and develop a comprehensive building model. By answering a series of simple questions, a structure that shows how variables directly or indirectly affect the system can be obtained. One of the best things about the ISM model is that it graphically reflects the structure of complex factors related to the subject. This makes it easier to understand and analyze the system. Overall, the ISM model is a valuable tool to make more informed decisions and improves the understanding of complex systems (Warfield, 1974). In policy analysis, the ISM method has been utilized due to its numerous benefits (Agrawal et al., 2020). It has proven effective in finding solutions for complex issues in renewable energy (Z.-Y. Zhao et al., 2019), electricity supply (Sinaga et al., 2019), and building energy performance (X. Xu & Zou, 2020). The steps in the ISM methodology are as follows (Khanam et al., 2015), (Chander et al., 2013):

Step 1. Defining the criteria for the problem with the help of expert opinion and literature review.

Step 2. By comparing the criteria listed in the first stage, the interrelationships between them are analyzed. In this analysis, there may be a one-way or two-way relationship between the two criteria, or the absence of any relationship is also expressed.

Step 3. A Structural Self-Interaction Matrix (SSIM) is created, which shows the bilateral relations between the criteria. At this stage, the above-mentioned pair wise analyzes are made through the following four symbols that show the conceptual relationship between each criterion (i and j).

- V – criterion i affects criterion j,
- A – criterion j affects criterion i,
- X – criteria i and j influence each other,
- O – There is no relationship between criteria i and j.

Step 4. Based on the analysis results in SSIM, the initial “Reachability” matrix is created, and this matrix is checked for “Transitivity”. The concept of transitivity here is the basic assumption used to describe conceptual relationships in ISM. E.g; If the A criterion is related to the B criterion, and the B criterion is also related to the C criterion, it is inferred that the A criterion will necessarily be related to the C criterion. At this stage, the symbols V, X, A, O, which are used to show the relationship between the criteria, are digitized as “0” or “1” according to the following situations.

- If the (i, j) analysis is set to V, the (i, j) value is expressed as 1 in the initial accessibility matrix, otherwise (j, i) is expressed as 0.
- If the (i, j) analysis is set to A, the (i, j) value is expressed as 0 in the initial accessibility matrix, and (j, i) is expressed as 1 in the opposite case.
- If the (i, j) analysis is set to X, the (i, j) value is expressed as 1 in the initial accessibility matrix, and vice versa (j, i) is expressed as 1.
- If the (i, j) analysis is set to O, the (i, j) value is expressed as 0 in the initial accessibility matrix, and on the contrary (j, i) is expressed as 0. Then, the initial accessibility matrix is combined with the transitivity between the criteria to form the final accessibility matrix.

Step 5. Partitioning the reachability matrix into different levels is performed. At this stage, “accessibility sets” and “premise sets” are decoupled from the final accessibility matrix. Then, from the intersection between these two sets, "intersection sets" are created for all criteria at each hierarchy level. If the accessibility and intersection set of the criteria are the same, these criteria are located at the top level of the ISM hierarchy. Criteria at this level do not affect other criteria other than those at their own level.

Step 6. Guided graphical representation is made in line with the results obtained from the accessibility matrix. At this stage, transitivity links are removed.

Step 7. At the end of the sixth step, the variable nodes are transformed into expressions and the final diagram is transformed into the interpretive structural model. At this stage, the dependency and influence levels of the criteria are analyzed by performing MICMAC (Matrice d'Impacts Croise's Multiplication Appliquee a Un Classement/Cross Impact Matrix Multiplication Applied to Classification) analysis. As a result of the analysis, the criteria are divided into four groups;

- I. Autonomous Group: The criteria in this group have low influence and low dependency power. The criteria in this group are independent as they have relatively little connection with other criteria in the system.
- II. Dependent Group: The criteria in this group have low influence but high dependency power.
- III. Linkage Group: The criteria in this group have high impact and high dependency power.
- IV. Independent Group: The criteria in this group have high impact, but low dependency power.

The criteria in the “III” and “IV” groups with high impact power are defined as the key criteria.

3.3.2. Literature Review of ISM

This model has been widely used with various MCDM methods in the literature, and the most significant findings of this review are presented in Table 3.7. After conducting a literature review on ISM, it became apparent that IVFF-ISM methodology is currently not being utilized in the realm of resilient cities or RUL. It is imperative to continue to explore and implement innovative approaches to build more resilient systems, and ISM could prove to be a valuable tool in achieving this objective.

Table 3.7: ISM studies with different MCDM applications

Reference	Integrated Method	Area	GDM
(J. L. Yang et al., 2008)	Fuzzy AHP	Vendor selection	Yes
(Kannan et al., 2009)	Fuzzy TOPSIS	Reverse logistics provider selection	Yes
(Shahbandarzadeh & Ghorbanpour, 2011)	Fuzzy ANP, Fuzzy AHP	Location selection of health centers	Yes
(Kang et al., 2012)	Fuzzy ANP	New product development	Yes
(Lin & Lu, 2013)	Fuzzy Delphi, Fuzzy ANP	Ecotourism sustainability potential evaluation	Yes
(W.-C. Chen et al., 2015)	Fuzzy ANP	New product development	Yes
(Piltan & Sowlati, 2016)	Fuzzy logic, ANP	Performance evaluation	No
(Gavareshki et al., 2017)	Fuzzy MICMAC analysis, Fuzzy AHP, VIKOR	Green supplier selection	Yes
(Lamba & Singh, 2018)	Fuzzy total ISM, DEMATEL	Big data enablers	Yes
(Saracoglu et al., 2018)	Grey systems theory, fuzzy logic, PEST analysis	Photovoltaic solar power plants	Yes
(Singh & Misra, 2018)	DEMATEL	Product lifecycle management	Yes
(Dachyar & Mahendra, 2019)	QFD, ANP	Small and medium enterprises	Yes
(Gardas et al., 2019)	Delphi, DEMATEL	Agricultural supply chain management	Yes
(RazaviToosi & Samani, 2019)	Fuzzy ANP, Fuzzy TOPSIS	Evaluating watershed management strategies	Yes

Reference	Integrated Method	Area	GDM
(S. Mishra et al., 2019)	PESTLE, SWOT analysis	International manufacturing networks	Yes
(Chauhan et al., 2020)	DEMATEL, ANP	Sustainable supply chain	Yes
(Sharma & Sehrawat, 2020)	AHP, TOPSIS	Cloud adoption	Yes
(Shardeo et al., 2020)	Fuzzy ANP, modified Total ISM	Blockchain technology adoption	Yes
(Bajpai & Misra, 2021)	Fuzzy DEMATEL	Digitalization in construction	No
(Gupta & Goyal, 2021)	Fuzzy AHP	Big data analytics	Yes
(Mukeshimana et al., 2021)	SWOT analysis	Renewable energy	Yes
(Nasrollahi et al., 2021)	Fuzzy DEMATEL	Resilient supplier selection	Yes
(Parizi et al., 2021)	Delphi, DEMATEL	Urban physical resilience	Yes
(Dixit et al., 2022)	Grey DEMATEL	Organic farming adaptation	Yes
(Makki & Alqahtani, 2022)	ANP	Financial technology enablers	Yes
(Singh et al., 2022)	DEMATEL	Supply chain enablers	Yes
(Sathyan et al., 2022)	Fuzzy DEMATEL	Supply chain responsiveness	Yes
(C. Wang et al., 2023)	DEMATEL, maximum mean de-entropy algorithm (MMDE)	Municipal solid waste management	Yes
(Hao et al., 2023)	DEMATEL, PF AHP	Risk assessment	Yes
(Mahdiraji et al., 2023)	IF sets, Delphi	Digital platforms	Yes
(Sun, 2023)	DEMATEL, QFD	CNC machine tools	No

3.4. Overview of MCDM Methods

In this thesis study, the AHP and VIKOR methods are used as an integrated methodology. This section provides an explanation of the AHP and VIKOR methodologies, supplemented by a review of relevant literature on these methods.

3.4.1. AHP Method

AHP method is a valuable tool and one of the most preferred MCDM techniques for decision makers dealing with complex options. It analyzes the relationship between criteria and sub-criteria of preferences and sorts them hierarchically (Saaty, 2006). This allows decision makers to express the superiority of alternatives over each other with numerical values, making it easier to analyze. AHP has several advantages over other MCDM techniques in terms of ease of application, repeatability, and supporting GDM. It also allows the analysis of the consistency of the results and modeling complex problems in a hierarchical structure. Additionally, AHP includes both concrete and abstract elements when evaluating alternatives in decision-making. Concrete elements involve objective information while intangible elements relate to subjective thoughts and feelings of the people involved in the process (Papapostolou et al., 2020). A major drawback of SWOT analysis is that it doesn't allow for quantitative measurement of the importance of decision factors, and it can be challenging to determine which factor has the most significant impact on strategic decision-making. However, these limitations can be overcome by using AHP, which enables more effective modeling of SWOT analysis (Tavana et al., 2016). Given the limitations of SWOT analysis and the benefits offered by the AHP, the employment of the AHP method in this thesis is entirely justified.

To effectively address a range of decision-making problems, AHP is widely used in various fuzzy environments. Kutlu Gündoğdu & Kahraman (2020) proposed spherical fuzzy AHP and applied in renewable energy location selection problem. Büyüközkan et al. (2020) applied IVIF-AHP method in digital service quality model. Kumar and Anbanandam (2020) utilized IF-AHP and IF-VIKOR to rank the freight transport companies. M. Gul (2020) applied PF-AHP and PF-VIKOR methods in health and safety risk assessment model. Gundogdu et al. (2021) utilized Picture fuzzy AHP to evaluate

public transport service quality. Otay & Kahraman (2022) proposed an integrated circular IF-AHP and circular IF-VIKOR methodology in supplier evaluation problem. Çalik et al. (2023) evaluated supply resilience by applying PF-AHP and PF-VIKOR methods. When we examine the FF-AHP method in the literature, S. Zeng et al. (2022) utilized FF-AHP for the evaluation of online teaching quality. Bouraima et al. (2023a) applied an integrated IVFF-AHP and IVFF-TOPSIS methodology. Karuppiah & Sankaranarayanan (2023) utilized AHP, DEMATEL and TOPSIS in FFS environment. Manirathinam et al. (2023) applied Fermatean neutrosophic fuzzy stratified AHP-MARCOS approach in sustainable renewable energy selection. Upon examining the literature, it has been found that the integrated SWOT analysis with IVFF-AHP methodology has not been previously explored. The IVFF-AHP methodology presents several advantages, including practicality with its hierarchical structure, ease of application, repeatability, flexibility, capacity for comprehensive comparisons, systematic assessment of complex problems, integration of relative significance weights for criteria to incorporate multiple expert perspectives, and the ability to verify input consistency. Utilizing the IVFF-AHP approach in this thesis to ascertain the importance of SWOT factors enables a nuanced understanding of crucial elements in the strategic analysis of RUL.

3.4.2. VIKOR Method

VIKOR, proposed by Opricovic in 1998 (Opricovic & Tzeng, 2004), is a widely used MCDM method for complex decision-making problems. Its objective is to find a solution that maximizes group benefit and minimizes individual regret while selecting and ordering alternatives. This approach is useful in situations where multiple criteria need to be considered in the final decision-making process for selecting alternatives. The main advantage of this method is that it determines a compromise order and achieves compromise resolution under specified weights, while also considering the distance from the ideal solution. However, it has a certain disadvantage that cannot cope with the uncertainty problem. To cope with uncertainties, VIKOR extended with fuzzy sets in the literature.

VIKOR and its extensions find applications across various diverse domains. When we examine the literature, there are few studies that utilizes VIKOR in FFS environment. Gül (2021) extended SAW, ARAS, and VIKOR in FFS environment for COVID-19 testing

laboratory selection problem. Akram, Muhiuddin, et al. (2022) proposed a complex Fermatean fuzzy N-soft VIKOR method. Attaullah et al. (2023) developed a Fermatean hesitant fuzzy rough set based VIKOR methodology. The integration of VIKOR in the IVFF environment is a novel approach that has not been previously explored in literature. This thesis presents the IVFF-VIKOR method for the first time to evaluate the RUL strategies, showcasing its potential benefits and applications.

3.5. Overview of Quality Function Deployment (QFD)

This section explains the QFD and gives its computational steps. Following that, a literature review of QFD is proposed.

3.5.1. Definition of QFD

The QFD method, which was introduced by Yoji Akao in 1966, is a unique approach that focuses on incorporating customer requests into the design phase of a product or service. It gained popularity in the Japanese Mitsubishi firm in 1972 and was later explored and used in the USA after 1984. Today, it is a widely accepted quality approach used all over the world (Chan & Wu, 2002).

QFD is a systematic approach that enables customers to identify their design requirements and transform them into product or service features that align with their needs and expectations. The fundamental framework of QFD is called the House of Quality (HOQ). HOQ facilitates the conversion process, making it a seamless experience for businesses to determine the “What’s” and “How’s” of their product or service, which is a critical aspect of the product development process. The first main function of QFD is to gain a comprehensive understanding of the customer's expectations. The second is to understand the design requirements necessary to meet these expectations (Camgoz Akdag et al., 2012). These design requirements are then prioritized using a structured algorithm. Figure 3.3 illustrates the framework of HOQ, which outlines this process.

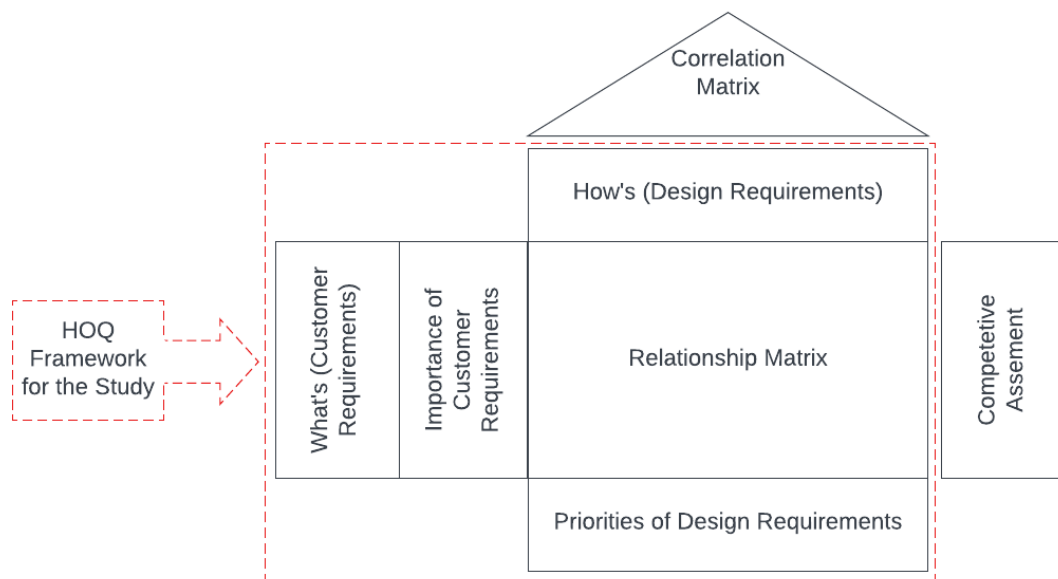


Figure 3.3: HOQ framework for the thesis study

To create the HOQ, a set of steps must be followed (Chan & Wu, 2002):

- The first step involves listing all the customer requirements (CRs) through literature reviews or expert opinions. At this stage, every expectation is documented and assigned as “What”.
- Subsequently, experts assign weights to these expectations based on their relative importance, and these weight values are integrated into the Importance of Customer Requirements column in the HOQ.
- In the third step, design requirements (DRs) that may impact CRs are listed and placed in the field specified as “How's” (Design Requirements) as a line matrix.
- Experts then evaluate the relationship between CRs and DRs, and the created matrix is placed in the middle body of the HOQ.
- The final step involves calculating which DR should be given more importance. By multiplying the CRs importance by each relationship matrix column, and the total column values created are calculated. These values are then written under each DR and placed as a column matrix in the bottom section of the HOQ.

By following these steps, it's possible to see the impact of customer expectations on the design in a quantitative manner and decide which DRs should be given more importance and investment while creating a product or service.

3.5.2. Literature Review of QFD

Although there are many QFD studies in the literature, no study has been found directly in the field of RUL. For this reason, the following research procedure was carried out to expand the literature review. As a basis for the literature review on QFD, the selection criteria of ("logistic*" or "last mile" or "freight transport*" or "city logistic*" or "urban logistic*" or "urban freight" or "city freight" or "urban goods" or "urban delivery" or "city delivery") + ("QFD" or "HOQ" or "quality function deployment" or "house of quality") + ("resilien*") keywords and the original language of English is applied to the search. Using the above-mentioned search criteria 10 publications were identified. Table 3.8 is proposed to show the QFD studies summarizing the main concept of each paper.

The foregoing review shows the prevalent focus of the QFD approach on aspects such as supply chain resilience and resilient supplier selection. Remarkably, within the existing body of literature, there remains a notable absence of QFD studies implemented within the IVFFS environment, marking a noteworthy gap in the extant research landscape. This thesis thus assumes a pioneering stance as the first to integrate IVFFS values into the QFD methodology, representing a novel approach within the domain. The proposition of a framework for planning the technological infrastructure of RUL through the integration of QFD methodology with IVFFS values within the GDM environment, as presented in this thesis, contributes significantly to the extant literature.

Table 3.8: Literature Review of QFD Studies

Reference	Integrated Method	Area	Application
(Lam & Bai, 2016)	-	Maritime supply chain resilience	Case Study
(Zanjirani et al., 2019)	Multi objective performance analysis, Taguchi loss function, TOPSIS	Lean, Agile, Resilient and Green supplier selection	Case Study
(Rehman & Ali, 2021)	Fuzzy logic, Fuzzy AHP, Fuzzy TOPSIS	Healthcare supply chain resilience	Numerical Example
(Alizadeh-Meghbrazi et al., 2022)	Fuzzy logic, Multi-objective model	Sustainable and resilient mask supply chain during the COVID-19	Case Study
(P. Kumar & Kumar Singh, 2022)	BWM	Agri-food supply chains during COVID-19	Case Study
(Rajak et al., 2022)	BWM	Supply chain during COVID-19	Case Study
(Wicaksono & Illés, 2022)	-	Food supply chain resilience	Numerical Example
(Chowdhury et al., 2023)	AHP	COVID-19 vaccine operations and distribution challenges	Case Study
(Khan & Ali, 2023)	Fuzzy logic, FUCOM	Cold supply chain during COVID-19	Case Study
(Khezeli et al., 2023)	Fuzzy logic, Genetic algorithm	Sustainable and resilient supply chain management	Case Study

4. RUL STRATEGY DETERMINATION

Having a smooth and effective urban logistics has become difficult because of the difficulties and destructive events, which make logistics activities vulnerable (Chowdhury & Quaddus, 2015). The presence of factors such as traffic congestion, infrastructure limitations, and natural disasters can severely impact logistics activities, leading to significant economic and social consequences. To mitigate such risks, it is crucial to adopt innovative technologies and strategies to enhance the resilience of the urban logistics system. Istanbul plays a significant role in Turkey's logistics sector as it is one of the most important logistics centers in the country. Istanbul's development in the logistics sector is remarkable, given its position as a bridge between Asia and Europe. It is worth noting that Istanbul plays a crucial role in logistics activities throughout the country, accounting for 60% of all movements (Akben, 2020). With its status as a megacity and its significant contributions to production, transportation, and foreign trade, it stands out as a leader in the field of city logistics applications. This section aims to present RUL strategic factors and identify strategies for Istanbul using the novel integrated SWOT-based IVFF AHP-VIKOR methodology. The following research questions (RQs) guide this endeavor.

RQ1: What is the situation of the current urban logistics of Istanbul and which factors are most critical to enhance resilience?

RQ2: Which strategies can be determined on the identified factors in the urban logistics of Istanbul, as revealed by the SWOT analysis?

RQ3: In what ways does the incorporation of an IVFF-MCDM framework into SWOT analysis contribute to its enhanced potential?

4.1. Proposed SWOT-based IVFF-MCDM Methodology

The goal of a SWOT analysis is to identify the most effective strategies that leverage internal strengths and external opportunities, while mitigating internal weaknesses and external threats (Havle et al., 2021). Although SWOT analysis is a widely used method, it does have its limitations. One of the main challenges is the inability to quantitatively measure each factor and its impact on decision-making. However, by combining the SWOT analysis approach with the MCDM techniques, this shortcoming can be overcome (Büyüközkan & Ilıcak, 2019). An integrated model that utilizes SWOT analysis with IVFF-AHP and IVFF-VIKOR methods can facilitate decision-making and help to make strategic choices that are best suited to their unique circumstances. IVFF-AHP employed to determine the relative weights of the SWOT dimensions, SWOT factors and sub-factors by constructing a pairwise comparison matrix. Finally, the IVFF-VIKOR was used to identify the most importance strategy. The flowchart of the proposed methodology is shown in Figure 4.1.

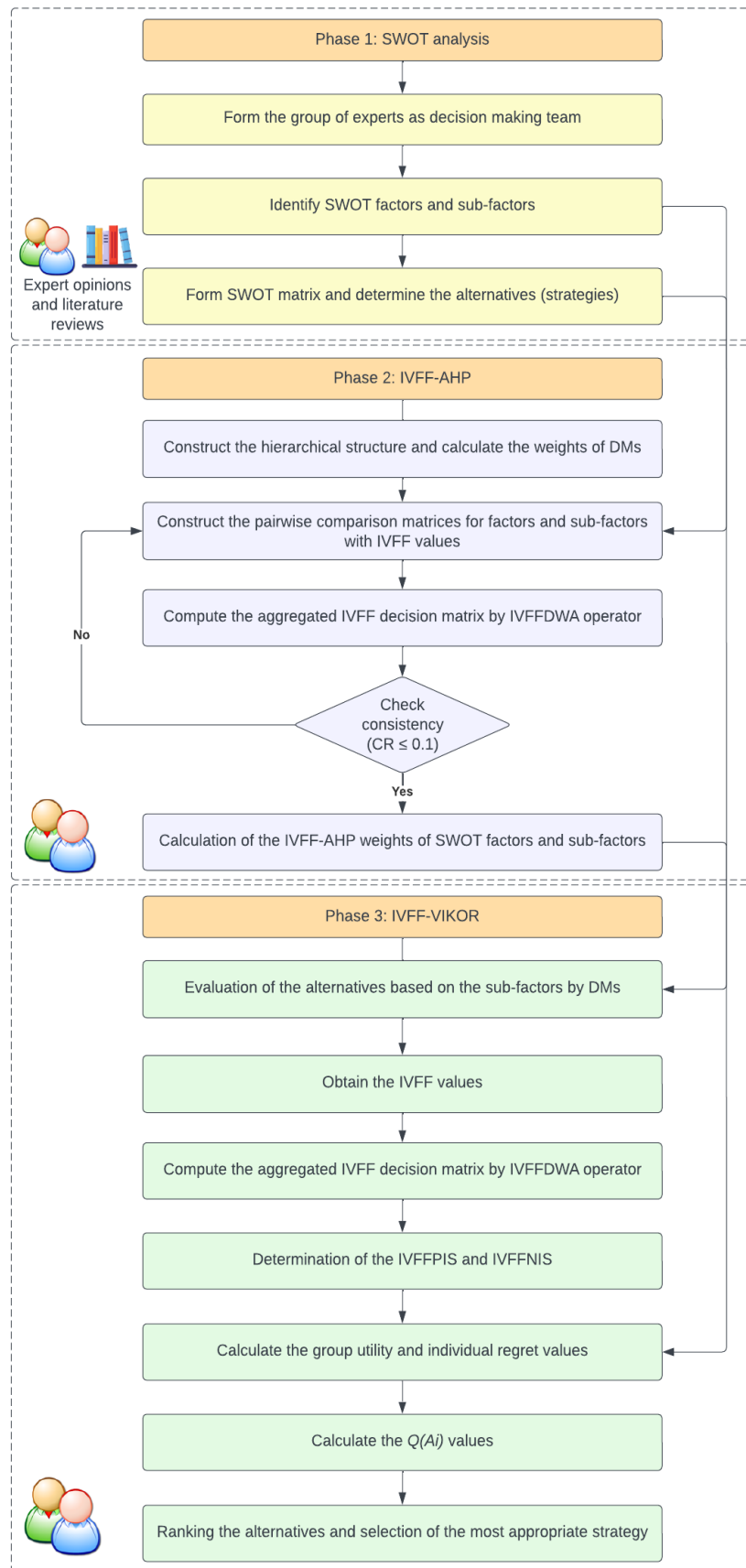


Figure 4.1: The flowchart of the proposed methodology

4.1.1. Computational Steps of IVFF-AHP

Here an MCDM approach using the AHP method in the IVFF environment is presented. IVFF-AHP method is introduced by Alkan & Kahraman (2022) to help organizations identify the crucial factors to be considered during the digitalization of the supply chain. Calculation steps of IVFF-AHP is presented as follows (Alkan & Kahraman, 2022):

Step 1. An expert group consisting of DMs is formed for the decision-making process. When selecting DMs, experience, knowledge and education levels, and willingness to help are considered.

Step 2. The evaluation criteria and alternatives for the goal are determined by benefiting from literature review and expert opinions.

Step 3. Calculate the weights of DMs. Let $E_k = (E_1, E_2, \dots, E_k)$, $k = 1, 2, \dots, K$ is a set of DMs and weights w_k for each E_k ; $\sum_{k=1}^K w_k = 1$. Here, the entropy method (F. Zhang & Xu, 2016) is applied to the IVFF environment. The importance degree of DMs is determined using the linguistic terms given in Table 4.1. The weights of the DMs are calculated using Equation (4.1.1.1) based on the linguistic terms.

$$w_k = \frac{\sqrt{\frac{1}{2}[(1-\pi_{\tilde{F}}^{l(k)})^2 + (1-\pi_{\tilde{F}}^{u(k)})^2]}}{\sum_{k=1}^K \sqrt{\frac{1}{2}[(1-\pi_{\tilde{F}}^{l(k)})^2 + (1-\pi_{\tilde{F}}^{u(k)})^2]}} \quad (4.1.1.1)$$

Table 4.1: Linguistic scale for the weights of DMs (Seikh & Mandal, 2023)

Linguistic variables	IVFFNs
Extremely significant (ES)	$([0.75, 0.85], [0.05, 0.15])$
Very significant (VS)	$([0.65, 0.75], [0.15, 0.25])$
Significant (S)	$([0.55, 0.65], [0.25, 0.35])$
Moderate (M)	$([0.45, 0.55], [0.35, 0.45])$
Insignificant (IS)	$([0.25, 0.35], [0.55, 0.65])$
Very insignificant (VIS)	$([0.15, 0.25], [0.65, 0.75])$
Extremely insignificant (EIS)	$([0.05, 0.15], [0.7, 0.85])$

Step 4. Construct the pairwise comparison matrix $Z = (z_{ij})_{m \times m}$ based on the opinions of DMs given in Table 4.2.

$$Z = \begin{bmatrix} 1 & z_{12} & \cdots & z_{1m} \\ z_{21} & 1 & \cdots & z_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1} & z_{m2} & \cdots & 1 \end{bmatrix}, \text{ where } z_{ij} = \langle [\mu_{ij}^l, \mu_{ij}^u], [v_{ij}^l, v_{ij}^u] \rangle \quad (4.1.1.2)$$

Table 4.2: Linguistic scale for criteria evaluation (Alkan & Kahraman, 2022)

Linguistic variables	IVFFNs			
	μ_l	μ_u	ν_l	ν_u
Extremely High Importance (EHI)	0.95	1	0	0
Very High Importance (VHI)	0.8	0.9	0.1	0.2
High Importance (HI)	0.7	0.8	0.2	0.3
Slightly More Importance (SMI)	0.6	0.65	0.35	0.4
Equally Importance (EI)	0.5	0.5	0.5	0.5
Slightly Less Importance (SLI)	0.35	0.4	0.6	0.65
Low Importance (LI)	0.2	0.3	0.7	0.8
Very Low Importance (VLI)	0.1	0.2	0.8	0.9
Extremely Low Importance (ELI)	0	0	0.95	1

Step 5. The consistency ratio (CR) of the pairwise comparison matrices (Z) is checked. Here, Saaty's (Saaty, 2006) classical consistency process is used. If $CR \leq 0.1$, then the evaluations are consistent. Otherwise, the evaluation process should be revised.

Step 6. Pairwise comparison matrices of each DM are combined to obtain a group decision matrix. To execute this, the IVFFDWA operator is utilized which is given in Equation (3.1.27).

Step 7. The differences matrix $D = (d_{ij})_{m \times m}$ between lower and upper points of the membership and non-membership functions is defined as follows:

$$\begin{aligned} d_{ij}^l &= (\mu_{ij}^l)^3 - (v_{ij}^u)^3, \\ d_{ij}^u &= (\mu_{ij}^u)^3 - (v_{ij}^l)^3 \end{aligned} \quad (4.1.1.3)$$

Step 8. The interval multiplicative matrix $S = (s_{ij})_{m \times m}$ calculated by the following equations:

$$\begin{aligned} s_{ij}^l &= \sqrt[3]{1000 d_{ij}^l} \\ s_{ij}^u &= \sqrt[3]{1000 d_{ij}^u} \end{aligned} \quad (4.1.1.4)$$

Step 9. The uncertainty value $T = (t_{ij})_{m \times m}$ of the z_{ij} is obtained as follows:

$$t_{ij} = 1 - (\mu_{ij_u}^3 - \mu_{ij_l}^3) - (v_{ij_u}^3 - v_{ij_l}^3) \quad (4.1.1.5)$$

Step 10. The matrix of unnormalized weights $R = (r_{ij})_{m \times m}$ is found by multiplying the uncertainty degrees with $S = (s_{ij})_{m \times m}$ as follows:

$$r_{ij} = \left(\frac{s_{ij}^l + s_{ij}^u}{2} \right) t_{ij} \quad (4.1.1.6)$$

Step 11. The normalized weights w_i are obtained by the following equation:

$$w_i = \frac{\sum_{j=1}^m r_{ij}}{\sum_{i=1}^m \sum_{j=1}^m r_{ij}} \quad (4.1.1.7)$$

4.1.2. Computational Steps of IVFF-VIKOR

A novel extension to the VIKOR method in the context of IVFF is presented. VIKOR is a commonly used method for MCDM problems, however, no previous studies have integrated VIKOR in IVFF environment. In this thesis, after the evaluation of evaluation criteria with IVFF-AHP, alternatives are evaluated by utilizing IVFF-VIKOR method. The steps of the proposed IVFF-VIKOR method are given below:

Step 12. Here, the expert group is formed for the evaluation of alternatives.

Step 13. The alternatives are evaluated based on the evaluation criteria. The linguistic terms given in Table 4.2 are used to evaluate the alternatives.

Step 14. Evaluation matrices of each DM are combined to obtain a group decision matrix ($\tilde{X}$). Let ($\tilde{X}$) has m alternatives and n sub-factor, $\tilde{x}_{ij} = ([\mu_{\tilde{F}}^l(\tilde{x}_{ij}), \mu_{\tilde{F}}^u(\tilde{x}_{ij})], [\nu_{\tilde{F}}^l(\tilde{x}_{ij}), \nu_{\tilde{F}}^u(\tilde{x}_{ij})])$ where $i=1,2,\dots,m$ and $j=1,2,\dots,n$. For the aggregation, the IVFFDWA operator is utilized which is explained in Equation (3.1.27).

Step 15. IVFF positive ideal solution (IVFFPIS) ($\tilde{f}_j^*$) and IVFF negative ideal solution (IVFFNIS) ($\tilde{f}_j^-$) are computed as follows:

$$\tilde{f}_j^* = [\mu_{\tilde{F}}^l(\tilde{x}_j^*), \mu_{\tilde{F}}^u(\tilde{x}_j^*)], [\nu_{\tilde{F}}^l(\tilde{x}_j^*), \nu_{\tilde{F}}^u(\tilde{x}_j^*)] \quad (4.1.2.1)$$

Here,

$$\begin{aligned} [\mu_{\tilde{F}}^l(\tilde{x}_j^*) &= \max_i(\mu_{\tilde{F}}^l(\tilde{x}_{ij})), \mu_{\tilde{F}}^u(\tilde{x}_j^*) = \max_i(\mu_{\tilde{F}}^u(\tilde{x}_{ij}))], \\ [\nu_{\tilde{F}}^l(\tilde{x}_j^*) &= \min_i(\nu_{\tilde{F}}^l(\tilde{x}_{ij})), \nu_{\tilde{F}}^u(\tilde{x}_j^*) = \min_i(\nu_{\tilde{F}}^u(\tilde{x}_{ij}))] \end{aligned} \quad (4.1.2.2)$$

$$\tilde{f}_j^- = [\mu_{\tilde{F}}^l(\tilde{x}_j^-), \mu_{\tilde{F}}^u(\tilde{x}_j^-)], [\nu_{\tilde{F}}^l(\tilde{x}_j^-), \nu_{\tilde{F}}^u(\tilde{x}_j^-)] \quad (4.1.2.3)$$

Here,

$$\begin{aligned} [\mu_{\tilde{F}}^l(\tilde{x}_j^-) &= \min_i(\mu_{\tilde{F}}^l(\tilde{x}_{ij})), \mu_{\tilde{F}}^u(\tilde{x}_j^-) = \min_i(\mu_{\tilde{F}}^u(\tilde{x}_{ij}))], \\ [\nu_{\tilde{F}}^l(\tilde{x}_j^-) &= \max_i(\nu_{\tilde{F}}^l(\tilde{x}_{ij})), \nu_{\tilde{F}}^u(\tilde{x}_j^-) = \max_i(\nu_{\tilde{F}}^u(\tilde{x}_{ij}))] \end{aligned} \quad (4.1.2.4)$$

Step 16. Calculate the group utility $S(A_i)$ and individual regret values $R(A_i)$. Here, the distance D is calculated as explained in Equation (3.1.25).

$$S(A_i) = \sum_{j=1}^n \left[w_j \frac{D(\tilde{f}_j^*, \tilde{x}_{ij})}{D(\tilde{f}_j^*, \tilde{f}_j^-)} \right] \quad (4.1.2.5)$$

$$R(A_i) = \max_j \left[w_j \frac{D(\tilde{f}_j^*, \tilde{x}_{ij})}{D(\tilde{f}_j^*, \tilde{f}_j^-)} \right] \quad (4.1.2.6)$$

Step 17. Calculate the $Q(A_i)$ values with the following equations. Here, v represents the weight of the strategy of maximum group utility and $(1 - v)$ represents the weight of the individual regret. Generally, v can be taken as 0.5 for the maximum group utility (Buyukozkan, Havle, et al., 2021).

$$Q(A_i) = v \left(\frac{(S(A_i) - S^*(A_i))}{(S^-(A_i) - S^*(A_i))} \right) + (1 - v) \left(\frac{(R(A_i) - R^*(A_i))}{(R^-(A_i) - R^*(A_i))} \right) \quad (4.1.2.7)$$

where,

$$S^*(A_i) = \min_i (S(A_i)), \quad S^-(A_i) = \max_i (S(A_i)) \quad (4.1.2.8)$$

$$R^*(A_i) = \min_i (R(A_i)), \quad R^-(A_i) = \max_i (R(A_i)) \quad (4.1.2.9)$$

Step 18. Alternatives are ranked according to $S(A_i)$, $R(A_i)$ and $Q(A_i)$ values. The best alternative (A_1) is determined based on two conditions:

Condition (1): Acceptable advantage.

$Q(A_2) - Q(A_1) \geq DQ$ where A_2 is the second alternative in the ranking list by Q .

$DQ = \frac{1}{m-1}$ and m is the number of alternatives. If $m < 4$ than the DQ value is taken as 0.25.

Condition (2): Acceptable stability in decision-making.

In this condition, alternative A_i is listed first in S_i and/or R_i values. When one of these conditions is not satisfied then a set of compromise solution is selected. These compromise solutions are consisting of:

1) If only second condition is not satisfied then alternatives A_1 and A_2 are determined as the best compromise solution.

2) If first condition is not satisfied, then A_m is determined by $Q(A_m) - Q(A_1) < DQ$ for maximum m (the positions of these alternatives are in closeness).

4.2. Application of the Proposed Methodology

In this section, a SWOT analysis of the urban logistics activities of Istanbul was conducted from a resilience perspective. During the creation of the SWOT analysis, both a literature review (ARUP, 2014), (Istanbul Metropolitan Municipality, 2015), (Hsieh et al., 2016), (Hernantes et al., 2019), (Cardoso et al., 2020), (Istanbul Metropolitan Municipality, 2020a) and the opinions of experts from the Istanbul Metropolitan Municipality (IMM) were utilized. The experts consisted of 21 individuals, with 12 possessing expertise in Urban and Regional Planning, 5 in Engineering, 3 in Architecture, and 1 in Archaeology. The SWOT factors and sub-factors were then evaluated using an integrated IVFF-AHP methodology, which allowed for a systematic and objective assessment of the critical factors affecting the resilience of the logistics system. Finally, alternative strategies were ranked using the IVFF-VIKOR methodology, identifying the most suitable strategy for enhancing the resilience of the urban logistics system.

4.2.1. SWOT Factor Weighting through IVFF-AHP

This section provides a SWOT analysis for Istanbul from RUL perspective and gives the importance weights of SWOT dimensions, factors, and sub-factors by using the IVFF-AHP method and by utilizing the IVFFDWA operator. Here, SWOT dimensions, factors and sub-factors are assumed to be independent of each other.

Step 1. A group of experts is formed during the evaluation of SWOT dimensions, SWOT factors, sub-factors and strategies. These experts consist of individuals working in IMM. The characteristics of the experts are detailed in Table 4.3.

Table 4.3: The characteristics of the DMs

DMs	Department of IMM	Profession	Education	Experience
DM1	Transportation	Engineer	Master's degree	>5 years
DM2	GIS directorate	Engineer	Bachelor's degree	2 years
DM3	Transportation	Urban planner	Master's degree	3 years
DM4	Transportation	Engineer	Master's degree	5 years
DM5	Urban planning	Urban planner	Master's degree	4 years

Step 2. The SWOT matrix, obtaining the SWOT dimensions, SWOT factors, sub-factors, and RUL strategies, is constructed and given in Figure 4.2 and Table 4.6. The constructed hierarchical model based on the goal and the SWOT matrix is given in Fig. 3.

Step 3. The importance weights of the five DMs have been determined using Equation (4.1.1.1) and the linguistic terms provided in Table 4.1. The resulting importance weights are presented in Table 4.4 based on the assigned linguistic terms.

Table 4.4: The importance weights of DMs

DMs	Ratings	IVFFNs	Importance weights
DM1	ES	$([0.75, 0.85], [0.05, 0.15])$	0.235 (w_1)
DM2	VS	$([0.65, 0.75], [0.15, 0.25])$	0.148 (w_2)
DM3	VS	$([0.65, 0.75], [0.15, 0.25])$	0.148 (w_3)
DM4	ES	$([0.75, 0.85], [0.05, 0.15])$	0.235 (w_4)
DM5	ES	$([0.75, 0.85], [0.05, 0.15])$	0.235 (w_5)

Step 4. DMs judgments are obtained through the linguistic scale presented in Table 4.2 based on pairwise comparisons. Firstly, DMs evaluated the SWOT dimensions, and after that, SWOT factors and sub-factors are evaluated by each DM. Due to page limitations, only the evaluations of the SWOT dimensions are provided by using IVFFNs are presented in Table 4.5.

Table 4.5: Pairwise comparison matrices for SWOT dimensions

Dimension	DM1	CR = 0.086			
	S	W	O	T	
S	EI	SLI	SMI	HI	
W	SMI	EI	SMI	VHI	
O	SLI	SLI	EI	HI	
T	LI	VLI	LI	EI	
	DM2	CR = 0.089			
	S	W	O	T	
S	EI	HI	SMI	VHI	
W	LI	EI	LI	SLI	
O	SLI	HI	EI	SMI	
T	VLI	SMI	SLI	EI	
	DM3	CR = 0.045			
	S	W	O	T	
S	EI	SLI	EI	HI	
W	SMI	EI	SMI	VHI	
O	EI	SLI	EI	VHI	
T	LI	VLI	VLI	EI	
	DM4	CR = 0.06			
	S	W	O	T	
S	EI	SMI	VHI	VHI	
W	SLI	EI	SMI	VHI	
O	VLI	SLI	EI	SMI	
T	VLI	VLI	SLI	EI	
	DM5	CR = 0.09			
	S	W	O	T	
S	EI	LI	SLI	HI	
W	HI	EI	SMI	VHI	
O	SMI	SLI	EI	VHI	
T	LI	VLI	VLI	EI	

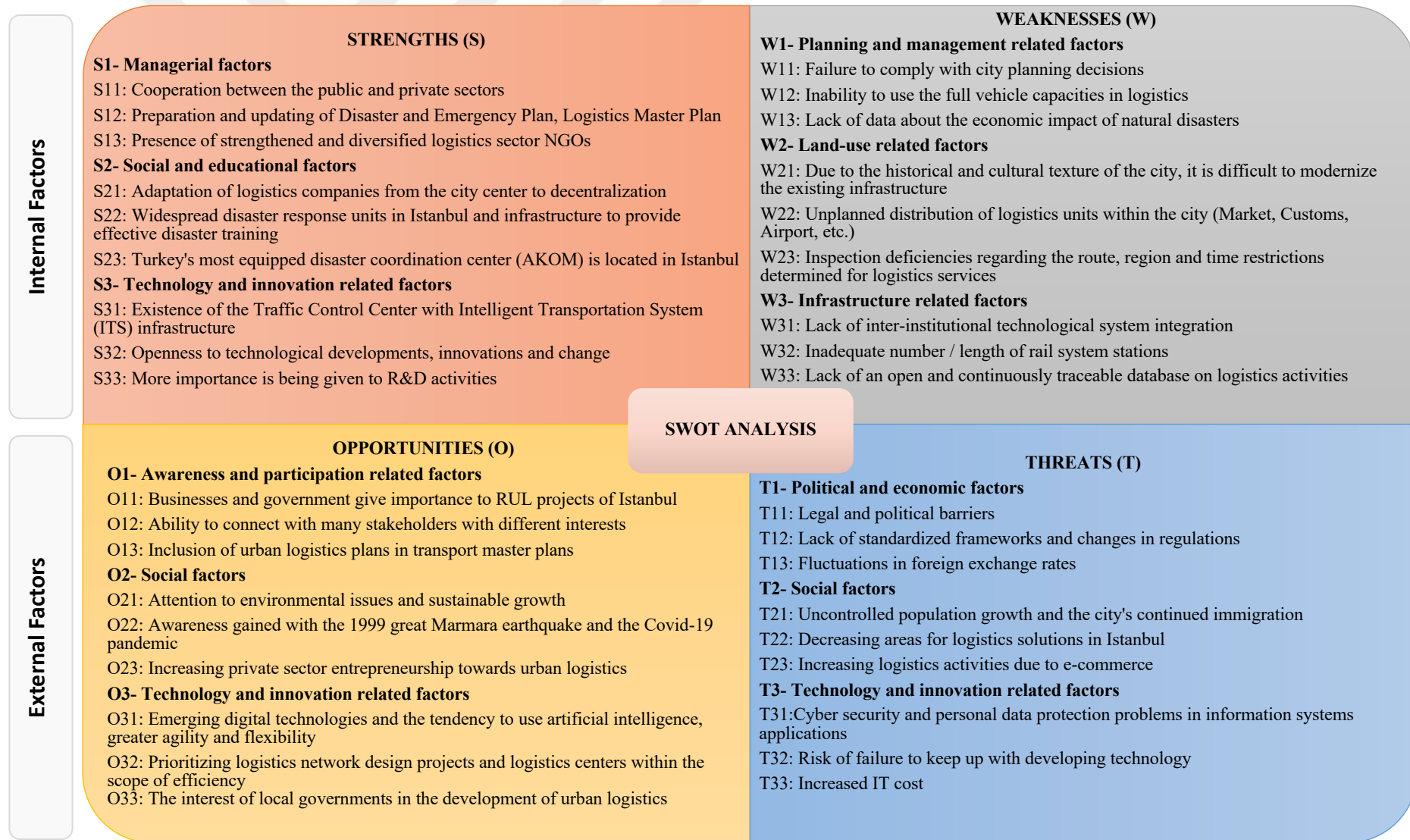


Figure 4.2: SWOT factors and sub-factors considered for RUL of Istanbul

Table 4.6: RUL strategies for Istanbul

	Strengths (S)	Weaknesses (W)
Opportunities (O)	SO Strategies: • <u>SO1</u>- Develop a strong multi-stakeholder collaboration. • <u>SO2</u>- Reducing greenhouse gas emissions, air pollution and solid waste from urban logistics by sustainable delivery vehicles. • <u>SO3</u>- Effectively manage traffic in urban logistics by using intelligent transportation systems and transportation infrastructure applications effectively.	WO Strategies: • <u>WO1</u>- Improve the risk/disaster capacity and social awareness for RUL. • <u>WO2</u>- Act in accordance with the principles of urban logistics in the selection of places that have an impact on traffic such as Market Halls, OIZs, and Shopping Centers. • <u>WO3</u>- Achieving high efficiency and reducing costs in freight and fleet matching so that resources can be used economically.
Threats (T)	ST Strategies: • <u>ST1</u>- Develop a continuity plan, emergency logistics plan for multiple disruptions. • <u>ST2</u>- Establish an integrated control center for real-time visibility, facilitating faster decision-making and enhancing the agility of urban logistics processes through the integration of current technologies. • <u>ST3</u>- Reduce migration to the Istanbul region, minimize urban freight logistics by creating logistics attraction centers around Istanbul.	WT Strategies: • <u>WT1</u>- Diversify the logistics network, reduce the share of road transport and increase the share of sea/rail/air transport with multi-modal transport to make Istanbul city logistics more resilient. • <u>WT2</u>- Create data redundancy to maintain information. • <u>WT3</u>- Give importance to R&D activities in the field of RUL and increase government incentives in this field.

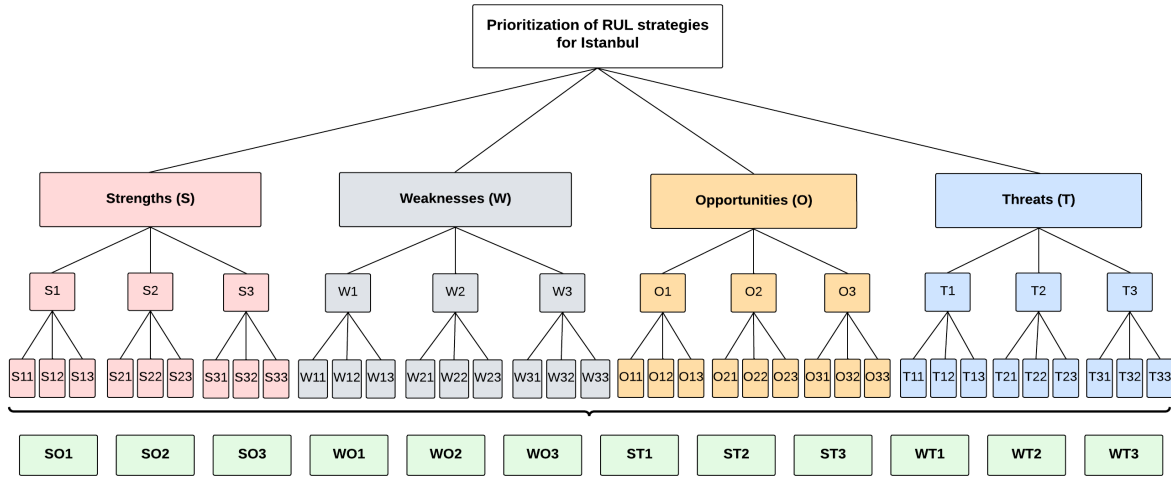


Figure 4.3: The hierarchical model of SWOT matrix

Step 5. The consistency ratio (CR) is checked for each pairwise comparison matrix, and each was found to be consistent based on the computed CR values. Table 4.5 shows the CR values for SWOT dimensions.

Step 6. DMs' evaluations are converted into IVFFNs and aggregated using the IVFFDWA operator to obtain the group decision. Here, we consider $\beta = 1$. The aggregated IVFF values concerning the SWOT dimensions are presented in Table 4.7.

Table 4.7: Aggregated pairwise comparison matrix for SWOT dimensions

Dimension	S				W			
	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u
S	0.500	0.500	0.500	0.500	0.518	0.601	0.336	0.450
W	0.578	0.663	0.293	0.398	0.500	0.500	0.500	0.500
O	0.454	0.495	0.483	0.534	0.470	0.560	0.354	0.488
T	0.175	0.271	0.732	0.833	0.342	0.390	0.580	0.660
Dimension	O				T			
	μ_l	μ_u	μ_l	μ_u	μ_l	μ_u	μ_l	μ_u
S	0.652	0.765	0.652	0.765	0.652	0.765	0.652	0.765
W	0.576	0.627	0.576	0.627	0.576	0.627	0.576	0.627
O	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
T	0.267	0.326	0.267	0.326	0.267	0.326	0.267	0.326

Step 7. The differences matrix between lower and upper points of the membership and non-membership functions was formed based on Equation (4.1.1.3) and presented in Table 4.8 for SWOT dimensions.

Table 4.8: The differences matrix for SWOT dimensions

Dimension	S		W		O		T	
S	0.000	0.000	0.048	0.179	0.250	0.444	0.406	0.624
W	0.130	0.266	0.000	0.000	0.117	0.197	0.464	0.696
O	-0.059	0.009	-0.013	0.131	0.000	0.000	0.370	0.584
T	-0.572	-0.373	-0.247	-0.136	-0.402	-0.278	0.000	0.000

Step 8. The interval multiplicative matrix was formed based on Equation (4.1.1.4) and presented in Table 4.9 for SWOT dimensions.

Table 4.9: The interval multiplicative matrix for SWOT dimensions

Dimension	S		W		O		T	
S	1.000	1.000	1.116	1.510	1.779	2.782	2.545	4.210
W	1.349	1.846	1.000	1.000	1.310	1.574	2.914	4.966
O	0.873	1.020	0.971	1.354	1.000	1.000	2.346	3.841
T	0.268	0.424	0.566	0.731	0.397	0.528	1.000	1.000

Step 9. The uncertainty value was obtained and given in Table 4.10 for SWOT dimensions.

Table 4.10: The uncertainty value for SWOT dimensions

Dimension	S	W	O	T
S	1.000	0.869	0.806	0.781
W	0.864	1.000	0.920	0.769
O	0.932	0.856	1.000	0.786
T	0.800	0.889	0.876	1.000

Step 10. Unnormalized weights were obtained based on Tables 4.8 and 4.9 by Equation (4.1.1.6). The unnormalized weights are given for SWOT dimensions in Table 4.11.

Table 4.11: The unnormalized weights for SWOT dimensions

Dimension	S	W	O	T
S	1.000	1.141	1.838	2.639
W	1.380	1.000	1.327	3.028
O	0.883	0.994	1.000	2.431
T	0.277	0.576	0.405	1.000

Step 11. The normalized weights are calculated by using Equation (4.1.1.7). The obtained final weights are given in Table 4.12 for SWOT dimensions, factors and sub-factors.

Table 4.12: The weights of SWOT dimensions, factors and sub-factors

SWOT dimensions	Weights	Factors	Weights	Sub-factors	Local weights	Global weights
S	0.316	S1	0.256	S11	0.435	0.0353
				S12	0.281	0.0228
				S13	0.284	0.0230
		S2	0.383	S21	0.445	0.0539
				S22	0.311	0.0377
				S23	0.244	0.0296
		S3	0.361	S31	0.385	0.0440
				S32	0.272	0.0310
				S33	0.343	0.0391
		W1	0.420	W11	0.407	0.0550
				W12	0.307	0.0415
				W13	0.286	0.0386
W	0.322	W2	0.249	W21	0.417	0.0335
				W22	0.312	0.0250
				W23	0.272	0.0218
		W3	0.331	W31	0.290	0.0309
				W32	0.408	0.0434
				W33	0.302	0.0321
		O1	0.318	O11	0.370	0.0298
				O12	0.256	0.0206
				O13	0.374	0.0302
		O2	0.314	O21	0.271	0.0216
				O22	0.408	0.0325
				O23	0.321	0.0256
O	0.254	O3	0.368	O31	0.356	0.0333
				O32	0.375	0.0351
				O33	0.269	0.0252
		T1	0.392	T11	0.477	0.0202
				T12	0.268	0.0113
				T13	0.255	0.0108
		T2	0.350	T21	0.436	0.0165
				T22	0.267	0.0101
				T23	0.297	0.0112
		T3	0.258	T31	0.396	0.0110
				T32	0.314	0.0088
				T33	0.289	0.0081

The results show that the most important SWOT dimensions for RUL of Istanbul are Weaknesses and Strengths. Therefore, it is essential to focus on internal factors to ensure successful RUL for Istanbul. After evaluating the SWOT dimensions, the DMs proceeded to evaluate the SWOT factors and sub-factors. Consistency of all comparison matrices was tested and found to be consistent. The weights of SWOT factors and sub-factors were

determined using the IVFF-AHP steps, similarly to the SWOT dimensions. The global weights of SWOT sub-factors were calculated by multiplying them with the weights of SWOT factors and dimensions. Among all the SWOT factors, Table 4.12 shows that the most important SWOT factor is “W1- Planning and management related factors”, which is not surprising since it falls under the Weaknesses dimension which is the most important SWOT dimension. After that, when the SWOT sub-factors are examined, “W11: Failure to comply with city planning decisions” is the most significant sub-factor according to global weights, followed by “S21: Adaptation of logistics companies from the city center to decentralization” and “S31: Existence of the Traffic Control Center with Intelligent Transportation System (ITS) infrastructure”. This implies that it is of utmost importance to ensure that city planning, and urban logistics planning are closely aligned. Coordinating the positioning of logistics companies with city planning decisions can significantly enhance the resilience of urban logistics. Furthermore, it is essential to adopt an integrated approach to urban logistics activities while leveraging ITS.

4.2.2. Strategy Assessment through IVFF-VIKOR

This section provides the ranking of alternative RUL strategies for Istanbul by using the novel IVFF-VIKOR method and by utilizing the IVFFDWA operator.

Step 12. Here, the same group of experts consisting of DMs in the IVIF AHP process is involved in the evaluation process conducted in the IVIF VIKOR part.

Step 13. The alternatives (strategies) are evaluated based on each sub-factor by using the linguistic terms given in Table 4.2 and the strategy evaluation matrices are presented in Table 4.13.

Step 14. Evaluation matrices of each DM are combined by using IVFFDWA operator, to obtain a group decision matrix. Here, we consider $\beta = 1$. The aggregated decision matrix for strategies is given in Table 4.14.

Step 15. IVFFPIS ($\tilde{f}_j^*$) and IVFFNIS ($\tilde{f}_j^-$) values are computed by using Equation (4.1.2.1)-(4.1.2.2) and given in Table 4.15.

Step 16. Group utility $S(A_i)$ and individual regret values $R(A_i)$ are computed by Equation (4.1.2.5) and Eq.(4.1.2.6) and presented in Table 4.16.



Table 4.13: Evaluation of strategies by DMs

DMs	Strategies	S11	S12	S13	S21	S22	S23	S31	S32	S33	W11	W12	W13	W21	W22	W23	W31	W32	W33	O11	O12	O13	O21	O22	O23	O31	O32	O33	T11	T12	T13	T21	T22	T23	T31	T32	T33	
DM1	S01	VHI	SMI	HI	SMI	HI	SMI	SMI	SMI	SMI	SMI	LI	LI	SLI	SLI	VLI	VLI	LI	LI	LI	HI	VHI	HI	HI	SMI	SMI	SMI	SMI	HI	SLI	LI	VLI	VLI	VLI	VLI	LI	LI	LI
	S02	VHI	SMI	SMI	VHI	VHI	HI	VHI	VHI	VHI	LI	LI	SMI	LI	SMI	VHI	LI	LI	VHI	VHI	HI	HI	SMI	VHI	HI	SMI	SMI	SMI	HI	HI	SLI	LI	SLI	SMI	SMI	SMI	SMI	SMI
	S03	LI	LI	LI	SMI	SMI	LI	VHI	SMI	HI	LI	VHI	VLI	HI	HI	LI	HI	SMI	HI	VHI	HI	HI	HI	HI	HI	VHI	VHI	HI	HI	SMI	HI	SMI	SMI	SMI	SMI	SMI	SMI	SMI
	WO1	SMI	HI	HI	SLI	HI	SLI	LI	LI	LI	SLI	SLI	SMI	SMI	SMI	SMI	LI	LI	LI	HI	SMI	SMI	VHI	VHI	HI	SMI	SMI	HI	HI	SMI	LI	LI	VLI	VLI	LI	LI	LI	
	WO2	HI	LI	SMI	VHI	LI	LI	SMI	LI	SMI	VHI	HI	LI	VHI	VHI	HI	HI	HI	HI	HI	HI	SMI	VHI	HI	SMI	SMI	SMI	HI	HI	SMI	HI	SLI	HI	VHI	HI	VLI	LI	VLI
	WO3	HI	LI	SMI	HI	LI	LI	HI	VLI	VLI	LI	VHI	LI	LI	LI	SMI	VHI	VHI	HI	LI	SMI	LI	SMI	LI	SMI	SMI	LI	HI	VHI	LI	SMI	SMI	LI	LI	SMI	VLI	SMI	LI
	ST1	HI	VHI	HI	SMI	VHI	VHI	HI	HI	SMI	VHI	SMI	VHI	SMI	SMI	SMI	SMI	HI	HI	HI	HI	VHI	VHI	HI	SMI	SMI	SMI	SMI	HI	HI	SMI	HI	HI	HI	HI	HI	HI	HI
	ST2	SMI	HI	SMI	SMI	SMI	SMI	HI	VHI	VHI	SLI	SMI	SMI	SMI	SMI	SMI	LI	LI	SLI	SLI	SMI	SMI	SMI	SMI	SMI	LI	LI	VHI	LI	HI	SMI	SMI	HI	HI	SMI	HI	HI	
	ST3	LI	LI	SMI	VHI	HI	HI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	HI	LI	LI	LI	SLI	LI	LI	SLI	SMI	SMI	LI	SMI	SMI	SMI	HI	HI	VHI	VHI	VHI	SLI	SLI	SLI	
	WT1	SMI	LI	SMI	SMI	VLI	VLI	SMI	LI	SMI	LI	HI	HI	SLI	SMI	SMI	SMI	SMI	VHI	VHI	HI	SMI	SMI	SMI	SMI	HI	SMI	SMI	VHI	HI	HI	SMI	SMI	HI	HI	LI	LI	VLI
DM2	WT2	SLI	LI	LI	LI	LI	SLI	SMI	SMI	SMI	VLI	VLI	LI	LI	LI	LI	HI	SLI	SMI	SMI	SLI	LI	SMI	LI	SMI	LI	SMI	LI	LI	SLI	LI	SLI	LI	LI	SMI	VHI	HI	HI
	WT3	HI	LI	SMI	LI	LI	SLI	SMI	SMI	SMI	HI	LI	LI	SMI	VLI	VLI	LI	LI	SMI	HI	HI	LI	SLI	LI	SMI	LI	LI	SMI	LI	LI	SLI	VHI	SLI	LI	LI	SMI	LI	LI
	S01	VHI	HI	VHI	HI	VHI	LI	LI	SMI	LI	LI	VLI	LI	HI	VHI	LI	LI	VLI	SLI	HI	HI	LI	VLI	LI	VLI	LI	VLI	HI	VLI	SLI	LI	VLI	VLI	VLI	LI	LI	LI	LI
	S02	HI	SMI	SLI	HI	HI	VHI	SMI	VHI	SMI	HI	HI	LI	LI	SMI	VLI	HI	HI	LI	SLI	SLI	SLI	LI	SMI	SLI	SLI	SLI	LI	LI	LI	LI	LI	SMI	LI	LI	SMI	LI	LI
	S03	SMI	HI	SMI	SMI	SMI	SMI	HI	SMI	HI	LI	VHI	VLI	HI	HI	LI	HI	SMI	HI	VHI	HI	HI	HI	HI	HI	VHI	VHI	HI	HI	SMI	SMI	SMI	SMI	SMI	HI	SMI	HI	HI
	WO1	SMI	HI	HI	SLI	HI	SLI	LI	LI	LI	SLI	SLI	SMI	SMI	SMI	SMI	LI	LI	LI	HI	SMI	SMI	VHI	VHI	HI	HI	HI	LI	SMI	LI	LI	VLI	VLI	LI	LI	LI	LI	
	WO2	HI	LI	SMI	VHI	LI	LI	SMI	VHI	HI	LI	VHI	VHI	HI	HI	HI	HI	HI	SMI	SMI	VHI	VHI	HI	SMI	SMI	SMI	HI	SMI	HI	SMI	HI	SLI	HI	VHI	HI	VLI	LI	VLI
	WO3	HI	LI	SMI	HI	LI	LI	HI	VLI	VLI	LI	VHI	LI	LI	LI	SMI	VHI	VHI	HI	LI	SMI	LI	SMI	SMI	SMI	LI	HI	VHI	LI	SMI	LI	LI	SLI	SMI	HI	SMI	LI	
	ST1	HI	VHI	HI	SMI	VHI	VHI	HI	HI	SMI	VHI	SMI	VHI	SMI	VHI	SLI	HI	SMI	SMI	HI	HI	VHI	VHI	HI	HI	SMI	SMI	HI	SMI	HI	HI	SMI	HI	HI	HI	HI	HI	HI
	ST2	LI	HI	VLI	VLI	LI	VHI	LI	VHI	VHI	SLI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	VLI	VLI	LI	LI	SMI	LI	LI	SMI	LI	LI	VHI	LI	HI	SMI	SMI	HI	HI	SMI	HI	HI
DM3	ST3	LI	LI	SMI	VHI	HI	HI	SMI	SMI	SMI	SMI	SMI	SMI	SLI	SLI	HI	LI	LI	LI	SLI	LI	LI	SLI	SMI	LI	SMI	SMI	SMI	SMI	HI	LI	SMI	LI	LI	SMI	SLI	SLI	SLI
	WT1	LI	LI	SMI	VLI	VLI	VLI	HI	SLI	SMI	SLI	LI	LI	SMI	LI	LI	SMI	LI	SLI	LI	SMI	SMI	SMI	SMI	SMI	HI	SMI	SMI	SMI	HI	LI	SMI	SMI	HI	HI	LI	VLI	
	WT2	SLI	LI	LI	LI	LI	LI	SLI	SMI	SMI	SMI	VLI	VLI	LI	LI	LI	LI	HI	SLI	SMI	SLI	LI	SMI	LI	LI	SMI	LI	LI	SLI	LI	SLI	LI	LI	SMI	VHI	HI	HI	
	WT3	HI	LI	SMI	LI	LI	SLI	SMI	SMI	SMI	HI	LI	LI	SMI	VLI	VLI	LI	LI	LI	SMI	HI	HI	LI	SLI	LI	LI	SMI	LI	LI	SLI	VHI	SLI	LI	LI	SMI	LI	LI	
	S01	HI	HI	HI	VHI	VHI	HI	HI	SMI	SMI	SMI	SMI	LI	SMI	SMI	SMI	SMI	HI	SMI	HI	LI	HI	LI	VLI	LI	VLI	HI	VLI	HI	VLI	SLI	SLI	LI	VLI	VLI	LI	LI	LI
	S02	HI	SMI	SLI	HI	HI	VHI	SMI	VHI	SMI	HI	HI	HI	SLI	HI	SLI	LI	LI	LI	SLI	SLI	SLI	LI	SMI	SLI	SLI	SLI	LI	LI	LI	LI	LI	SMI	LI	LI	LI	SMI	
	S03	SMI	HI	SMI	SMI	SMI	SMI	HI	SMI	HI	LI	VHI	SMI	VHI	LI	LI	SMI	LI	SMI	LI	SMI	SMI	SMI	SMI	HI	SMI	SMI	VHI	HI	HI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	
	WO1	LI	VHI	VHI	HI	HI	HI	HI	HI	LI	LI	SLI	SLI	SMI	SMI	SMI	SMI	LI	LI	LI	LI	SLI	LI	SMI	LI	LI	SMI	LI	LI	SLI	LI	LI	LI	LI	LI	LI		
	WO2	VHI	SMI	VHI	LI	LI	SMI	LI	LI	SMI	VHI	HI	LI	VHI	VHI	HI	HI	HI	HI	HI	HI	HI	HI	LI	SMI	LI	LI	SMI	LI	LI	SLI	VHI	SLI	LI	LI	VHI	SLI	LI
	WO3	VHI	SLI	HI	SMI	SMI	HI	HI	HI	VLI	LI	VHI	LI	LI	LI	SMI	VHI	VHI	HI	LI	SMI	LI	SMI	SMI	SMI	LI	HI	VHI	LI	SMI	LI	LI	SLI	SMI	LI	LI	LI	
DM4	ST1	SMI	SLI	SLI	SMI	SMI	SMI	VLI	VLI	SMI	VHI	SMI	VHI	SLI	HI	SMI	SMI	HI	HI	HI	VHI	VHI	HI	HI	HI	SMI	SMI	SMI	HI	HI	SMI	HI	SMI	HI	HI	HI	HI	HI
	ST2	VHI	HI	SMI	SMI	HI	HI	SMI	HI	SLI	HI	VHI	SMI	SLI	SMI	SMI	SMI	SMI	VLI	VLI	VHI	VHI	HI	LI	SMI	LI	SMI	SMI	LI	HI	VHI	LI	HI	LI	LI	LI	LI	
	ST3	VHI	SMI	VHI	SLI	HI	SMI	SMI	HI	LI	LI	SLI	SLI	SMI	SMI	SMI	LI	LI	LI	SMI	HI	HI	HI	VHI	VHI	HI	HI	SMI	HI	SMI	LI	HI	SMI	LI	HI	HI	HI	
	WT1	HI	VHI	SMI	SLI	SLI	SMI	SMI	SMI	SMI	SLI	HI	HI	LI	SMI	LI	LI	SMI	LI	SLI	LI	SMI	SMI	VLI	VLI	LI	LI	SMI	LI	LI	VHI	SLI	LI	HI	SMI	VHI	LI	
	WT2	LI	SLI	SLI	SLI	HI	LI	LI	LI	SMI	LI	SMI	LI	SLI	LI	LI	SMI	SLI	LI	SMI	SLI	LI	LI	SLI	LI	LI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	
	WT3	SMI	LI	SMI	SLI	SMI	SMI	HI	LI	LI	SMI	LI	SMI	VLI	VLI	LI	LI	LI	SMI	HI	HI	LI	SLI	LI	LI	SMI	LI	LI	SLI	VHI	SLI	LI	LI	SMI	SMI	SMI	SMI	
	S01	VHI	HI	VHI	VHI	HI	HI	HI	SMI	SMI	SMI	SMI	LI	SMI	SMI	SMI	SMI	SMI	VHI	LI	HI	VHI	LI	VLI	LI	VLI	LI	VLI	LI	LI	LI	VLI	VLI	VLI	LI	LI	LI	
	S02	HI	SMI	LI	VHI	HI	HI	SMI	HI	SMI	HI	VHI	HI	LI	HI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	SMI	LI	LI	LI	LI	LI	LI	LI	LI	HI	SMI	LI	
	S03	SLI	HI	SLI	SMI	SLI	HI	HI	SMI	HI	LI	HI	SMI	HI	LI	LI	SMI	LI	SMI	LI	SMI	SMI	SMI	SMI	SMI	LI	HI	HI	HI	SMI	SMI	LI	LI	SMI	SMI	SMI	SMI	
	WO1	LI	HI	HI	HI	HI	HI	HI	HI	LI	LI	LI	SMI	SMI	SMI	SMI	SMI	LI	LI	LI	LI	LI	LI	VHI	VHI	HI	LI	HI	HI	HI	VHI	HI	HI	HI	LI	LI	SLI	
DM5	WO2	VHI	SMI	HI	LI	LI	SMI	LI	LI	SMI	HI	HI	LI	HI	HI	HI	HI	VHI	VHI	HI	HI	VHI	HI	SMI	SMI	SMI	LI	HI	SMI	HI	SMI	VHI	VHI	LI	LI	SLI		
	WO3	HI	SLI	HI	VHI	VLI	SLI	HI	VLI	SMI	VHI	HI	LI	VHI	HI	HI	HI	HI	HI	HI	HI	LI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI
	ST1	VHI	HI	HI	HI	VHI	HI	VHI	HI	SMI	VHI	SMI	VHI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SMI	SM										

Table 4.14: Aggregated matrix of strategies

Alternatives	S11				S12				S13				S21				S22				S23				S31				S32				S33			
	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u
SO1	0.79	0.89	1.00	1.00	0.68	0.78	0.99	0.99	0.77	0.88	1.00	0.99	0.76	0.87	1.00	0.99	0.74	0.85	1.00	0.99	0.68	0.78	0.97	0.95	0.65	0.75	0.97	0.94	0.60	0.65	0.99	0.98	0.58	0.63	0.96	0.94
SO2	0.70	0.80	1.00	0.99	0.60	0.65	0.99	0.98	0.42	0.48	0.91	0.85	0.78	0.88	1.00	1.00	0.73	0.84	1.00	0.99	0.74	0.85	1.00	0.99	0.68	0.78	0.99	0.98	0.76	0.87	1.00	0.99	0.68	0.78	0.99	0.98
SO3	0.46	0.51	0.92	0.88	0.66	0.76	0.96	0.92	0.46	0.51	0.92	0.88	0.60	0.65	0.99	0.98	0.52	0.57	0.95	0.94	0.63	0.72	0.96	0.92	0.73	0.84	1.00	0.99	0.60	0.65	0.99	0.98	0.70	0.80	1.00	0.99
WO1	0.46	0.52	0.91	0.84	0.72	0.83	1.00	0.99	0.72	0.83	1.00	0.99	0.63	0.74	0.97	0.95	0.70	0.80	1.00	0.99	0.63	0.74	0.97	0.95	0.63	0.73	0.94	0.89	0.63	0.73	0.94	0.89	0.20	0.30	0.87	0.79
WO2	0.77	0.88	1.00	0.99	0.53	0.58	0.93	0.88	0.70	0.80	0.99	0.99	0.66	0.80	0.91	0.85	0.20	0.30	0.87	0.79	0.53	0.58	0.93	0.88	0.46	0.52	0.91	0.84	0.20	0.30	0.87	0.79	0.60	0.65	0.99	0.98
WO3	0.77	0.88	1.00	0.99	0.24	0.32	0.88	0.80	0.67	0.76	0.99	0.99	0.65	0.73	0.99	0.98	0.53	0.58	0.93	0.88	0.63	0.73	0.94	0.89	0.70	0.80	1.00	0.99	0.71	0.84	0.89	0.79	0.10	0.20	0.79	0.65
ST1	0.65	0.73	0.99	0.98	0.66	0.80	0.92	0.86	0.56	0.67	0.92	0.86	0.60	0.65	0.99	0.98	0.71	0.82	0.99	0.99	0.71	0.82	0.99	0.99	0.55	0.66	0.85	0.72	0.55	0.66	0.85	0.72	0.60	0.65	0.99	0.98
ST2	0.68	0.79	0.97	0.94	0.70	0.80	1.00	0.99	0.58	0.63	0.94	0.88	0.58	0.63	0.94	0.88	0.65	0.75	0.97	0.94	0.71	0.81	0.99	0.99	0.61	0.69	0.97	0.94	0.75	0.86	1.00	0.99	0.66	0.80	0.92	0.86
ST3	0.66	0.78	0.94	0.89	0.53	0.58	0.93	0.88	0.75	0.86	0.99	0.99	0.66	0.80	0.92	0.86	0.70	0.80	1.00	0.99	0.65	0.73	0.99	0.98	0.60	0.65	0.99	0.98	0.67	0.76	0.99	0.99	0.46	0.52	0.91	0.84
WT1	0.65	0.75	0.97	0.94	0.66	0.78	0.94	0.89	0.52	0.57	0.95	0.94	0.41	0.47	0.88	0.80	0.22	0.29	0.84	0.73	0.39	0.44	0.87	0.77	0.55	0.63	0.96	0.94	0.53	0.59	0.94	0.91	0.37	0.43	0.89	0.82
WT2	0.28	0.35	0.89	0.82	0.24	0.32	0.88	0.80	0.24	0.32	0.88	0.80	0.24	0.32	0.88	0.80	0.63	0.73	0.94	0.89	0.28	0.35	0.89	0.82	0.46	0.52	0.91	0.84	0.46	0.52	0.91	0.84	0.60	0.65	0.99	0.98
WT3	0.65	0.73	0.99	0.98	0.20	0.30	0.87	0.79	0.60	0.65	0.99	0.98	0.24	0.32	0.88	0.80	0.53	0.58	0.93	0.88	0.54	0.59	0.96	0.94	0.67	0.76	0.99	0.99	0.46	0.52	0.91	0.84	0.55	0.67	0.91	0.84
Alternatives	W11				W12				W13				W21				W22				W23				W31				W32				W33			
	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u
SO1	0.58	0.63	0.96	0.94	0.20	0.30	0.87	0.79	0.53	0.58	0.91	0.84	0.54	0.59	0.95	0.92	0.59	0.66	0.97	0.96	0.63	0.73	0.92	0.84	0.63	0.73	0.91	0.82	0.53	0.58	0.93	0.88	0.71	0.84	0.92	0.85
SO2	0.66	0.76	0.96	0.92	0.73	0.85	0.96	0.93	0.65	0.75	0.97	0.94	0.24	0.32	0.88	0.80	0.67	0.76	0.99	0.99	0.59	0.73	0.89	0.80	0.43	0.53	0.88	0.81	0.43	0.53	0.88	0.81	0.59	0.73	0.89	0.82
SO3	0.20	0.30	0.87	0.79	0.76	0.87	1.00	0.99	0.53	0.58	0.89	0.78	0.72	0.83	1.00	0.99	0.55	0.67	0.91	0.84	0.20	0.30	0.87	0.79	0.65	0.73	0.99	0.98	0.46	0.52	0.91	0.84	0.65	0.73	0.99	0.98
WO1	0.30	0.36	0.90	0.84	0.30	0.36	0.90	0.84	0.60	0.65	0.99	0.98	0.60	0.65	0.99	0.98	0.60	0.65	0.99	0.98	0.60	0.65	0.99	0.98	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79
WO2	0.76	0.87	1.00	0.99	0.70	0.80	1.00	0.99	0.20	0.30	0.87	0.79	0.76	0.87	1.00	0.99	0.76	0.87	1.00	0.99	0.70	0.80	1.00	0.99	0.70	0.80	1.00	0.99	0.76	0.86	1.00	0.99	0.76	0.86	1.00	0.99
WO3	0.20	0.30	0.87	0.79	0.76	0.87	1.00	0.99	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.60	0.65	0.99	0.98	0.76	0.87	1.00	0.99	0.76	0.87	1.00	0.99	0.76	0.86	1.00	0.99
ST1	0.76	0.87	1.00	0.99	0.60	0.65	0.99	0.98	0.76	0.87	1.00	0.99	0.30	0.36	0.90	0.84	0.70	0.80	1.00	0.99	0.60	0.65	0.99	0.98	0.60	0.65	0.99	0.98	0.70	0.80	1.00	0.99	0.76	0.86	1.00	0.99
ST2	0.63	0.74	0.97	0.95	0.70	0.80	0.99	0.99	0.60	0.65	0.99	0.98	0.30	0.36	0.90	0.84	0.42	0.48	0.91	0.85	0.60	0.65	0.99	0.98	0.56	0.61	0.95	0.92	0.56	0.61	0.95	0.92	0.22	0.28	0.81	0.68
ST3	0.46	0.52	0.91	0.84	0.47	0.52	0.92	0.86	0.30	0.36	0.90	0.84	0.30	0.36	0.90	0.84	0.76	0.86	1.00	0.99	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.30	0.36	0.90	0.84
WT1	0.68	0.78	0.98	0.97	0.68	0.78	0.97	0.95	0.25	0.33	0.88	0.81	0.60	0.65	0.99	0.98	0.40	0.46	0.89	0.82	0.40	0.46	0.89	0.82	0.68	0.78	0.99	0.98	0.59	0.73	0.89	0.82	0.50	0.60	0.91	0.85
WT2	0.17	0.27	0.83	0.72	0.53	0.58	0.89	0.78	0.20	0.30	0.87	0.79	0.24	0.32	0.88	0.80	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.56	0.67	0.92	0.86	0.28	0.35	0.89	0.82	0.60	0.65	0.99	0.98
WT3	0.53	0.58	0.93	0.88	0.20	0.30	0.87	0.79	0.60	0.65	0.99	0.98	0.10	0.20	0.79	0.65	0.10	0.20	0.79	0.65	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.60	0.65	0.99	0.98

Alternatives	O11				O12				O13				O21				O22				O23				O31				O32				O33			
	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u
SO1	0.49	0.60	0.90	0.84	0.73	0.84	1.00	0.99	0.76	0.86	1.00	0.99	0.48	0.60	0.89	0.82	0.39	0.44	0.82	0.69	0.40	0.46	0.89	0.82	0.39	0.44	0.82	0.69	0.70	0.80	1.00	0.99	0.58	0.73	0.82	0.69
SO2	0.63	0.76	0.92	0.86	0.50	0.60	0.91	0.85	0.26	0.34	0.88	0.81	0.26	0.34	0.88	0.81	0.40	0.46	0.89	0.82	0.60	0.65	0.99	0.98	0.42	0.48	0.91	0.85	0.42	0.48	0.91	0.85	0.50	0.60	0.91	0.85
SO3	0.66	0.80	0.91	0.85	0.65	0.73	0.99	0.98	0.65	0.73	0.99	0.98	0.65	0.73	0.99	0.98	0.70	0.80	1.00	0.99	0.65	0.73	0.99	0.98	0.66	0.80	0.92	0.86	0.76	0.87	1.00	0.99	0.70	0.80	1.00	0.99
WO1	0.56	0.67	0.92	0.86	0.46	0.52	0.91	0.84	0.46	0.52	0.91	0.84	0.78	0.89	1.00	0.99	0.78	0.89	0.98	0.95	0.68	0.78	0.97	0.95	0.36	0.42	0.88	0.81	0.68	0.78	0.97	0.95	0.68	0.78	0.98	0.97
WO2	0.70	0.80	1.00	0.99	0.67	0.76	0.99	0.99	0.66	0.80	0.91	0.85	0.78	0.89	0.99	0.98	0.68	0.78	0.97	0.95	0.58	0.63	0.96	0.94	0.60	0.65	0.99	0.98	0.68	0.78	0.97	0.95	0.68	0.78	0.97	0.95
WO3	0.20	0.30	0.87	0.79	0.60	0.65	0.99	0.98	0.20	0.30	0.87	0.79	0.60	0.65	0.99	0.98	0.60	0.65	0.99	0.98	0.20	0.30	0.87	0.79	0.70	0.80	1.00	0.99	0.80	0.90	1.00	1.00	0.20	0.30	0.87	0.79
ST1	0.70	0.80	1.00	0.99	0.76	0.87	1.00	0.99	0.76	0.87	1.00	0.99	0.70	0.80	1.00	0.99	0.70	0.80	1.00	0.99	0.70	0.80	1.00	0.99	0.60	0.65	0.99	0.98	0.70	0.80	1.00	0.99	0.60	0.65	0.99	0.98
ST2	0.22	0.28	0.81	0.68	0.68	0.79	0.97	0.94	0.68	0.79	0.97	0.94	0.65	0.75	0.97	0.94	0.46	0.52	0.91	0.84	0.53	0.58	0.93	0.88	0.20	0.30	0.87	0.79	0.71	0.82	0.99	0.99	0.53	0.58	0.93	0.88
ST3	0.20	0.30	0.87	0.79	0.53	0.58	0.93	0.88	0.63	0.74	0.97	0.95	0.67	0.76	0.99	0.99	0.63	0.73	0.94	0.89	0.70	0.80	0.99	0.99	0.74	0.86	0.97	0.95	0.74	0.85	0.99	0.99	0.67	0.76	0.99	0.99
WT1	0.48	0.60	0.89	0.82	0.60	0.65	0.99	0.98	0.60	0.65	0.99	0.98	0.46	0.51	0.84	0.72	0.55	0.66	0.85	0.72	0.46	0.52	0.91	0.84	0.28	0.35	0.89	0.82	0.66	0.80	0.91	0.85	0.65	0.73	0.99	0.98
WT2	0.30	0.36	0.90	0.84	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.47	0.52	0.92	0.86	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.47	0.52	0.92	0.86	0.53	0.58	0.93	0.88	0.28	0.35	0.89	0.82
WT3	0.76	0.86	1.00	0.99	0.70	0.80	1.00	0.99	0.20	0.30	0.87	0.79	0.30	0.36	0.90	0.84	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.60	0.65	0.99	0.98	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79
Alternatives	T11				T12				T13				T21				T22				T23				T31				T32				T33			
	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u
SO1	0.30	0.36	0.90	0.84	0.20	0.30	0.87	0.79	0.10	0.20	0.79	0.65	0.10	0.20	0.79	0.65	0.10	0.20	0.79	0.65	0.10	0.20	0.79	0.65	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.29	0.35	0.89	0.83
SO2	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.59	0.70	0.94	0.89	0.40	0.46	0.89	0.82	0.66	0.74	0.99	0.98	0.55	0.60	0.94	0.90	0.40	0.46	0.89	0.82	0.40	0.46	0.89	0.82	0.58	0.63	0.96	0.94
SO3	0.70	0.80	1.00	0.99	0.66	0.74	0.99	0.98	0.60	0.65	0.99	0.98	0.60	0.65	0.99	0.98	0.54	0.62	0.93	0.87	0.58	0.68	0.93	0.87	0.60	0.65	0.99	0.98	0.65	0.73	0.99	0.98	0.70	0.80	1.00	0.99
WO1	0.20	0.30	0.87	0.79	0.64	0.73	0.97	0.94	0.69	0.83	0.93	0.88	0.58	0.70	0.92	0.86	0.58	0.69	0.88	0.77	0.58	0.69	0.88	0.77	0.24	0.32	0.88	0.80	0.20	0.30	0.87	0.79	0.29	0.35	0.89	0.83
WO2	0.58	0.63	0.97	0.96	0.72	0.83	1.00	0.99	0.30	0.36	0.90	0.84	0.63	0.72	0.97	0.94	0.78	0.89	0.98	0.95	0.77	0.88	1.00	0.99	0.22	0.29	0.84	0.73	0.20	0.30	0.87	0.79	0.28	0.34	0.85	0.75
WO3	0.20	0.30	0.87	0.79	0.52	0.57	0.95	0.94	0.62	0.72	0.95	0.91	0.49	0.54	0.92	0.86	0.50	0.55	0.93	0.90	0.67	0.76	0.99	0.99	0.23	0.30	0.85	0.75	0.46	0.52	0.91	0.84	0.24	0.32	0.88	0.80
ST1	0.70	0.80	1.00	0.99	0.61	0.72	0.96	0.94	0.51	0.56	0.95	0.93	0.70	0.80	1.00	0.99	0.70	0.80	1.00	0.99	0.70	0.80	1.00	0.99	0.70	0.80	1.00	0.99	0.70	0.80	1.00	0.99	0.76	0.86	1.00	0.99
ST2	0.55	0.67	0.91	0.84	0.55	0.63	0.96	0.94	0.70	0.80	0.99	0.99	0.68	0.78	0.97	0.95	0.70	0.80	1.00	0.99	0.63	0.72	0.97	0.94	0.46	0.52	0.91	0.84	0.63	0.72	0.97	0.94	0.63	0.72	0.97	0.94
ST3	0.70	0.80	1.00	0.99	0.61	0.69	0.97	0.94	0.63	0.73	0.94	0.89	0.68	0.78	0.99	0.98	0.59	0.73	0.89	0.82	0.71	0.83	0.97	0.95	0.28	0.35	0.89	0.82	0.63	0.74	0.97	0.95	0.63	0.74	0.97	0.95
WT1	0.55	0.67	0.91	0.84	0.52	0.62	0.91	0.84	0.70	0.80	0.99	0.99	0.46	0.52	0.91	0.84	0.70	0.80	1.00	0.99	0.65	0.73	0.99	0.98	0.66	0.78	0.94	0.89	0.49	0.54	0.92	0.86	0.49	0.54	0.87	0.77
WT2	0.53	0.58	0.93	0.88	0.24	0.32	0.88	0.80	0.54	0.59	0.96	0.94	0.53	0.58	0.93	0.88	0.20	0.30	0.87	0.79	0.60	0.65	0.99	0.98	0.66	0.80	0.91	0.85	0.63	0.72	0.97	0.94	0.63	0.72	0.95	0.89
WT3	0.30	0.36	0.90	0.84	0.76	0.87	1.00	0.99	0.30	0.36	0.90	0.84	0.20	0.30	0.87	0.79	0.20	0.30	0.87	0.79	0.67	0.76	0.99	0.99	0.24	0.32	0.88	0.80	0.53	0.58	0.93	0.88	0.49	0.54	0.92	0.86

Table 4.15: Computed IVFFPIS ($\tilde{f}_j^*$) and IVFFNIS ($\tilde{f}_j^-$) values

Sub-factors	$\tilde{f}_j^*$ values				$\tilde{f}_j^-$ values			
	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u
S11	0.790	0.892	0.888	0.823	0.279	0.346	0.999	0.996
S12	0.721	0.826	0.869	0.787	0.200	0.300	0.998	0.992
S13	0.771	0.877	0.876	0.800	0.237	0.320	0.999	0.995
S21	0.778	0.883	0.876	0.799	0.237	0.320	0.999	0.995
S22	0.739	0.846	0.840	0.729	0.200	0.295	0.998	0.993
S23	0.739	0.846	0.866	0.767	0.279	0.346	0.998	0.993
S31	0.732	0.838	0.846	0.721	0.463	0.519	0.998	0.992
S32	0.763	0.870	0.846	0.721	0.200	0.300	0.999	0.994
S33	0.700	0.800	0.787	0.647	0.100	0.200	0.997	0.991
W11	0.175	0.271	0.999	0.994	0.763	0.870	0.834	0.720
W12	0.200	0.300	0.999	0.994	0.763	0.870	0.869	0.784
W13	0.200	0.300	0.999	0.994	0.763	0.870	0.869	0.784
W21	0.100	0.200	0.999	0.994	0.763	0.870	0.787	0.647
W22	0.100	0.200	0.999	0.994	0.763	0.870	0.787	0.647
W23	0.200	0.300	0.997	0.991	0.700	0.800	0.869	0.787
W31	0.200	0.300	0.999	0.994	0.763	0.870	0.869	0.787
W32	0.200	0.300	0.999	0.994	0.763	0.870	0.869	0.787
W33	0.200	0.279	0.998	0.994	0.758	0.864	0.812	0.682
O11	0.758	0.864	0.812	0.682	0.200	0.279	0.998	0.994
O12	0.763	0.870	0.869	0.787	0.200	0.300	0.999	0.994
O13	0.763	0.870	0.869	0.787	0.200	0.300	0.999	0.994
O21	0.785	0.888	0.844	0.719	0.265	0.337	0.998	0.994
O22	0.779	0.886	0.820	0.688	0.200	0.300	0.997	0.991
O23	0.700	0.800	0.869	0.787	0.200	0.300	0.997	0.991
O31	0.736	0.856	0.820	0.688	0.200	0.300	0.997	0.991
O32	0.800	0.900	0.869	0.787	0.200	0.300	1.000	0.997
O33	0.700	0.800	0.822	0.689	0.200	0.300	0.997	0.991
T11	0.200	0.300	0.997	0.991	0.700	0.800	0.869	0.787
T12	0.200	0.300	0.999	0.994	0.763	0.870	0.869	0.787
T13	0.100	0.200	0.993	0.987	0.695	0.825	0.787	0.647
T21	0.100	0.200	0.997	0.991	0.700	0.800	0.787	0.647
T22	0.100	0.200	0.997	0.991	0.779	0.886	0.787	0.647
T23	0.100	0.200	0.999	0.995	0.771	0.877	0.787	0.647
T31	0.200	0.295	0.997	0.991	0.700	0.800	0.840	0.729
T32	0.200	0.300	0.997	0.991	0.700	0.800	0.869	0.787
T33	0.237	0.320	0.998	0.994	0.758	0.864	0.854	0.751

Step 17. $Q(A_i)$ values are computed by Equation (4.1.2.7)-(4.1.2.9) and presented in Table 4.16.

Step 18. The rank order of the $S(A_i)$, $R(A_i)$ and $Q(A_i)$ values are given in Table 4.16 to evaluate the importance of alternatives.

After ranking the alternatives, the two conditions that explained in VIKOR steps should be checked. According the first condition, $0.1427 - 0.0206 \geq 0.0909$. Hence, the first condition of the method is satisfied. Then, the second condition is checked. Table 4.16 shows that the best strategy is ST2 based on $Q(A_i)$ values and it is also the best strategy based on the $R(A_i)$ values. Based on the results, ST2 alternative has acceptable stability. This compromise solution is stable within a decision-making process by consensus (for $v = 0.5$). Hence, the ranked order of the strategies are as follows based on the $Q(A_i)$ values:

ST2 > WO1 > ST3 > SO1 > WT1 > SO2 > SO3 > WO3 > ST1 > WO2 > WT3 > WT2

Table 4.16: Computed (A_i) , $R(A_i)$ and $Q(A_i)$ values and the ranked order of the strategies

Strategies	$S(A_i)$	Order	$R(A_i)$	Order	$Q(A_i)$	Order
SO1	0.5488	5	0.0383	4	0.2796	4
SO2	0.6356	7	0.0432	5	0.5311	6
SO3	0.6189	6	0.0542	8	0.6550	7
WO1	0.5222	2	0.0327	1	0.1427	2
WO2	0.6931	12	0.0577	9	0.8608	10
WO3	0.6889	11	0.0523	6	0.7749	8
ST1	0.6533	8	0.0577	9	0.7777	9
ST2	0.4540	1	0.0341	2	0.0206	1
ST3	0.5445	4	0.0348	3	0.2194	3
WT1	0.5238	3	0.0527	7	0.4349	5
WT2	0.6882	10	0.0673	11	0.9899	12
WT3	0.6853	9	0.0673	11	0.9838	11

The strategy evaluation process indicates the RUL strategies that should be focused on for Istanbul. The most important strategy is determined as “ST2- Establish an integrated

control center for real-time visibility, facilitating faster decision-making and enhancing the agility of urban logistics processes through the integration of current technologies.”. The use of technology in urban logistics operations will help to reduce delivery times, manage traffic in real-time, and prepare for unexpected events. Following this strategy, the second most important one is “WO1- Improve the risk/disaster capacity and social awareness for RUL.” By strategically focusing on improving risk and disaster capacity within resilient urban logistics, we not only mitigate potential disruptions but also contribute to the overall safety and well-being of communities. This approach ensures that urban logistics systems are better equipped to handle unforeseen challenges, fostering a more resilient and adaptive framework that aligns with the dynamic needs of our evolving urban environments. The third most important strategy is determined as “ST3- Reduce migration to the Istanbul region, minimize urban freight logistics by creating logistics attraction centers around Istanbul.” This strategy will be important to develop policies that support citizens who want to leave Istanbul and create environmentally conscious logistics centers with a supply chain clustering approach to reduce the burden of urban logistics activities in Istanbul.

4.3. Comparative Analysis

Different MCDM methods may yield different yet similar results. Here, to evaluate the robustness of the results, IVFF-VIKOR is compared to IVFF-TOPSIS and IVFF-MARCOS in ranking the strategies. TOPSIS is a widely used method for evaluating and ranking alternatives in MCDM analysis and is well-known in the literature. On the other hand, MARCOS is a newer addition to the field but has gained significant popularity in various industries and applications, highlighting its versatility among MCDM techniques. All three methods are based on distance-based analysis, but with distinct focuses (Havle et al., 2021). VIKOR aims to maximize group benefit and minimize individual regret by focusing on compromise solutions, while TOPSIS adopts an approach that aims to select alternatives among those closest to the PIS and furthest from the NIS. MARCOS, on the other hand, is based on utility theory and incorporates the subjective preferences of decision makers to determine overall utility. These three methods contribute to decision-making processes with different optimization objectives and evaluation criteria. Hence,

different results may be obtained when other MCDM methods are used to solve the same decision problem.

Figure 4.4 shows that the ranking given by IVFF-MARCOS and IVFF-TOPSIS differs from that of the proposed method. According to IVFF-MARCOS and IVFF-TOPSIS, WO1 is the best alternative, followed by ST2. However, in IVFF-VIKOR, ST2 is the best alternative, followed by WO1. The examination of IVFF-MARCOS and IVFF-TOPSIS results reveals a striking similarity in the values assigned to these two strategies. At this juncture, it is crucial to underscore the significance of both strategies, emphasizing their importance in the context of the assessment.

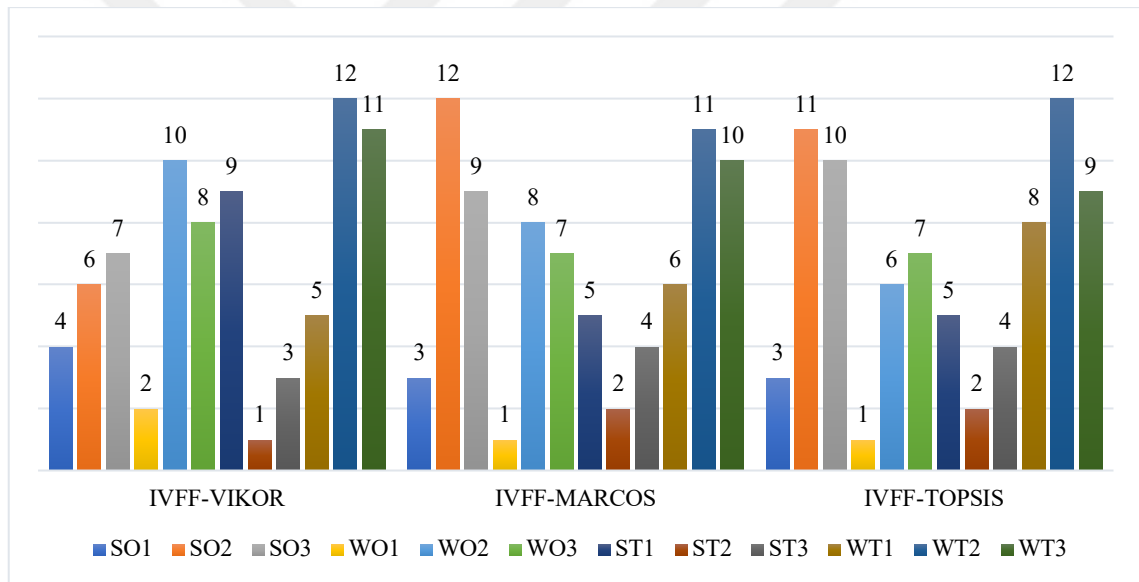


Figure 4.4: Comparison with different IVFF-MCDM techniques

A sensitivity analysis is presented in the next section, to demonstrate the validity and viability of the proposed methodology.

4.4. Sensitivity Analysis

Sensitivity analysis plays an important role in checking the robustness and accuracy of decision results and applicability. Integrating sensitivity analysis with MCDM results enables the assessment of the responsiveness of the obtained outcomes when criteria importance undergoes changes.

In this section, sensitivity for both the SWOT sub-factors weights and the ranking of the strategies by varying the values of β in the IVFFDWA operator is observed. Firstly, sensitivity analysis results for SWOT sub-factors are given in Table 4.17 and Table 4.18. Second, sensitivity analysis for the ranking of strategies is carried out and presented in Table 4.19 under varying β values and with different criteria weights.

Table 4.17: Weights of the SWOT sub-factors with varying β

Sub-factors	Weights									
	$\beta = 1$	$\beta = 2$	$\beta = 3$	$\beta = 4$	$\beta = 5$	$\beta = 6$	$\beta = 7$	$\beta = 8$	$\beta = 9$	$\beta = 10$
S11	0.0353	0.0362	0.0368	0.0372	0.0375	0.0377	0.0379	0.0380	0.0380	0.0381
S12	0.0228	0.0222	0.0218	0.0216	0.0214	0.0214	0.0213	0.0213	0.0212	0.0212
S13	0.0230	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231
S21	0.0539	0.0561	0.0573	0.0580	0.0585	0.0587	0.0589	0.0590	0.0591	0.0592
S22	0.0377	0.0394	0.0403	0.0408	0.0412	0.0414	0.0415	0.0417	0.0417	0.0418
S23	0.0296	0.0314	0.0327	0.0335	0.0340	0.0343	0.0345	0.0347	0.0349	0.0350
S31	0.0440	0.0430	0.0430	0.0432	0.0435	0.0436	0.0438	0.0439	0.0440	0.0441
S32	0.0310	0.0300	0.0299	0.0300	0.0302	0.0304	0.0306	0.0307	0.0308	0.0309
S33	0.0391	0.0381	0.0380	0.0383	0.0385	0.0387	0.0389	0.0390	0.0391	0.0392
W11	0.0550	0.0526	0.0509	0.0498	0.0491	0.0486	0.0483	0.0480	0.0478	0.0476
W12	0.0415	0.0400	0.0391	0.0387	0.0384	0.0382	0.0381	0.0380	0.0380	0.0379
W13	0.0386	0.0370	0.0360	0.0353	0.0348	0.0345	0.0342	0.0340	0.0339	0.0337
W21	0.0335	0.0319	0.0307	0.0299	0.0295	0.0291	0.0289	0.0287	0.0286	0.0285
W22	0.0250	0.0244	0.0238	0.0235	0.0233	0.0231	0.0230	0.0229	0.0229	0.0228
W23	0.0218	0.0218	0.0213	0.0210	0.0207	0.0205	0.0204	0.0203	0.0202	0.0201
W31	0.0309	0.0315	0.0315	0.0314	0.0313	0.0312	0.0312	0.0311	0.0311	0.0310
W32	0.0434	0.0382	0.0357	0.0344	0.0337	0.0332	0.0328	0.0325	0.0323	0.0322
W33	0.0321	0.0301	0.0290	0.0283	0.0279	0.0276	0.0274	0.0272	0.0271	0.0269
O11	0.0298	0.0301	0.0304	0.0306	0.0307	0.0308	0.0309	0.0310	0.0311	0.0311
O12	0.0206	0.0209	0.0209	0.0210	0.0210	0.0210	0.0211	0.0211	0.0211	0.0211
O13	0.0302	0.0315	0.0325	0.0332	0.0336	0.0338	0.0341	0.0342	0.0343	0.0345
O21	0.0216	0.0209	0.0207	0.0205	0.0203	0.0202	0.0201	0.0200	0.0199	0.0199
O22	0.0325	0.0335	0.0342	0.0347	0.0350	0.0351	0.0353	0.0353	0.0354	0.0354
O23	0.0256	0.0240	0.0233	0.0228	0.0226	0.0224	0.0222	0.0221	0.0221	0.0220
O31	0.0333	0.0343	0.0353	0.0359	0.0362	0.0365	0.0366	0.0367	0.0368	0.0368
O32	0.0351	0.0387	0.0405	0.0415	0.0421	0.0425	0.0428	0.0430	0.0431	0.0432
O33	0.0252	0.0251	0.0253	0.0255	0.0256	0.0258	0.0259	0.0259	0.0260	0.0260
T11	0.0202	0.0210	0.0212	0.0213	0.0214	0.0215	0.0215	0.0216	0.0217	0.0217
T12	0.0113	0.0116	0.0116	0.0116	0.0115	0.0115	0.0115	0.0114	0.0114	0.0114
T13	0.0108	0.0111	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112
T21	0.0165	0.0185	0.0193	0.0196	0.0197	0.0198	0.0198	0.0198	0.0198	0.0198
T22	0.0101	0.0104	0.0104	0.0103	0.0103	0.0102	0.0102	0.0102	0.0102	0.0102
T23	0.0112	0.0113	0.0111	0.0109	0.0108	0.0107	0.0106	0.0105	0.0105	0.0104
T31	0.0110	0.0124	0.0130	0.0133	0.0134	0.0135	0.0135	0.0135	0.0136	0.0136
T32	0.0088	0.0095	0.0097	0.0097	0.0098	0.0098	0.0098	0.0098	0.0098	0.0097
T33	0.0081	0.0085	0.0085	0.0084	0.0084	0.0084	0.0084	0.0083	0.0083	0.0083

Table 4.18: Order of the SWOT sub-factors with varying β [illegible]

According to Table 4.17 and Table 4.18, the ranking order of the SWOT sub-factors differs under different values of the β parameter. When $\beta = 1$, the first three most important sub-factors are $W11 > S21 > S31$, while for $1 < \beta < 10$, the order of the three most important sub-factors appears to be $S21 > W11 > S31$. When $\beta = 1$, the weights of $W11$ and $S21$ are very close to each other, therefore, the ranking of the two most important sub-factors changed with different β values. However, across all β values, the sub-factor with the lowest evaluation remains consistent with $T33$.

Table 4.19: Order of the strategies with varying β and criteria weights

Strategies	Order of strategies									
	$\beta = 1$	$\beta = 2$	$\beta = 3$	$\beta = 4$	$\beta = 5$	$\beta = 6$	$\beta = 7$	$\beta = 8$	$\beta = 9$	$\beta = 10$
SO1	4	5	5	5	5	5	5	5	5	5
SO2	6	6	7	9	10	12	12	12	12	12
SO3	7	7	9	8	8	8	9	9	9	9
WO1	2	2	2	2	2	2	2	2	2	1
WO2	10	8	6	6	6	6	6	6	6	6
WO3	8	10	10	10	9	10	10	10	10	10
ST1	9	9	8	7	7	7	7	7	7	7
ST2	1	1	1	1	1	1	1	1	1	2
ST3	3	3	4	4	4	4	4	4	4	4
WT1	5	4	3	3	3	3	3	3	3	3
WT2	12	12	11	11	11	9	8	8	8	8
WT3	11	11	12	12	12	11	11	11	11	11

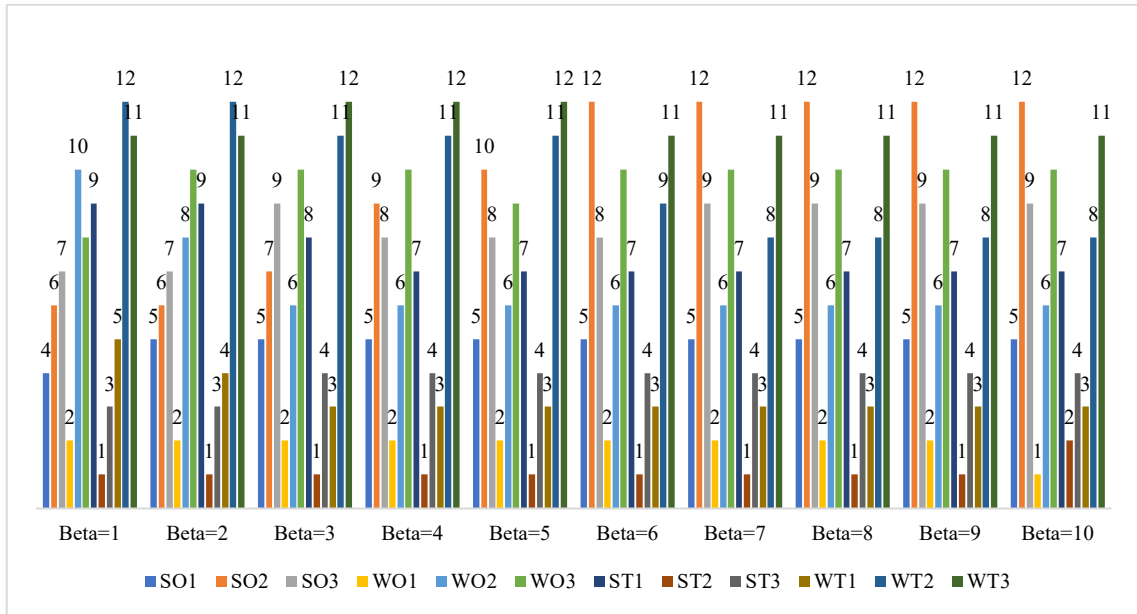


Figure 4.5: The results of sensitivity analysis for strategies

According to Table 4.19 and Figure 4.5, it has been observed that the ST2 strategy always stands out as the most important strategy despite the changing β values. It was seen that the ranking of the first two strategies changed only when the $\beta = 10$, but when the results were examined, it was seen that the weights of these two strategies were close when $\beta = 10$. Considering the significant changes in the decision-making process, it seems that sensitivity analysis yields reliable and consistent outcomes. The proposed methodology appears to be a stable and dependable decision-making tool, as evidenced by the fact that even extreme modifications do not result in significant changes in the overall results. This suggests that the methodology offers a practical and reliable decision-making environment for decision makers and practitioners.

4.5. Concluding Remarks on RUL Strategy Determination

Developing resilience capabilities is crucial for cities to maintain strong logistics activities and withstand unexpected events. Recent occurrences such as the COVID-19 outbreak and natural disasters like earthquakes have demonstrated the significance of RUL networks. It is essential for cities to prioritize building resilience to ensure the smooth functioning of their logistics operations. To enhance the efficiency and effectiveness of RUL, it is crucial to analyze the current situation and select appropriate strategies. This will not only support RUL but also promote sustainability and improve

the livability of cities. The proposed methodology offers implementers the necessary tools to determine the essential factors that require prioritization when choosing the RUL strategies for Istanbul.

The study proposes a strong methodology for researchers and managers to prioritize the factors and strategies identified through SWOT analysis. The approach combines the benefits of AHP and VIKOR, resulting in efficient handling of complex decision-making problems and logical outcomes. To address the uncertainties in decision-making, the methodology is integrated into the IVFF environment, and the IVFFDWA operator is employed to take a more flexible approach in obtaining group decisions. This integrated approach is capable of delivering consistent and reliable results, making it a valuable tool for practitioners.

5. RUL CRITICAL SUCCESS FACTORS DETERMINATION

Cities need to be proactive and prepared to handle unexpected events that may arise in terms of their economic development, sustainability, and livability. The concept of RUL plays a crucial role in this regard. By implementing strategies that promote efficient and adaptable logistics systems, cities can better withstand disruptions caused by natural disasters, economic downturns, and other unforeseeable events. This not only helps to ensure the continued functioning of critical supply chains but also contributes to the overall resilience and well-being of urban areas. It is important for city planners and policymakers to prioritize RUL initiatives as a means of building strong, sustainable, and livable cities for generations to come. However, when the existing literature was examined, it is noteworthy that there are very few studies on RUL evaluation (Büyükoçkan et al., 2022). To fill this gap, this section evaluates the factors for the successful implementation of RUL for Istanbul by addressing the following RQs:

RQ1: What are the critical factors for the successful implementation of RUL in Istanbul?

RQ2: Which factors exhibit a higher level of driving power, indicating their strong influence on other critical success factors for RUL?

RQ3: How are these factors interrelated?

RQ4: How does the ISM contribute to a more nuanced understanding of critical success factors for RUL?

To answer these RQs, this section aims to identify the critical success factors for the successful implementation of RUL for Istanbul by conducting literature reviews and gathering expert opinions.

5.1. Proposed IVFF-ISM Methodology

In this section, to establish contextual interrelationships among the critical success factors IVFF-ISM methodology is proposed. Furthermore, a MICMAC analysis is used to classify the factors based on their driving and dependence powers. The basic procedure of the developed methodology is given in Figure 5.1.



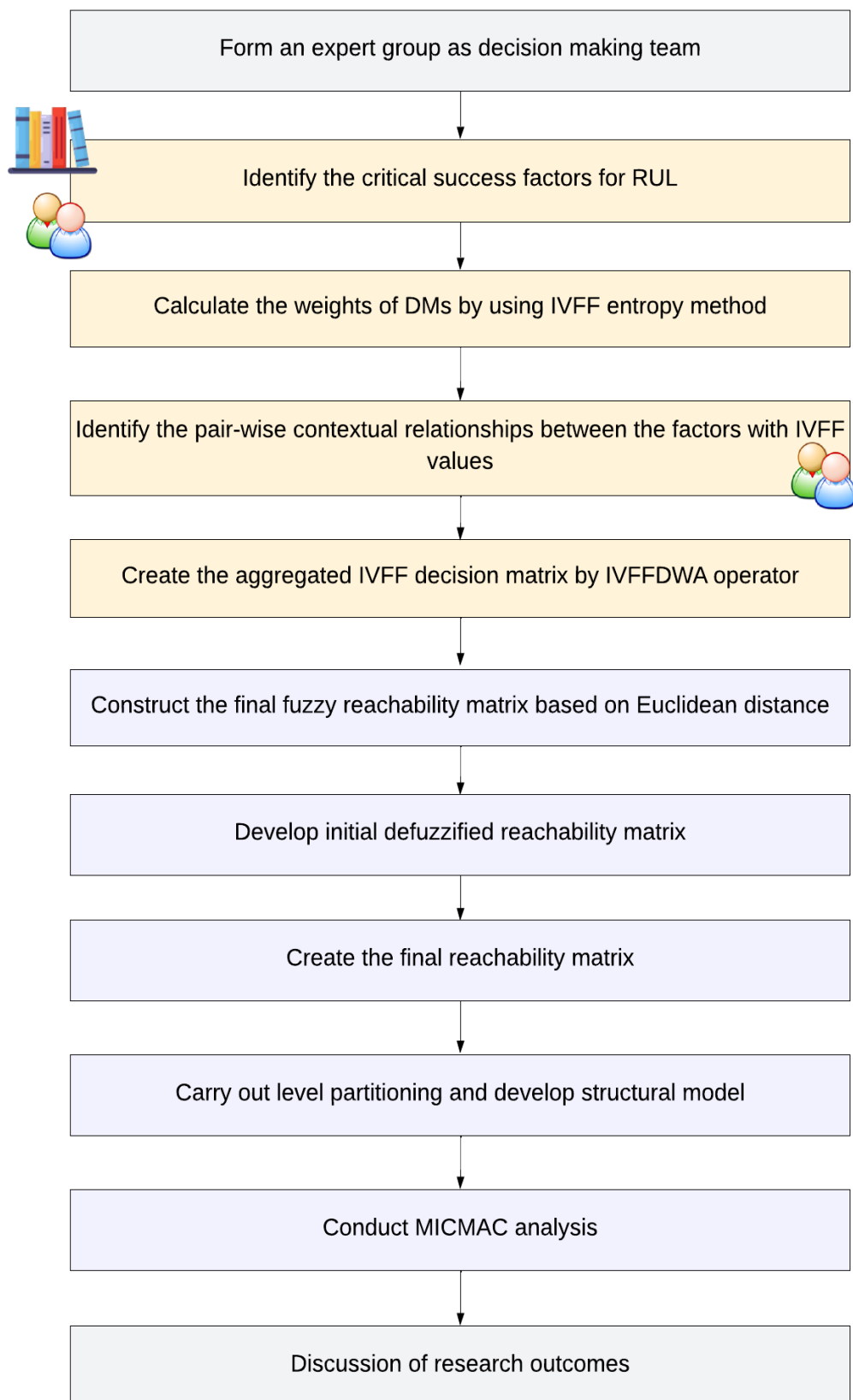


Figure 5.1: The flowchart of the IVFF-ISM methodology

5.1.1. Computational Steps of IVFF-ISM Methodology

Step 1. An expert group comprising of DMs has been established for the decision-making process. Selection of DMs was based on their experience, knowledge, and willingness to help.

Step 2. By benefiting from literature research and expert opinions, determine the evaluation criteria for RUL success.

Step 3. Calculate the weights of DMs. Let $E_k = (E_1, E_2, \dots, E_k)$, $k = 1, 2, \dots, K$ is a set of DMs and weights w_k for each E_k ; $\sum_{k=1}^K w_k = 1$. Here, the entropy method (F. Zhang & Xu, 2016) is applied to the IVFF environment. The importance degree of DMs is determined using the linguistic terms given in Table 5.1. The weights of the DMs are calculated using Equation (5.1.1) based on the linguistic terms.

$$w_k = \frac{\sqrt{\frac{1}{2}[(1-\pi_{\bar{F}}^{l(k)})^2 + (1-\pi_{\bar{F}}^{u(k)})^2]}}{\sum_{k=1}^K \sqrt{\frac{1}{2}[(1-\pi_{\bar{F}}^{l(k)})^2 + (1-\pi_{\bar{F}}^{u(k)})^2]}} \quad (5.1.1)$$

Table 5.1: Linguistic scale for the weights of DMs (Seikh & Mandal, 2023)

Linguistic variables	IVFFNs
Extremely significant (ES)	([0.75, 0.85], [0.05, 0.15])
Very significant (VS)	([0.65, 0.75], [0.15, 0.25])
Significant (S)	([0.55, 0.65], [0.25, 0.35])
Moderate (M)	([0.45, 0.55], [0.35, 0.45])
Insignificant (IS)	([0.25, 0.35], [0.55, 0.65])
Very insignificant (VIS)	([0.15, 0.25], [0.65, 0.75])
Extremely insignificant (EIS)	([0.05, 0.15], [0.7, 0.85])

Step 4. Identify the pair-wise contextual relationships between the factors. A factor can influence or be affected by other factors. The nature of this impact may be uncertain. Five linguistic terms (Very High, High, Low, Very Low, and No Influence) are used to deal

with uncertainties when determining the extent of the relationship between two factors (Shaw et al., 2022).

In ISM, a structural self-interaction matrix (SSIM) is created based on pair-wise comparisons of the factors using the symbols of V, A, X and O to indicate the strength of contextual relationship. Explanations of the symbols are as follows:

V: factor i influences factor j , A: factor j influences factor i , X: factor i and j influence each other, and O: factor i and j do not influence each other.

All linguistic terms with IVFFS numbers are given in Table 5.1. First, the SSIM is created with the linguistic terms specified in Table 5.2. It is then transformed into a fuzzy accessibility matrix by replacing linguistic terms with their corresponding IVFFNs as shown in Table 5.3. For a study with n factors including K experts, K IVFF reachability matrices each with $n \times n$ dimensions, are obtained. Here, the evaluation of the i^{th} alternative on the j^{th} criterion made by the k^{th} DM is symbolized as $\tilde{E}_{ijk} = (\alpha_{E_{ijk}}, \beta_{E_{ijk}})$.

Table 5.2: Linguistic terms and IVFFNs (Ilieva & Yankova, 2022)

Linguistic variable	Influence score	IVFFNs
Very High (VH)	4	$([0.8, 0.95], [0, 0.15])$
High (H)	3	$([0.6, 0.7], [0.2, 0.3])$
Low (L)	2	$([0.45, 0.55], [0.4, 0.55])$
Very Low (VL)	1	$([0.3, 0.4], [0.6, 0.7])$
No Influence (NO)	0	$([0, 0.2], [0.8, 0.95])$

Step 5. Create the aggregated IVFF decision matrix. Pairwise comparison matrices of each DM are combined to obtain a group decision matrix. To execute this, the IVFFDWA operator is utilized which is explained in Equation (3.1.27).

Step 6. The distance of each aggregated IVFFN from all five IVFFNs corresponding to linguistic terms (Very high, High, Low, Very Low and No) is calculated using Euclidean distance of IVFFNs. As the value of Euclidean distance between two IVFFNs approaches zero, they will be closer to each other. The aggregated IVFFN is then replaced by the

linguistic term with the shortest distance, thus obtaining the aggregate linguistic reachability matrix. The Euclidean distance between IVFFNs is given in Equation (3.1.25).

Step 7. The de-fuzzified reachability matrix is generated from the concatenated linguistic reachability matrix by replacing linguistic terms with binary digits (1 and 0). The symbols of VH and H can be replaced with 1 and others with 0 to get a de-fuzzified reachability matrix.

Table 5.3: IVFFNs for different symbols in SSIM

Symbols in SSIM	IVFFNs for (i,j)				IVFFNs for (j,i)			
	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u
V(VH)	0.8	0.95	0	0.15	0	0.2	0.8	0.95
V(H)	0.6	0.7	0.2	0.3	0	0.2	0.8	0.95
V(L)	0.45	0.55	0.4	0.55	0	0.2	0.8	0.95
V(VL)	0.3	0.4	0.6	0.7	0	0.2	0.8	0.95
A(VH)	0	0.2	0.8	0.95	0.8	0.95	0	0.15
A(H)	0	0.2	0.8	0.95	0.6	0.7	0.2	0.3
A(L)	0	0.2	0.8	0.95	0.45	0.55	0.4	0.55
A(VL)	0	0.2	0.8	0.95	0.3	0.4	0.6	0.7
X(VH)	0.8	0.95	0	0.15	0.8	0.95	0	0.15
X(H)	0.6	0.7	0.2	0.3	0.6	0.7	0.2	0.3
X(L)	0.45	0.55	0.4	0.55	0.45	0.55	0.4	0.55
X(VL)	0.3	0.4	0.6	0.7	0.3	0.4	0.6	0.7
X(VH,H)	0.8	0.95	0	0.15	0.6	0.7	0.2	0.3
X(VH,L)	0.8	0.95	0	0.15	0.45	0.55	0.4	0.55
X(VH,VL)	0.8	0.95	0	0.15	0.3	0.4	0.6	0.7
O(NO)	0	0.2	0.8	0.95	0	0.2	0.8	0.95

Step 8. Create the final reachability matrix. Here, to transform the reachability matrix obtained in Step 7 into the final reachability matrix, the transitivity rule is applied. The concept of transitivity here is the basic assumption used to describe conceptual

relationships in ISM. e.g; If the A criterion is related to the B criterion, and the B criterion is also related to the C criterion, it is inferred that the A criterion will necessarily be related to the C criterion.

Step 9. For level partitioning and diagramming, an iterative process is made by dividing factors into different levels to develop the hierarchical structure.

Step 10. To determine the driving power and dependence of factors, MICMAC analysis is made. As a result of the analysis, the criteria are divided into four groups.

- I) Autonomous Group: The criteria in this group have low influence and low dependency power. The criteria in this group are independent as they have relatively little connection with other criteria in the system.
- II) Dependent Group: The criteria in this group have low influence but high dependency power.
- III) Linkage Group: The criteria in this group have high impact and high dependency power.
- IV) Independent Group: The criteria in this group have high impact, but low dependency power.

The criteria in the “III” and “IV” groups with high impact power are defined as the key criteria.

5.2. Application of the Proposed Methodology

Step 1. A group of experts is formed to identify and evaluate the success factors for RUL of Istanbul. These experts consist of individuals working in IMM. The characteristics of the experts are detailed in Table 5.4.

Table 5.4: The characteristics of the DMs

DMs	Department of IMM	Profession	Education	Experience
DM1	Transportation	Engineer	Master's degree	>5 years
DM2	GIS directorate	Engineer	Bachelor's degree	2 years
DM3	Transportation	Urban planner	Master's degree	3 years
DM4	Transportation	Engineer	Master's degree	5 years
DM5	Urban planning	Urban planner	Master's degree	4 years

Step 2. With the help of literature review and expert opinions, factors were determined and explained in this step. A total of 21 success factors have been identified under four main factors for the successful implementation of RUL and given in Table 5.6.

Table 5.5: The importance weights of DMs

DMs	Ratings	IVFFNs	Importance weights
DM1	ES	$([0.75, 0.85], [0.05, 0.15])$	0.235 (w_1)
DM2	VS	$([0.65, 0.75], [0.15, 0.25])$	0.148 (w_2)
DM3	VS	$([0.65, 0.75], [0.15, 0.25])$	0.148 (w_3)
DM4	ES	$([0.75, 0.85], [0.05, 0.15])$	0.235 (w_4)
DM5	ES	$([0.75, 0.85], [0.05, 0.15])$	0.235 (w_5)

Table 5.6: Success factors of RUL for Istanbul

Main Factors	Factors	Description
Management and strategy related factors (MS)	Awareness to RUL (MS1)	It is a vital way of achieving success by transforming behavior from passive to proactive (Kiba-janiak, 2016).
	Multi-stakeholder collaboration and leaders' commitment (MS2)	It displays that inclusive and constructive cooperation should be ensured among all actors involved in the decision-making process for successful RUL implementation (Sony et al., 2021; Tortorella et al., 2022).
	Education and training (MS3)	Educating the community and businesses supports the successful implementation of RUL by providing a city that knows what to do in the event of unexpected events (Tortorella et al., 2022).
	Financial management (MS4)	It refers to the effective and efficient management of funds by planning and preparing for the future in such a manner as to accomplish the objectives of the organizations (Tortorella et al., 2022).
	Government regulations (MS5)	It ensures that the interests of stakeholders are supported, developed and promoted. It displays clear government regulations drive the implementations of RUL (Kiba-janiak, 2016).

Main Factors	Factors	Description
Safety and security-related factors (SS)	Information sharing (SS1)	It ensures information integrity and reduces unnecessary information, making processes more efficient (Kiba-janiak, 2016).
	Real-Time visibility and monitoring (SS2)	It demonstrates as the ability to monitor products, deliveries and services by improving RUL management (Aifandopoulou & Xenou, 2019).
	Increased flexibility and adaptive capacity (SS3)	It refers to resilience and flexibility to perturbation, ability to reconfigure themselves with minimum loss of function (Kiba-janiak, 2016).
	Improved forecasting (SS4)	It displays the pre-detection of disasters and risks, taking measures to prevent the damages that may occur before the disaster, and carrying out recovery works after the disaster (UN-Habitat, 2021).
	Urban hazard and exposure mapping (SS5)	It indicates the robust systems in place to map the city's exposure and vulnerability to hazards based on current data (Aifandopoulou & Xenou, 2019).
	Resource management (SS6)	It refers to spare capacity that is deliberately created so that functions can be performed in the event of interruption or deterioration (Aifandopoulou & Xenou, 2019).

Main Factors	Factors	Description
Technology-related factors (TE)	Technological skills (TE1)	It refers to expertise, training and proficiency in this field (Moeuf et al., 2020)
	Technological functionality (TE2)	It includes the hardware, software and network resources necessary for the existence, operation, management and integration of information technologies with other functions of the system (Büyüközkan & Göçer, 2018).
	Technology adaptation (TE3)	It involves changing existing conditions to comply with new digital technologies as well as adapting current technologies (Sony et al., 2021)
	Trust and collaboration (TE4)	It refers to working together with the technology suppliers towards greater RUL transparency, promoting higher ethical and environmental standards, and positive change (Büyüközkan & Göçer, 2018).
	Interoperability (TE5)	It refers to systems or business processes working together to perform a common operation (Büyüközkan & Göçer, 2018).
Infrastructure and environment related factors (IE)	Urban planning (IE1)	It refers to the effective planning of transportation systems and logistics distribution within the city (Aifandopoulou & Xenou, 2019)
	Effective traffic management (IE2)	It refers to developing task distributions and identification of monitoring systems (Aifandopoulou & Xenou, 2019).
	Flexible public spaces, logistics villages and land allocation (IE3)	It refers to the opportunities to improve parking management and urban logistics delivery spaces in the cities (Kiba-janiak, 2016).
	Effective supply chain management (IE4)	It refers to the improvement of product flow through accurate demand and improve inventory management (Sony et al., 2021)
	Integration between transport modes (IE5)	It involves the combining of different modes of transport to maximize ease and efficiency (Kiba-janiak, 2016).

Step 3. The linguistic terms provided in Table 5.1 were used to determine the importance weights of the five DMs using Equation (5.1.1). Table 5.5 presents the resulting importance weights based on the assigned linguistic terms.

Step 4. Pair-wise relationships between the sub-factors were determined. Due to page limitations, only the evaluations of DM1 are provided. Then, in order to get the initial fuzzy reachability matrix, linguistic terms were replaced by corresponding IVFFNs.



Table 5.7: Pair-wise relationships between the sub-factors for DM1

Sub-factors	IE5	IE4	IE3	IE2	IE1	TE5	TE4	TE3	TE2	TE1	SS6	SS5	SS4	SS3	SS2	SS1	MS5	MS4	MS3	MS2	MS1
MS1	V(VH)	V(VH)	V(VH)	V(L)	V(VH)	O(NO)	O(NO)	V(H)	V(H)	V(H)	O(NO)	O(NO)	X(H)	V(VH)	V(VH)	V(VH)	V(L)	V(H)	V(H)	V(H)	-
MS2	V(VL)	V(VL)	O(NO)	O(NO)	V(VH)	O(NO)	V(H)	V(VH)	V(H)	V(VH)	V(VH)	V(VH)	X(VH)	V(H)	V(VH)	V(VH)	O(NO)	V(H)	V(H)	-	
MS3	O(NO)	V(L)	O(NO)	O(NO)	O(NO)	V(H)	O(NO)	O(NO)	O(NO)	X(VH)	V(L)	V(H)	V(H)	V(L)	V(L)	V(H)	V(L)	V(H)	-		
MS4	V(H)	V(H)	V(H)	O(NO)	V(VH)	O(NO)	V(VH)	V(VH)	V(VH)	V(L)	V(H)	V(H)	V(H)	O(NO)	V(VH)	X(VH)	O(NO)	-			
MS5	V(H)	V(L)	V(H)	V(H)	V(VH)	O(NO)	V(VL)	V(L)	V(L)	O(NO)	O(NO)	V(H)	V(H)	O(NO)	V(L)	V(L)	-				
SS1	O(NO)	X(VH)	O(NO)	X(VH)	V(H)	V(H)	V(VH)	V(L)	X(VH)	X(H)	V(H)	V(VH)	V(VH)	V(VH)	V(VH)	-					
SS2	V(VL)	V(VH)	O(NO)	V(VH)	O(NO)	O(NO)	A(VH)	A(VH)	A(VH)	A(VH)	O(NO)	V(VH)	V(VH)	V(VH)	-						
SS3	O(NO)	V(H)	X(VH)	X(H)	V(H)	O(NO)	O(NO)	O(NO)	O(NO)	O(NO)	O(NO)	V(H)	O(NO)	-							
SS4	O(NO)	V(H)	O(NO)	V(L)	O(NO)	O(NO)	A(H)	A(VH)	A(VH)	A(VH)	O(NO)	V(VH)	-								
SS5	O(NO)	X(VH)	O(NO)	O(NO)	X(VH)	O(NO)	O(NO)	A(VH)	A(VH)	A(VH)	A(VH)	-									
SS6	O(NO)	O(NO)	O(NO)	O(NO)	O(NO)	O(NO)	O(NO)	O(NO)	O(NO)	X(L)	-										
TE1	O(NO)	O(NO)	O(NO)	V(H)	O(NO)	V(H)	V(H)	V(VH)	V(VH)	-											
TE2	O(NO)	O(NO)	O(NO)	V(H)	O(NO)	A(VH)	V(H)	V(VH)	-												
TE3	O(NO)	O(NO)	O(NO)	O(NO)	O(NO)	V(VH)	V(VH)	-													
TE4	O(NO)	V(VL)	V(VL)	V(VL)	O(NO)	V(H)	-														
TE5	O(NO)	V(VL)	V(VL)	V(VH)	O(NO)	-															
IE1	A(VH)	X(VH)	X(VH)	X(VH)	-																
IE2	V(VH)	X(VH)	X(VH)	-																	
IE3	X(H)	X(VH)	-																		
IE4	A(VH)	-																			
IE5	-																				

Step 5. DMs' evaluations are aggregated using the IVFFDWA operator to obtain the group decision. Here, we consider $\beta = 1$. Table 5.8 shows the aggregated IVFF reachability matrix for sub-factors.

Step 6. The distance of each aggregated IVFFN from all five IVFFNs corresponding to linguistic terms is calculated as explained in Step 6 of Section 5.1. Table 5.9 shows the final IVFF reachability matrix of factors.

Step 7. The de-fuzzified reachability matrix is created replacing VH and H by 1 and others by 0 in the final IVFF reachability matrix.

Step 8. The transitivity rule is applied.

Step 9. The sub-factors are divided into different levels through an iterative process, resulting in a hierarchical structure shown in Figure 5.2. The level partitioning of sub-factors is given in Table 5.10.

Step 10. The driving power and dependence of sub-factors are computed by summing the rows and columns of the de-fuzzified reachability matrix in Table 5.11 and shown in Figure 5.3.

Table 5.8: Aggregated IVFF reachability matrix of sub-factors

Sub-factors	IE5				IE4				IE3				IE2				IE1				TE5				TE4			
	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u
MS1	0.69	0.90	0.71	0.91	0.62	0.85	0.71	0.91	0.62	0.85	0.67	0.89	0.51	0.61	0.54	0.79	0.77	0.94	0.25	0.36	0.16	0.26	0.78	0.94	0.39	0.48	0.76	0.94
MS2	0.30	0.39	0.71	0.90	0.38	0.48	0.64	0.85	0.37	0.47	0.75	0.93	0.37	0.46	0.69	0.89	0.80	0.95	0.00	0.15	0.00	0.20	0.80	0.95	0.61	0.81	0.43	0.53
MS3	0.19	0.28	0.77	0.94	0.45	0.55	0.61	0.85	0.39	0.48	0.76	0.94	0.19	0.28	0.77	0.94	0.42	0.51	0.74	0.92	0.56	0.66	0.59	0.84	0.42	0.51	0.74	0.92
MS4	0.46	0.55	0.73	0.92	0.46	0.55	0.73	0.92	0.47	0.56	0.68	0.89	0.32	0.41	0.70	0.90	0.77	0.94	0.25	0.36	0.56	0.66	0.59	0.84	0.62	0.85	0.67	0.89
MS5	0.64	0.85	0.66	0.89	0.39	0.49	0.74	0.92	0.43	0.52	0.71	0.91	0.55	0.65	0.53	0.79	0.77	0.94	0.25	0.36	0.46	0.55	0.73	0.92	0.68	0.89	0.42	0.53
SS1	0.28	0.36	0.75	0.93	0.66	0.89	0.73	0.92	0.39	0.48	0.76	0.94	0.74	0.92	0.41	0.51	0.42	0.51	0.74	0.92	0.46	0.55	0.73	0.92	0.58	0.84	0.74	0.92
SS2	0.23	0.33	0.74	0.92	0.66	0.86	0.59	0.84	0.37	0.47	0.75	0.93	0.62	0.85	0.62	0.85	0.28	0.36	0.75	0.93	0.00	0.20	0.80	0.95	0.19	0.28	0.77	0.94
SS3	0.62	0.85	0.71	0.91	0.49	0.58	0.67	0.89	0.58	0.84	0.74	0.92	0.44	0.54	0.68	0.89	0.49	0.58	0.67	0.89	0.46	0.55	0.73	0.92	0.53	0.63	0.66	0.89
SS4	0.59	0.84	0.73	0.92	0.63	0.85	0.66	0.89	0.49	0.58	0.67	0.89	0.49	0.58	0.67	0.89	0.33	0.42	0.74	0.92	0.19	0.28	0.77	0.94	0.19	0.28	0.77	0.94
SS5	0.00	0.20	0.80	0.95	0.61	0.84	0.67	0.89	0.40	0.49	0.74	0.92	0.39	0.48	0.76	0.94	0.64	0.85	0.66	0.89	0.58	0.84	0.76	0.94	0.28	0.37	0.77	0.94
SS6	0.19	0.28	0.77	0.94	0.49	0.58	0.67	0.89	0.28	0.37	0.77	0.94	0.30	0.39	0.74	0.93	0.19	0.28	0.77	0.94	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95
TE1	0.39	0.48	0.76	0.94	0.30	0.39	0.74	0.93	0.33	0.42	0.74	0.92	0.50	0.60	0.60	0.84	0.33	0.42	0.74	0.92	0.60	0.70	0.20	0.30	0.60	0.70	0.20	0.30
TE2	0.34	0.43	0.78	0.94	0.34	0.43	0.78	0.94	0.55	0.79	0.75	0.93	0.61	0.81	0.61	0.84	0.39	0.48	0.76	0.94	0.00	0.20	0.80	0.95	0.62	0.85	0.71	0.91
TE3	0.24	0.33	0.78	0.94	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95	0.56	0.80	0.73	0.92	0.00	0.20	0.80	0.95	0.80	0.95	0.00	0.15	0.80	0.95	0.00	0.15
TE4	0.63	0.85	0.60	0.84	0.40	0.50	0.69	0.89	0.19	0.28	0.77	0.94	0.40	0.50	0.59	0.81	0.39	0.48	0.67	0.89	0.46	0.55	0.73	0.92	0.00	0.00	0.00	0.00
TE5	0.50	0.60	0.69	0.90	0.31	0.40	0.73	0.92	0.26	0.45	0.75	0.93	0.66	0.89	0.73	0.92	0.00	0.20	0.80	0.95	0.00	0.00	0.00	0.00	0.34	0.43	0.78	0.94
IE1	0.74	0.92	0.58	0.84	0.76	0.94	0.58	0.84	0.66	0.89	0.73	0.92	0.80	0.95	0.00	0.15	0.00	0.00	0.00	0.00	0.53	0.63	0.66	0.89	0.39	0.48	0.67	0.89
IE2	0.58	0.84	0.76	0.94	0.76	0.94	0.58	0.84	0.78	0.94	0.51	0.78	0.00	0.00	0.00	0.00	0.58	0.84	0.76	0.94	0.53	0.63	0.66	0.89	0.00	0.20	0.80	0.95
IE3	0.66	0.86	0.40	0.49	0.74	0.92	0.53	0.79	0.00	0.00	0.00	0.00	0.66	0.89	0.73	0.92	0.58	0.84	0.76	0.94	0.49	0.58	0.71	0.91	0.00	0.20	0.80	0.95
IE4	0.00	0.20	0.80	0.95	0.00	0.00	0.00	0.00	0.58	0.84	0.76	0.94	0.58	0.84	0.76	0.94	0.58	0.84	0.76	0.94	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95
IE5	0.00	0.00	0.00	0.00	0.75	0.93	0.15	0.23	0.46	0.55	0.73	0.92	0.73	0.92	0.58	0.84	0.58	0.84	0.76	0.94	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95
Sub-factors	TE3				TE2				TE1				SS6				SS5				SS4				SS3			
	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u	μ_i	μ_u	ν_i	ν_u
MS1	0.46	0.55	0.73	0.92	0.48	0.58	0.53	0.63	0.53	0.63	0.57	0.80	0.00	0.20	0.80	0.95	0.52	0.78	0.75	0.93	0.46	0.55	0.73	0.92	0.61	0.84	0.73	0.92
MS2	0.62	0.85	0.65	0.87	0.46	0.55	0.73	0.92	0.73	0.92	0.66	0.89	0.69	0.90	0.71	0.91	0.69	0.90	0.67	0.89	0.64	0.85	0.59	0.84	0.54	0.64	0.59	0.84
MS3	0.42	0.51	0.74	0.92	0.50	0.60	0.66	0.89	0.75	0.93	0.51	0.78	0.69	0.89	0.30	0.43	0.67	0.86	0.25	0.36	0.55	0.65	0.62	0.86	0.55	0.65	0.53	0.79
MS4	0.61	0.84	0.73	0.92	0.66	0.86	0.52	0.78	0.58	0.80	0.67	0.89	0.64	0.83	0.25	0.36	0.64	0.82	0.52	0.78	0.64	0.83	0.25	0.36	0.49	0.58	0.71	0.91
MS5	0.30	0.39	0.74	0.93	0.39	0.49	0.74	0.92	0.24	0.33	0.78	0.94	0.16	0.26	0.78	0.94	0.60	0.70	0.20	0.30	0.50	0.60	0.69	0.90	0.53	0.63	0.66	0.89
SS1	0.53	0.79	0.74	0.92	0.67	0.89	0.69	0.90	0.59	0.81	0.69	0.90	0.42	0.51	0.74	0.92	0.59	0.84	0.73	0.92	0.67	0.89	0.69	0.90	0.59	0.84	0.73	0.92
SS2	0.49	0.58	0.67	0.89	0.46	0.55	0.73	0.92	0.43	0.53	0.67	0.89	0.43	0.53	0.67	0.89	0.77	0.93	0.13	0.22	0.78	0.94	0.51	0.78	0.77	0.93	0.13	0.22
SS3	0.39	0.48	0.76	0.94	0.63	0.82	0.59	0.84	0.49	0.58	0.71	0.91	0.53	0.63	0.66	0.89	0.55	0.65	0.62	0.86	0.49	0.58	0.71	0.91	0.00	0.00	0.00	0.00
SS4	0.28	0.37	0.77	0.94	0.39	0.48	0.76	0.94	0.43	0.53	0.67	0.89	0.39	0.48	0.67	0.89	0.70	0.90	0.52	0.78	0.00	0.00	0.00	0.00	0.51	0.78	0.78	0.94
SS5	0.39	0.48	0.76	0.94	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95	0.00	0.00	0.00	0.00	0.51	0.78	0.78	0.94	0.51	0.78	0.78	0.94
SS6	0.33	0.42	0.74	0.92	0.50	0.60	0.66	0.89	0.33	0.42	0.74	0.92	0.00	0.00	0.00	0.00	0.70	0.90	0.52	0.78	0.36	0.45	0.72	0.92	0.51	0.78	0.78	0.94
TE1	0.80	0.95	0.00	0.15	0.80	0.95	0.00	0.15	0.00	0.00	0.00	0.00	0.52	0.62	0.54	0.79	0.78	0.94	0.11	0.19	0.63	0.85	0.54	0.79	0.00	0.20	0.80	0.95
TE2	0.59	0.84	0.63	0.82	0.00	0.00	0.00	0.00	0.00	0.20	0.80	0.95	0.24	0.33	0.78	0.94	0.78	0.94	0.11	0.19	0.73	0.92	0.66	0.89	0.51	0.78	0.78	0.94
TE3	0.00	0.00	0.00	0.00	0.51	0.78	0.78	0.94	0.00	0.20	0.80	0.95	0.33	0.42	0.74	0.92	0.74	0.92	0.58	0.84	0.58	0.84	0.74	0.92	0.34	0.43	0.78	0.94
TE4	0.00	0.20	0.80	0.95	0.51	0.78	0.78	0.94	0.00	0.20	0.80	0.95	0.46	0.55	0.73	0.92	0.46	0.55	0.73	0.92	0.39	0.48	0.76	0.94	0.00	0.20	0.80	0.95
TE5	0.00	0.20	0.80	0.95	0.80	0.95	0.00	0.15	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95	0.46	0.55	0.73	0.92	0.34	0.43	0.78	0.94	0.34	0.43	0.78	0.94
IE1	0.00	0.20	0.80	0.95	0.39	0.48	0.76	0.94	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95	0.64	0.85	0.66	0.89	0.00	0.20	0.80	0.95	0.34	0.43	0.78	0.94
IE2	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95	0.00	0.20	0.80	0.95	0.39	0.48	0.76	0.94	0.00	0.20	0.80	0.95	0.56	0.80		

Table 5.9: Final IVFF reachability matrix of sub-factors

Sub-factors	IE5	IE4	IE3	IE2	IE1	TE5	TE4	TE3	TE2	TE1	SS6	SS5	SS4	SS3	SS2	SS1	MS5	MS4	MS3	MS2	MS1
MS1	NO	NO	NO	VL	VH	NO	NO	NO	L	VL	NO	NO	NO	NO	NO	NO	VL	H	NO	VL	-
MS2	NO	NO	NO	NO	VH	NO	H	NO	NO	VH	NO	VH	NO	NO	VH	VH	NO	NO	VL	-	NO
MS3	NO	VL	NO	NO	NO	NO	NO	NO	NO	VH	VH	VH	NO	VL	VH	VH	VL	-	NO	NO	NO
MS4	NO	NO	NO	NO	VH	NO	NO	NO	VH	NO	H	VH	H	NO	VH	VH	NO	-	NO	NO	NO
MS5	NO	NO	NO	VL	VH	NO	VH	NO	NO	NO	NO	H	NO	NO	VL	VL	-	NO	NO	NO	NO
SS1	NO	NO	NO	VH	NO	NO	NO	NO	NO	NO	NO	NO	NO	VH	NO	VH	-	NO	NO	NO	NO
SS2	NO	VH	NO	NO	NO	NO	NO	NO	NO	NO	NO	VH	VH	VH	-	NO	NO	NO	NO	NO	NO
SS3	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	-	VH	NO	NO	NO	NO	NO	NO
SS4	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	VH	-	NO	NO	NO	NO	NO	NO	NO	NO
SS5	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	-	NO	NO	VH	NO	NO	NO	NO	NO	NO
SS6	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	-	VH	NO	NO	NO	NO	NO	NO	NO	NO	NO
TE1	NO	NO	NO	NO	NO	H	H	VH	VH	-	VL	VH	NO	NO	VH	NO	NO	NO	NO	NO	NO
TE2	NO	NO	NO	NO	NO	NO	NO	VH	-	NO	NO	VH	VH	NO	VH	NO	NO	NO	NO	NO	NO
TE3	NO	NO	NO	NO	NO	VH	VH	-	NO	NO	NO	VH	NO	NO	NO	NO	NO	NO	NO	NO	NO
TE4	VH	NO	NO	VL	NO	NO	-	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
TE5	NO	NO	NO	NO	NO	-	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
IE1	VH	VH	NO	VH	-	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
IE2	NO	VH	VH	-	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
IE3	VH	VH	-	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
IE4	NO	-	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
IE5	-	VH	NO	VH	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Table 5.10: Level Partitioning of factors

Sub-factors	Reachability Set	Antecedent Set	Intersection Set	Level
MS1	1	1	1	6
MS2	2	2	2	6
MS3	3	3	3	6
MS4	4	1, 4	4	5
MS5	5	5	5	4
SS1	6	1, 2, 3, 4, 6	6	3
SS2	7, 8, 9, 10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16	7, 8, 9, 10	2
SS3	7, 8, 9, 10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16	7, 8, 9, 10	2
SS4	7, 8, 9, 10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16	7, 8, 9, 10	2
SS5	7, 8, 9, 10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16	7, 8, 9, 10	2
SS6	11	1, 3, 4, 11	11	3
TE1	12	2, 3, 12	12	5
TE2	13, 14, 16	1, 2, 3, 4, 12, 13, 14, 16	13, 14, 16	4
TE3	13, 14, 16	1, 2, 3, 4, 12, 13, 14, 16	13, 14, 16	4
TE4	15	1, 2, 3, 4, 5, 12, 13, 14, 15, 16	15	3
TE5	13, 14, 16	1, 2, 3, 4, 12, 13, 14, 16	13, 14, 16	4
IE1	17	1, 2, 4, 5, 17	17	3
IE2	18, 19, 21	1, 2, 3, 4, 5, 6, 12, 13, 14, 15, 16, 17, 18, 19, 21	18, 19, 21	2
IE3	18, 19, 21	1, 2, 3, 4, 5, 6, 12, 13, 14, 15, 16, 17, 18, 19, 21	18, 19, 21	2
IE4	20	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21	20	1
IE5	18, 19, 21	1, 2, 3, 4, 5, 6, 12, 13, 14, 15, 16, 17, 18, 19, 21	18, 19, 21	2

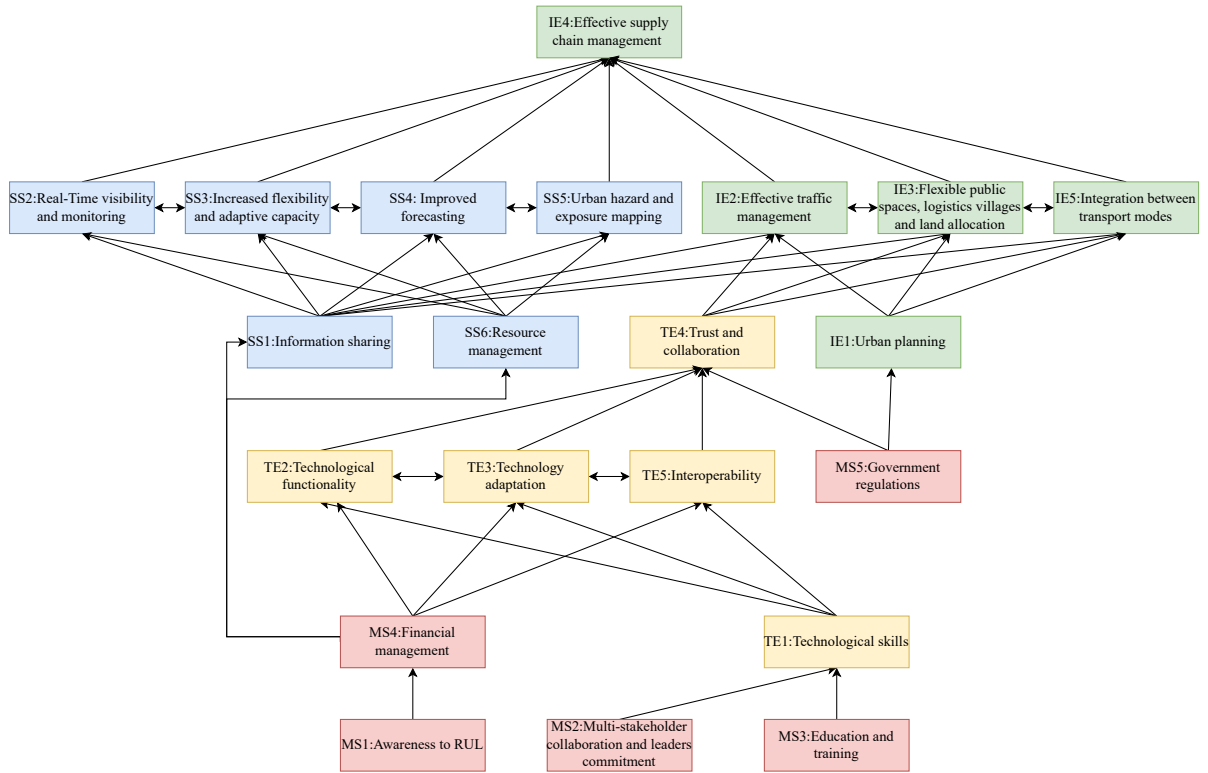


Figure 5.2: ISM model of sub-factors

As a result of the operations, 21 sub-factors were divided into six hierarchical levels, as seen in Figure 5.2. MS1, MS2 and MS3 sub-factors are at the sixth level in the ISM. These sub-factors are of great importance and form the basis of the hierarchy. Any changes, whether positive or negative, that occur in these sub-factors will affect other sub-factors. Therefore, it is crucial for practitioners and decision makers to pay close attention to these sub-factors to ensure successful implementation of RUL for Istanbul. It is important to first adopt RUL and understand its benefits. Raising awareness through trainings on the subject of RUL is also essential to ensure that all stakeholders are informed and engaged. Furthermore, multi-stakeholder cooperation is critical to the success of RUL implementation. Collaboration among various stakeholders such as government entities, private sector organizations, and civil society groups can help to identify challenges and create solutions. Finally, the commitment of leaders is essential to ensure the sustainability of the RUL projects in Istanbul. By taking these steps, decision makers and practitioners can successfully implement RUL in Istanbul and create a more sustainable and livable city.

After that, it has been observed that the MS4 and TE1 sub-factors are at the fifth level of the ISM hierarchy. These sub-factors are closely linked to the advancement of RUL training and awareness, and effective collaboration with stakeholders and leaders. When we analyze the general structure of ISM, it becomes evident that management and strategy-related factors are the most critical components that significantly influence the success of RUL. Therefore, any managerial or strategic steps taken in this area will have a direct impact on all other sub-factors. To achieve success in RUL, it is imperative to focus on building strong management and strategy frameworks. This will enable organizations to develop a comprehensive understanding of the field, identify potential roadblocks and challenges, and implement effective measures to overcome them.

The fourth level of the hierarchy includes the sub-factors of TE2, TE3, TE5 and MS5. Also, there is a two-way interaction between TE2, TE3 and TE3, TE5. One of the critical areas that financial management can impact is technological development in the field of RUL. Efficient financial management can lead to more significant investments in research and development, resulting in better technological advancements. Additionally, effective financial management can ensure that resources are allocated appropriately, enabling accurate and timely information sharing, and facilitating urban planning, which are in the third level of the ISM hierarchy. Moreover, government regulations also play a vital role in shaping RUL. Regulations such as truck route regulations, transportation regulations, permits to enter certain areas, or vehicle regulations to regulate vehicle sizes or emissions, can have a significant impact on urban planning and the overall success of RUL operations. By enforcing such regulations, governments can ensure that logistics operations are carried out in a safe, efficient, and sustainable manner while promoting trust and cooperation between stakeholders. Finally, increasing technological skills through training and courses can enhance the technology adaptation. By investing in training, individuals can acquire the skills needed to develop and maintain advanced technologies. This can lead to the creation of more efficient and sustainable technological systems, which can contribute to the successful implementation of RUL.

At the second level of the hierarchy, safety and security-related factors and infrastructure and environment-related factors are directly impacted by various sub-factors like technological functionality, effective management of resources, information sharing, and

urban planning. Also, there is a two-way interaction between SS2, SS3, SS4, SS5 and IE2, IE3, IE5. Advanced technologies can enhance a faster and safer logistics process by ensuring the effective and efficient use of logistics resources. Another crucial factor is the effective management of resources, which can have a significant impact on increasing the flexibility and adaptive capacity of RUL. Information sharing is another important factor that affects safety and security-related factors and infrastructure and environment-related factors. By ensuring effective information sharing, it will be possible to increase real-time visibility and enable more accurate forecasting against disruptive events. Also, by carrying out urban planning while considering RUL plans, it will be possible to ensure effective management of traffic and achieve logistics villages and areas in accordance with RUL. Incorporating smart technologies is also crucial in making the processes more efficient and flexible. By leveraging advanced technologies like AI, IoT, and Big Data, it will be possible to optimize resource use, enhance security, and improve RUL.

Finally, it was observed that the IE4: Effective supply chain management sub-factor was at the top of the hierarchy. This sub-factor is influenced by lower-level sub-factors. Hence, achieving the sub-factors below the hierarchy is necessary to attain effective supply chain management. Effective supply chain management enhances resilience in urban logistics by promoting risk reduction, visibility, collaboration, flexible inventory management, technology integration, and diversification. All these factors collectively contribute to the ability of urban logistics systems to bear and recover from disruptions, ensuring the consistent availability of goods and services in cities.

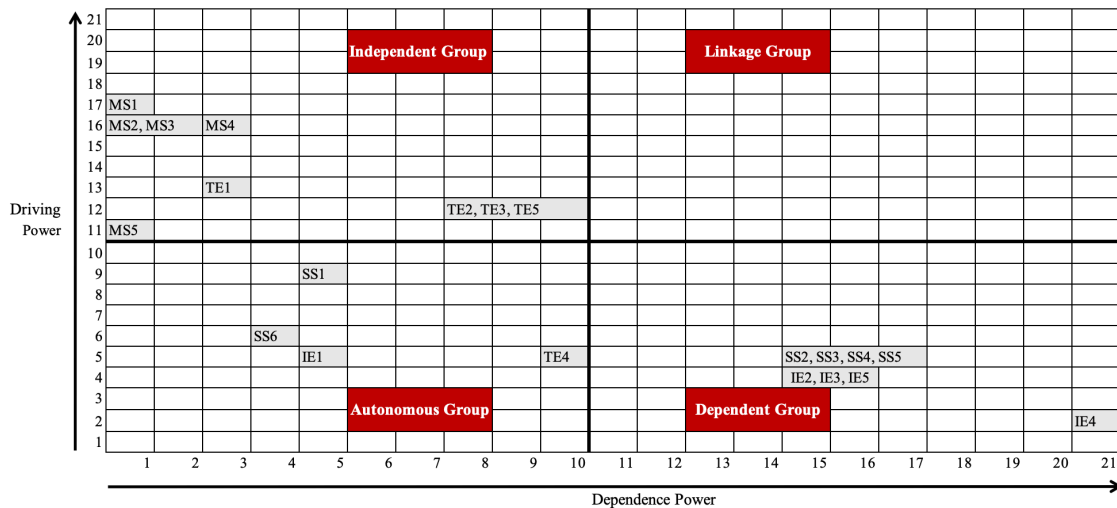


Figure 5.3: Driving power and dependency of sub-factors

To further analyze the sub-factors, MICMAC analysis is conducted. Figure 5.3 depicts the categorization of sub-factors in four clusters based on their driving power and dependence. The sub-factors with low driver power and dependence are shown in the Autonomous group in the MICMAC analysis. This group contains the sub-factors of SS6, IE1, SS1, TE4 as they neither usually drive nor are driven by other sub-factors. IE2, IE3, IE4, IE5, SS2, SS3, SS4, SS5 sub-factors are at the top level of hierarchy as shown in Fig.1 hence, these are dependent on the driving sub-factors positioned at the lower level of the hierarchy. In this study, there is no sub-factor that has the characteristics of the linkage group. It can be seen that MS1, MS2, MS3, MS4, MS5, TE1, TE2, TE3, TE5 are the independent or driving sub-factors. The results of MICMAC analysis also reveal that management and strategy-related factors and technology-related factors have a relatively high driving force. In our ISM model, these sub-factors form the basis of RUL success. This means that giving importance to these factors will primarily affect the success of RUL and the success of other factors.

5.3. Discussion on RUL Critical Success Factors Determination

City logistics stakeholders and governance face a challenging task when it comes to managing and implementing RUL. There are numerous factors that come into play when making decisions about RUL, which can make the process difficult. However, this thesis has provided some insight into the critical success factors involved in the successful

implementation of RUL in Istanbul. This section not only contributes to the theoretical understanding of RUL, but also provides valuable information for urban logistics decision makers and practitioners.

The section revealed that the sub-factors with the highest impact level are “multi-stakeholder collaboration and leaders’ commitment”, “education and training”, and “awareness to RUL”. These factors play a critical role in ensuring the successful implementation of RUL. Thus, it is important for the authorities to understand the significance of RUL and identify all urban logistics stakeholders. It is essential to consider the interests of all RUL stakeholders while implementing any policy, measure, or practice. Achieving consensus among the stakeholders is also important for RUL applications. Moreover, technology-related factors have also been identified as other important factors with a high level of impact. Success in managerial and technological areas, will contribute to the success of security, and environmental factors and lead RUL towards success.

In this section of the thesis, the 21 sub-factors were examined holistically. When the main factor groups were also examined, the results showed that the management and strategy-related factors had a strong influence on other factors. Figure 5.4 provides a visualization of relationship, which highlights the interconnectedness of the main factors.

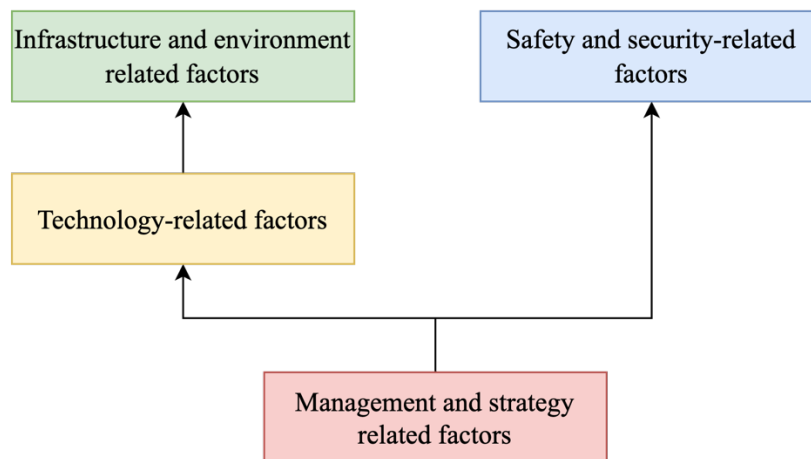


Figure 5.4: ISM model of main factors

When focusing on RUL, it is crucial to analyze each main factor group independently, to gain a deeper understanding of the interrelationships between factors and how they

contribute to the success of RUL. The ISM model of each main factor group, depicted in Figure 5.5, provides a comprehensive understanding of the factors involved in achieving success in RUL. By considering each factor group separately, practitioners and decision makers can determine the impact of each factor and develop strategies and plans that account for all key factors.

Figure 5.5 highlights the critical role of increasing awareness of RUL from a managerial and strategic perspective for successful implementation in Istanbul. Further examination of the technology-related factors show that technological capabilities, knowledge, and skills are the most crucial factors in achieving success in this area. This requires organizations to have the necessary resources and expertise to act effectively in various situations. Apart from technology, safety and security related factors are other important considerations for RUL. Effective disaster preparedness requires accurate and timely information sharing and inter-institutional information integration. In terms of infrastructure and environment related factors, urban planning and integration between transportation modes are the most effective factors.

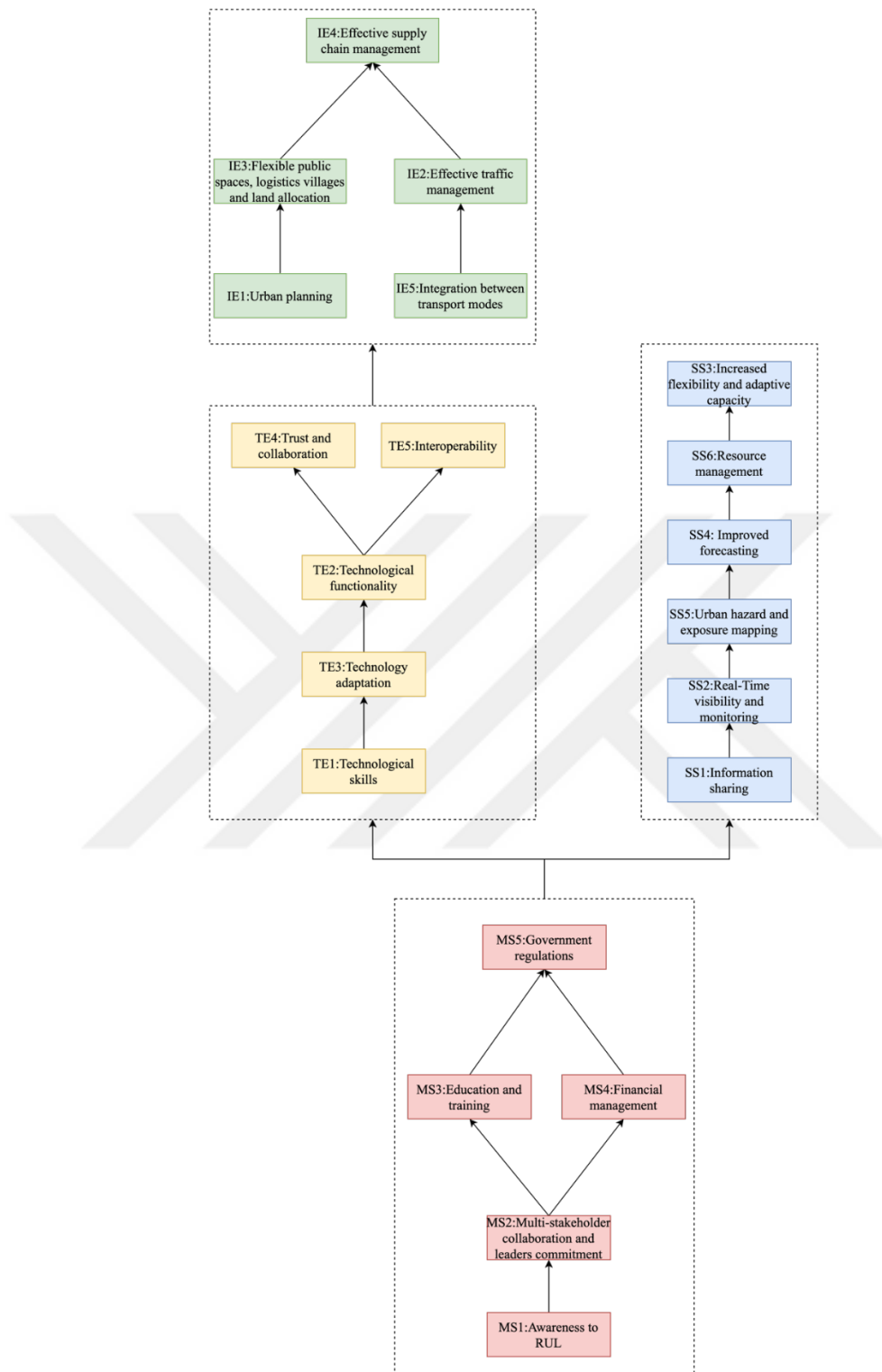


Figure 5.5: ISM model of each main factor

5.4. Concluding Remarks on RUL Critical Success Factors Determination

ISM is an important technique for practitioners to assess causality, demonstrate relationships, provide understanding of interactions, and aid decision making. The analysis made in this section helps to analyze the factors in successful RUL implementation for the province of Istanbul. The obtained results are useful for executives responsible for decision-making processes due to the analytical nature of the proposed approach in this study.

This study revealed that various factors related to management and strategy play a crucial role in the success of RUL, and these factors also have an impact on other factors. The participation of stakeholders in the RUL processes and the commitment of leaders is important in contributing to success. Analyzing and understanding the critical success factors can help city governments determine their position in the RUL area and identify areas where strategic efforts should be focused. The introduced methodology is a valuable tool that can assist in analyzing critical success factors under complex and uncertain conditions with multiple criteria involved.

6. RUL TECHNOLOGICAL INFRASTRUCTURE DESIGN

In today's world, e-commerce and personal deliveries have become increasingly popular, leading to an urgent need to address the complex logistics processes in urban areas from various perspectives such as economic, social, and environmental. The concept of RUL is important to meet this need and improve the quality of life in cities by contributing to their sustainability goals. To achieve the goal of RUL which is to create logistics systems that can withstand various challenges that cities face and adapt to rapidly changing conditions, while also ensuring sustainable operations, planning for technological infrastructure is crucial to manage the complexity of logistics systems in cities and respond effectively to various challenges. The approach must go beyond traditional logistics methods to address factors such as traffic congestion, environmental impacts, emergencies, and unexpected events. Technological design aims to integrate innovation and smart solutions to optimize, accelerate, and make RUL operations. This section aims to determine the important technologies of RUL for Istanbul using an innovative IVFF-QFD approach. A 2-staged QFD was utilized to identify key RUL practices in response to resilience requirements and the most important technologies needed to meet these practices. The following RQs guide this endeavor.

RQ1: What are the key resilience requirements and how do these requirements align with overall RUL goals?

RQ2: How can the RUL requirements be translated into measurable criteria for the selection of appropriate technologies?

RQ3: Which technologies were identified as potential solutions to address the prioritized RUL requirements?

6.1. The Proposed 2-Staged IVFF-QFD Methodology

This section proposes a novel IVFF-QFD methodology for exploring the RUL needs and technological requirements for the technologic infrastructure of RUL. The flowchart of the proposed methodology is illustrated in Figure 6.1.

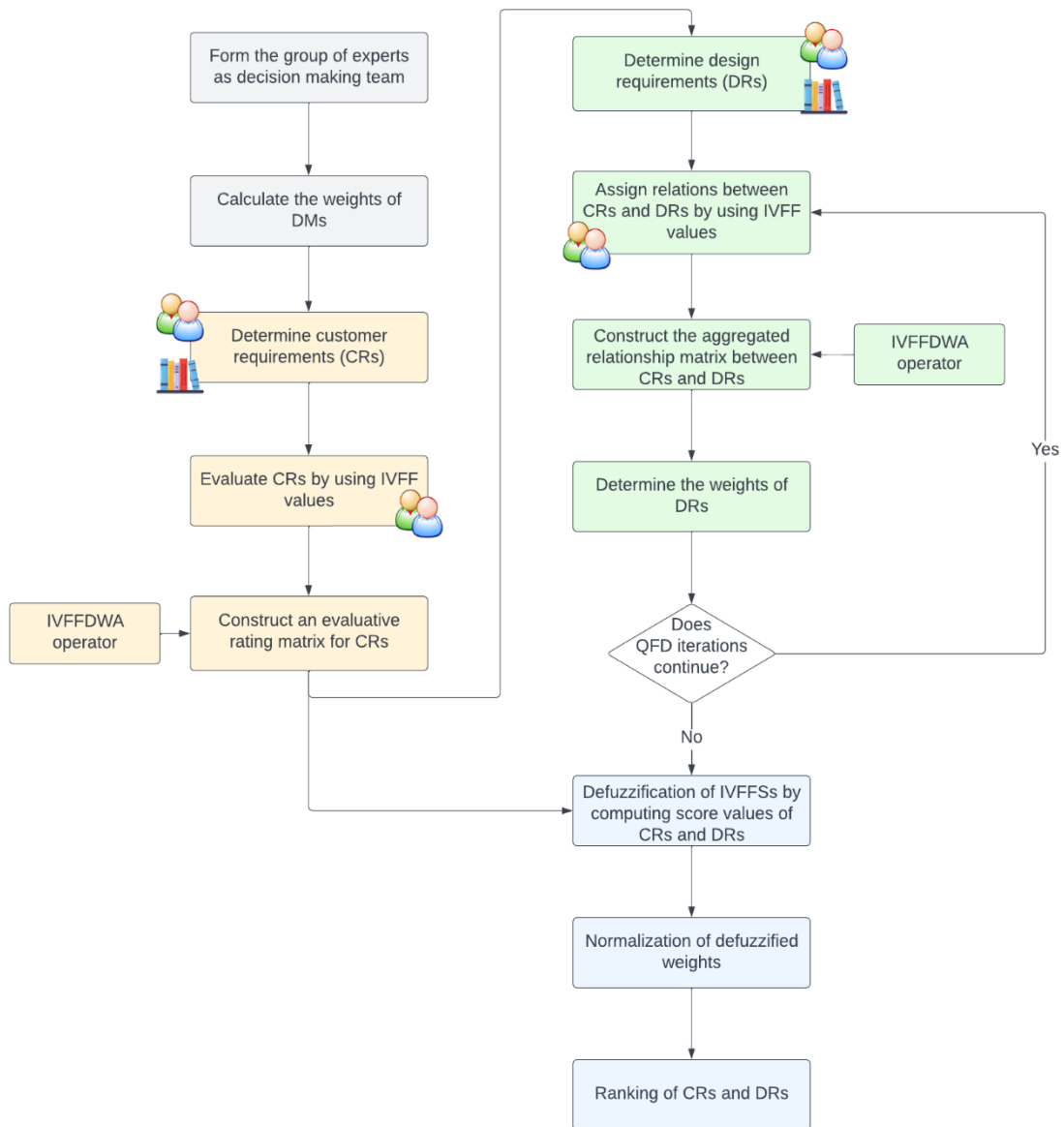


Figure 6.1: The flowchart of the IVFF-QFD methodology

6.1.1. Computational Steps of 2-Staged IVFF-QFD Methodology

Step 1- Create a decision-making group consisting of DMs. When selecting DMs, various factors are taken into consideration such as their experience, knowledge and education levels, and willingness to help.

Step 2- Calculate the weights of DMs. Let $E_k = (E_1, E_2, \dots, E_k)$, $k = 1, 2, \dots, K$ is a set of DMs and weights w_k for each E_k ; $\sum_{k=1}^K w_k = 1$. Here, the entropy method (F. Zhang & Xu, 2016) is applied to the IVFF environment. The importance degree of DMs is determined using the linguistic terms given in Table 6.1. The weights of the DMs are calculated using Equation (6.1.1) based on the linguistic terms.

$$w_k = \frac{\sqrt{\frac{1}{2} \left[\left(1 - \pi_{\bar{F}}^{l(k)} \right)^2 + \left(1 - \pi_{\bar{F}}^{u(k)} \right)^2 \right]}}{\sum_{k=1}^K \sqrt{\frac{1}{2} \left[\left(1 - \pi_{\bar{F}}^{l(k)} \right)^2 + \left(1 - \pi_{\bar{F}}^{u(k)} \right)^2 \right]}} \quad (6.1.1)$$

Table 6.1: Linguistic scale for the weights of DMs (Seikh & Mandal, 2023)

Linguistic variables	IVFFNs
Extremely significant (ES)	([0.75, 0.85], [0.05, 0.15])
Very significant (VS)	([0.65, 0.75], [0.15, 0.25])
Significant (S)	([0.55, 0.65], [0.25, 0.35])
Moderate (M)	([0.45, 0.55], [0.35, 0.45])
Insignificant (IS)	([0.25, 0.35], [0.55, 0.65])
Very insignificant (VIS)	([0.15, 0.25], [0.65, 0.75])
Extremely insignificant (EIS)	([0.05, 0.15], [0.7, 0.85])

Step 3- Determine customer requirements (CRs) based on expert opinions and literature reviews. Then evaluate CRs based on the opinions of DMs by using the IVFF linguistic scale given in Table 6.2. Here, $CR = (CR_1, CR_2, \dots, CR_m)$ where $i = 1, 2, \dots, m$. $CR^k = (\widetilde{CR}_i^k)_{1 \times m} = \left(\left[\mu_{\bar{F}_i}^{L(k)}, \mu_{\bar{F}_i}^{U(k)} \right], \left[\nu_{\bar{F}_i}^{L(k)}, \nu_{\bar{F}_i}^{U(k)} \right] \right)_{1 \times m}$ is the linguistic decision-making matrix of the weight of the CRs.

Table 6.2: Linguistic terms and corresponding IVFFNs (Alkan & Kahraman, 2022)

Linguistic variables (Importance, Relation)	IVFFNs			
	μ_l	μ_u	ν_l	ν_u
Extremely High (EH)	0.95	1	0	0
Very Very High (VVH)	0.8	0.9	0.1	0.2
Very High (VH)	0.7	0.8	0.2	0.3
High (H)	0.6	0.65	0.35	0.4
Fair (F)	0.5	0.5	0.5	0.5
Low (L)	0.35	0.4	0.6	0.65
Very Low (VL)	0.2	0.3	0.7	0.8
Very Very Low (VVL)	0.1	0.2	0.8	0.9
Extremely Low (EL)	0	0	0.95	1

Step 4- Construct an evaluative rating matrix for CRs. Let $CR = (\widetilde{CR}_i)_{1 \times m}$ be the matrix of CR. To aggregate the CRs, IVFFDWA aggregation operator is utilized which is explained in Equation (3.1.27), to allow for a more flexible and comprehensive fusion of individual opinions into group opinions.

Step 5- Determine the DRs based on expert opinions and literature reviews considering the subject and the CRs. Here, $DR = (DR_1, DR_2, \dots, DR_n)$ where $j = 1, 2, \dots, n$. $DR^k = (\widetilde{DR}_j^k)_{1 \times n} = \left(\left[\mu_{\widetilde{F}_j}^{L(k)}, \mu_{\widetilde{F}_j}^{U(k)} \right], \left[\nu_{\widetilde{F}_j}^{L(k)}, \nu_{\widetilde{F}_j}^{U(k)} \right] \right)_{1 \times n}$ is the linguistic decision matrix of DRs.

Step 6- Detect the relationship matrix between the CRs and DRs based on the judgments of the DMs, using the IVFF linguistic scale given in Table 6.2. Here, $CD^k = (\widetilde{CD}_{ij}^k)_{m \times n} = \left(\left[\mu_{\widetilde{F}_{ij}}^{L(k)}, \mu_{\widetilde{F}_{ij}}^{U(k)} \right], \left[\nu_{\widetilde{F}_{ij}}^{L(k)}, \nu_{\widetilde{F}_{ij}}^{U(k)} \right] \right)_{m \times n}$ is the linguistic decision matrix of CR_i and DR_j .

Step 7- Construct the collective relationship matrix between CRs and DRs. Let $CD = (\widetilde{CD}_{ij})_{m \times n}$ be the relationship matrix between CR_i and DR_j . Similar to Step 4, the aggregation is derived by IVFFDWA aggregation operator.

Step 8- Determine the weights of DRs (W_j^o). The importance of DRs determined by the relationship between CRs and DRs ($\widetilde{CD}_{ij}$) and the weights of CRs ($\widetilde{CR}_i$), as given in the Equation (6.1.2).

$$(W_j^o) = \sum_{i=1}^m (\widetilde{CR}_i \times \widetilde{CD}_{ij})$$

$$= \sum_{i=1}^m \left(\left[\mu_{\widetilde{F}_1}^L, \mu_{\widetilde{F}_2}^L, \mu_{\widetilde{F}_1}^U, \mu_{\widetilde{F}_2}^U \right], \left[\sqrt[3]{\left(\nu_{\widetilde{F}_1}^L \right)^3 + \left(\nu_{\widetilde{F}_2}^L \right)^3 - \left(\nu_{\widetilde{F}_1}^L \right)^3 \left(\nu_{\widetilde{F}_2}^L \right)^3}, \sqrt[3]{\left(\nu_{\widetilde{F}_1}^U \right)^3 + \left(\nu_{\widetilde{F}_2}^U \right)^3 - \left(\nu_{\widetilde{F}_1}^U \right)^3 \left(\nu_{\widetilde{F}_2}^U \right)^3} \right] \right) \quad (6.1.2)$$

If QFD iteration continues, then $W_j^o = \widetilde{CR}_i$ and go to Step 6. The representation of the two-stage IVFF-QFD is shown in Figure 6.2.

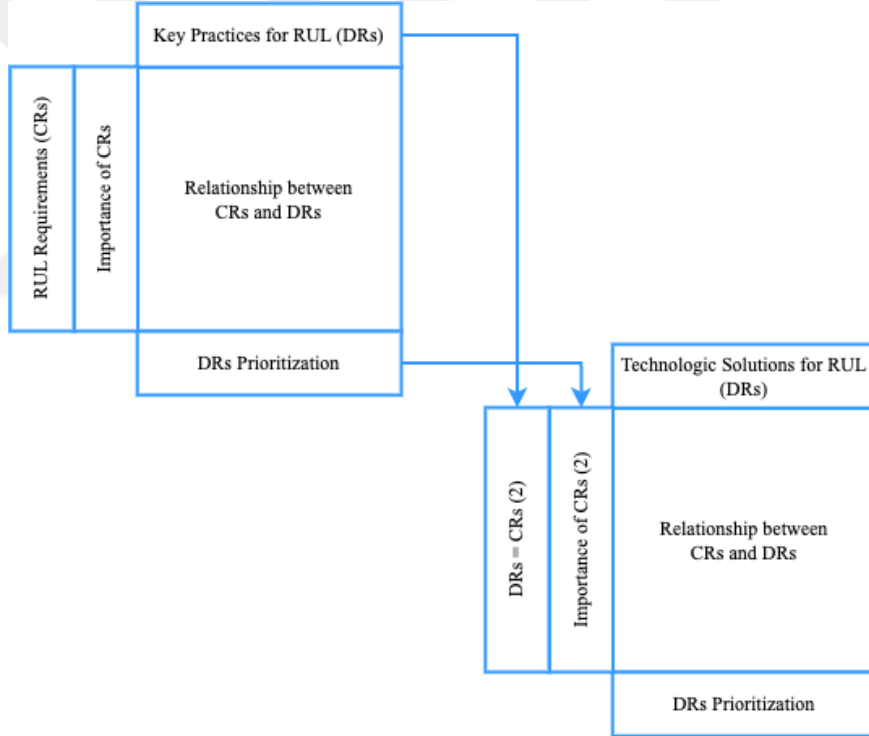


Figure 6.2: The representation of the two-staged IVFF-QFD

Step 9- Defuzzification of IVFFSs (W_j^{Def}). Find the score value of each CR and DR as given in Equation (3.1.24), to obtain the defuzzified values. Nonetheless, employing this scoring function could yield unfavorable outcomes. To mitigate this, a positive scoring function is derived by incorporating a value of 1 into the calculation results (Seker & Aydin, 2023).

Then, normalize the defuzzified weights.

$$W_j = \frac{w_j^{Def}}{\sum_{j=1}^n w_j^{Def}}, \quad \text{where } \sum_{j=1}^n W_j = 1 \quad (6.1.3)$$

6.2. Application of the Proposed Methodology

The technological infrastructure is of paramount importance in the realm of RUL. In the dynamic landscape of urban environments, where logistical challenges are abundant, a well-thought-out technological framework becomes the backbone of a resilient logistics system. A robust technological infrastructure not only enables the efficient flow of goods but also contributes to the adaptability and responsiveness of logistics operations in the face of unforeseen disruptions.

This section introduces a 2-staged IVFF-QFD approach for the technological design of RUL in Istanbul. Expert opinions from professionals at IMM were gathered and analyzed. Initially, the resilience requirements for urban logistics, labeled as CRs (What's), were identified. Key practices for RUL, serving as solutions to meet these requirements, were then outlined as DRs (How's). Subsequently, the QFD process was extended, and technological solutions enabling the implementation of key practices for RUL were specified as additional DRs² (How's).

6.2.1. First Stage of the IVFF-QFD Process

Step 1- A DM group is formed consisting of individuals working in IMM. The characteristics of the DMs are detailed in Table 6.3.

Table 6.3: The characteristics of the DMs

DMs	Department of IMM	Profession	Education	Experience
DM1	Transportation	Engineer	Master's degree	>5 years
DM2	GIS directorate	Engineer	Bachelor's degree	2 years
DM3	Transportation	Urban planner	Master's degree	3 years
DM4	Transportation	Engineer	Master's degree	5 years
DM5	Urban planning	Urban planner	Master's degree	4 years

Step 2- The importance weights of DMs calculated using Equation (6.1.1) and the linguistic terms provided in Table 6.1. The importance weights of DMs are given in Table 6.4.

Table 6.4: The importance weights of DMs

DMs	Ratings	IVFFNs	Importance weights
DM1	ES	$([0.75, 0.85], [0.05, 0.15])$	0.235 (w_1)
DM2	VS	$([0.65, 0.75], [0.15, 0.25])$	0.148 (w_2)
DM3	VS	$([0.65, 0.75], [0.15, 0.25])$	0.148 (w_3)
DM4	ES	$([0.75, 0.85], [0.05, 0.15])$	0.235 (w_4)
DM5	ES	$([0.75, 0.85], [0.05, 0.15])$	0.235 (w_5)

Step 3- By benefiting from literature reviews and experts' opinions, 17 RUL requirements are determined as CRs and presented in Table 6.5. CRs are evaluated by each DM using the IVFF linguistic scale and presented in Table 6.6.

Table 6.5: CRs and their explanation for QFD

RUL (CRs)	requirements	Explanation
CR1	Safety and Security	Involves protecting goods, people, and infrastructure from potential risks or threats during logistics operations in urban areas (ARUP, 2014).
CR2	Efficiency	Streamlining processes and resource utilization to achieve optimal performance and minimize resource waste in urban logistics (CIVITAS, 2015).
CR3	Flexibility	The capacity to adjust logistics operations quickly in response to changing circumstances or unexpected events within urban environments (POLIS, and Rupprecht Consult - Forschung & Beratung GmbH (eds), 2021).
CR4	Adaptability	The ability to modify logistics strategies and processes to address evolving challenges and capitalize on emerging opportunities in urban settings (POLIS, and Rupprecht Consult - Forschung & Beratung GmbH (eds), 2021).
CR5	Redundancy	Building backup systems and processes to mitigate disruptions, ensuring continued functionality in the face of unforeseen events (POLIS, and Rupprecht Consult - Forschung & Beratung GmbH (eds), 2021).
CR6	Recovery Capability	The ability to recover and resume normal operations swiftly following disruptions or crises in urban logistics.
CR7	Robustness	Involves minimizing the impact of potential hazards and ensure that the infrastructure can continue to function effectively over the long term (POLIS, and Rupprecht Consult - Forschung & Beratung GmbH (eds), 2021).
CR8	Predictive Ability	The capability to anticipate future challenges or disruptions and proactively plan for effective urban logistics management (ARUP, 2014).
CR9	Sustainability	Integrating environmentally conscious practices into urban logistics (ARUP, 2014).
CR10	Innovation	Embracing and integrating new technologies and creative solutions to enhance and modernize urban logistics operations (Arafah et al., 2018).
CR11	Reliability	Ensuring consistent and dependable performance of urban logistics processes to industry standards (ARUP, 2014).

RUL requirements (CRs)		Explanation
CR12	Agility	The ability to swiftly and efficiently adapt to changes in demand, technology, or market conditions within urban logistics (ARUP, 2014).
CR13	Visibility	Enhancing transparency and real-time monitoring of logistics processes (Arafah et al., 2018).
CR14	Collaboration	Encouraging effective cooperation and information sharing among stakeholders (Büyüközkan et al., 2022).
CR15	Risk Awareness	Establishing a keen understanding of potential risks and vulnerabilities within urban logistics to implement preemptive risk management strategies (Büyüközkan et al., 2022).
CR16	Resourcefulness	Involves that practitioners are able to quickly adapt to changing circumstances and find new ways to achieve their goals in times of stress or shocks (POLIS, and Rupprecht Consult - Forschung & Beratung GmbH (eds), 2021).
CR17	Responsiveness	Timely and effective responses to changing conditions, customer needs, and unforeseen events (POLIS, and Rupprecht Consult - Forschung & Beratung GmbH (eds), 2021).

Table 6.6: The linguistic evaluation of the CRs

CRs	DM1	DM2	DM3	DM4	DM5
CR1	F	EH	VVH	EH	VVH
CR2	F	EH	F	VH	VVH
CR3	EH	H	VVH	VVH	VVH
CR4	VVH	VH	VVH	VVH	VVH
CR5	H	VH	VVH	VH	VH
CR6	H	EH	VVH	VH	VH
CR7	VH	EH	EH	EH	VVH
CR8	VH	F	VH	EH	H
CR9	L	VVH	VH	EH	H
CR10	H	VVH	H	VVH	H
CR11	L	EH	VH	EH	VVH
CR12	EH	VH	VVH	VVH	VVH
CR13	F	VH	H	EH	F
CR14	F	VVH	VH	VH	F
CR15	VH	EH	EH	VH	F
CR16	L	VVH	EH	H	VH
CR17	H	VH	EH	VH	VH

Step 4- DMs' evaluations are converted into IVFFNs and aggregated using the IVFFDWA operator to obtain the group decision. Here, we consider $\beta = 1$. The aggregated IVFF values for CRs are presented in Table 6.7.

Table 6.7: Aggregated matrix for CRs

CRs	μ_l	μ_u	ν_l	ν_u
CR1	0.901	0.802	0.320	0.328
CR2	0.828	0.784	0.377	0.390
CR3	0.878	0.729	0.193	0.246
CR4	0.790	0.864	0.127	0.221
CR5	0.706	0.810	0.249	0.321
CR6	0.832	0.791	0.242	0.309
CR7	0.921	0.776	0.129	0.203
CR8	0.857	0.697	0.323	0.357
CR9	0.858	0.735	0.414	0.463
CR10	0.714	0.765	0.301	0.351
CR11	0.898	0.764	0.396	0.442
CR12	0.880	0.709	0.122	0.208
CR13	0.850	0.602	0.411	0.422
CR14	0.667	0.774	0.403	0.418
CR15	0.876	0.701	0.330	0.354
CR16	0.821	0.754	0.415	0.466
CR17	0.825	0.751	0.248	0.318

Step 5- Key practices for RUL as DRs are determined to meet the CRs. Table 6.8 explains the DRs.

Table 6.8: DRs and their explanation for QFD-First Stage

Key practices for RUL (DRs)		Explanation
DR1	Small-Scale Logistics Solutions	It aims to make urban logistic streams more efficient with applications such as pick-up points (Istanbul Metropolitan Municipality, 2018).
DR2	Hybrid Logistics	It refers to the practice of optimizing transportation resources by combining the transportation of goods and people using various modes such as multifunctional drones, shared vehicles, or pipelines (Istanbul Metropolitan Municipality, 2018).
DR3	Dynamic Route Optimization	It involves the real-time adjustment of transportation routes to optimize efficiency, reduce costs, and adapt to changing conditions (Istanbul Metropolitan Municipality, 2020b).
DR4	Diversification of Transportation Modes	It refers to the use of various transportation methods, such as rail, road, air, and sea, to enhance flexibility and resilience in logistics operations (Istanbul Metropolitan Municipality, 2020b).
DR5	Zero Emission Delivery	It focuses on utilizing environmentally friendly vehicles or methods to eliminate carbon emissions during the transportation of goods (CIVITAS, 2015).
DR6	Collaboration Tools	It enables seamless communication and coordination among stakeholders in the supply chain, promoting efficient information exchange and collaboration (Tabibian & Movahed, 2016).
DR7	Digitally Enhanced Human Resources	It involves the trained human resources of digital tools and technologies to enhance the capabilities and efficiency within logistics operations (Büyüközkan & Göçer, 2018).
DR8	Real-Time Data Collection	It involves the continuous gathering and analysis of data during logistics processes to enable immediate decision-making and optimization (Arup et al., 2015).
DR9	Advanced Safety and Emergency Systems	It aims to employ technology to enhance safety measures and provide immediate responses in emergency situations within logistics operations (POLIS, and Rupprecht Consult - Forschung & Beratung GmbH (eds), 2021).

Key practices for RUL (DRs)		Explanation
DR10	Warehouse Management Systems	It aims to optimize the storage and retrieval of goods within warehouses (POLIS, and Rupprecht Consult - Forschung & Beratung GmbH (eds), 2021).
DR11	Traffic Flow Management and Monitoring Systems	It aims to monitor and manage urban traffic flows to minimize congestion, improve transportation efficiency, and reduce delivery times (Büyükoçkan & Mukul, 2019).
DR12	Fleet Management Systems	It utilizes technology to oversee and optimize the operations of a fleet of vehicles, enhancing efficiency, safety, and maintenance (Büyükoçkan & Mukul, 2019).
DR13	Intelligent Communication Systems	It involves the use of advanced communication technologies to facilitate real-time information among logistics stakeholders (Arup et al., 2015).
DR14	Digital Risk Awareness Systems	It utilizes technology to identify, assess, and mitigate risks within logistics operations, enhancing overall resilience (Arup et al., 2015).
DR15	Urban Logistics as A Service (Ulaas)	It is a service-oriented approach that aims to enhance the efficiency, sustainability, and overall effectiveness of urban logistics operations (Istanbul Metropolitan Municipality, 2018).
DR16	On-Board Automation	It involves the development of advanced solutions in vehicles through the use of sensors and monitoring technology (Istanbul Metropolitan Municipality, 2018).
DR17	Smart Parking Spaces	It aims to optimize parking solutions, providing real-time information on available parking spots and improving overall traffic flow (Istanbul Metropolitan Municipality, 2018).

Step 6- The relationship between the CRs and DRs is established by each DM using the IVFF linguistic scale and presented in Table 6.9.

Step 7- DMs' evaluations are converted into IVFFNs and aggregated using the IVFFDWA operator to obtain the group decision. Here, we consider $\beta = 1$. The aggregated IVFF values for the relationship between CRs and DRs are presented in Table 6.10.

Step 8- Using the IVFF summation and multiplication operations, the importance of DRs (W_j^o) are determined.

Step 9- Score values of DRs and CRs are determined to obtain crisp values. Even though the IVFFSs values are used for the remaining calculations, it is more practical and easier to visualize the importance weights of DRs and CRs by defuzzifying them. The resulting normalized defuzzified values are then presented in Table 6.11 and Table 6.12.



Table 6.9: The relationship between the CRs and DRs according to DM's opinions

CR/DR	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	DR13	DR14	DR15	DR16	DR17
CR1	DM1:VH	DM1:H				DM1:VH		DM1:VH	DM1:EH		DM1:VH	DM1:VH		DM1:VVH	DM1:H	DM1:VH	DM1:F
	DM2:H	DM2:VH				DM2:H		DM2:VVH	DM2:EH		DM2:H	DM2:VH		DM2:H	DM2:H	DM2:H	DM2:VH
	DM3:VH	DM3:H				DM3:H		DM3:VH	DM3:EH		DM3:H	DM3:H		DM3:H	DM3:H	DM3:VVH	DM3:F
	DM4:H	DM4:L				DM4:L		DM4:VH	DM4:EH		DM4:EH	DM4:VH		DM4:EH	DM4:VH	DM4:VH	DM4:H
	DM5:H	DM5:VH				DM5:VL		DM5:VVH	DM5:EH		DM5:VVH	DM5:H		DM5:VVH	DM5:VVH	DM5:VH	DM5:L
CR2	DM1:EH	DM1:EH	DM1:EH	DM1:H	DM1:VVH						DM1:H	DM1:H			DM1:VH		DM1:L
	DM2:VH	DM2:EH	DM2:EH	DM2:VVH	DM2:VH						DM2:H	DM2:F			DM2:H		DM2:H
	DM3:VVH	DM3:VVH	DM3:VH	DM3:VH	DM3:VH						DM3:H	DM3:F			DM3:H		DM3:F
	DM4:VH	DM4:VVH	DM4:VVH	DM4:VH	DM4:H						DM4:VH	DM4:H			DM4:VH		DM4:F
	DM5:EH	DM5:VVH	DM5:VVH	DM5:H	DM5:H						DM5:H	DM5:H			DM5:VVH		DM5:H
CR3	DM1:VH	DM1:VH	DM1:H	DM1:H		DM1:L		DM1:F							DM1:H		DM1:H
	DM2:H	DM2:VH	DM2:H	DM2:H		DM2:VVL									DM2:H		DM2:VH
	DM3:VH	DM3:VH	DM3:VH	DM3:L		DM3:F		DM3:L							DM3:H		DM3:EH
	DM4:EH	DM4:EH	DM4:H	DM4:VH		DM4:VL		DM4:H							DM4:VVH		DM4:VH
	DM5:EH	DM5:EH	DM5:H	DM5:H		DM5:L		DM5:H							DM5:VH		DM5:VH
CR4		DM1:H		DM1:F			DM1:L	DM1:H					DM1:L	DM1:H	DM1:H		
		DM2:VVH		DM2:L			DM2:H	DM2:F					DM2:L	DM2:F	DM2:H		
		DM3:H		DM3:H			DM3:H	DM3:F					DM3:VL	DM3:H	DM3:VH		
		DM4:VH		DM4:L			DM4:H	DM4:L					DM4:L	DM4:L	DM4:VVH		
		DM5:VVH		DM5:H			DM5:VH	DM5:L					DM5:L	DM5:VH	DM5:VH		
CR5	DM1:L			DM1:H		DM1:L			DM1:F			DM1:L		DM1:VVH	DM1:VH		
	DM2:VL			DM2:H		DM2:VVL			DM2:F			DM2:H		DM2:VH	DM2:H		
	DM3:VL			DM3:VH		DM3:VL			DM3:H			DM3:L		DM3:VH	DM3:VH		
	DM4:VL			DM4:H		DM4:L			DM4:H			DM4:H		DM4:EH	DM4:VH		
	DM5:VVL			DM5:VVH		DM5:L			DM5:H			DM5:F		DM5:VVH	DM5:VVH		
CR6		DM1:VH	DM1:EH		DM1:L	DM1:VH	DM1:H	DM1:H	DM1:H		DM1:F		DM1:L	DM1:EH			
		DM2:VH	DM2:VVH		DM2:VVL	DM2:H	DM2:VH	DM2:VH	DM2:VH		DM2:F		DM2:L	DM2:VH			
		DM3:VH	DM3:VH		DM3:H	DM3:H	DM3:VH	DM3:VH	DM3:VH		DM3:H		DM3:VL	DM3:VH			
		DM4:H	DM4:H		DM4:VL	DM4:VH	DM4:VVH	DM4:VVH	DM4:H		DM4:H		DM4:VL	DM4:H			
		DM5:H	DM5:VH		DM5:VVL	DM5:H	DM5:H	DM5:VH	DM5:VVH		DM5:H		DM5:L	DM5:VVH			
CR7	DM1:H	DM1:H		DM1:H	DM1:H			DM1:H	DM1:H	DM1:H	DM1:EH	DM1:H	DM1:H	DM1:EH	DM1:EH		
	DM2:H	DM2:H		DM2:H	DM2:H			DM2:H	DM2:VVH	DM2:VH	DM2:H	DM2:VH	DM2:VH	DM2:VH	DM2:EH		
	DM3:F	DM3:F		DM3:VH	DM3:VH			DM3:VH	DM3:VH	DM3:VH	DM3:H	DM3:H	DM3:H	DM3:VH	DM3:VVH		
	DM4:H	DM4:F		DM4:VH	DM4:H			DM4:VVH	DM4:EH	DM4:VH	DM4:VH	DM4:VVH	DM4:H	DM4:EH	DM4:EH		
	DM5:F	DM5:H		DM5:H	DM5:H			DM5:VH	DM5:VH	DM5:H	DM5:VH	DM5:H	DM5:H	DM5:VVH	DM5:EH		
CR8			DM1:EH	DM1:VL	DM1:VVL		DM1:H	DM1:EH			DM1:VH			DM1:H	DM1:H		
			DM2:H	DM2:VVL	DM2:VVL		DM2:H	DM2:VH			DM2:VH			DM2:H	DM2:H		
			DM3:VH	DM3:L	DM3:L		DM3:H	DM3:VVH			DM3:EH			DM3:VH	DM3:H		
			DM4:H	DM4:H	DM4:L		DM4:H	DM4:EH			DM4:EH			DM4:EH	DM4:H		
			DM5:VVH	DM5:VVL	DM5:VVL		DM5:VH	DM5:EH			DM5:VVH			DM5:VH	DM5:VH		

CR/DR	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	DR13	DR14	DR15	DR16	DR17
CR9	DM1:L	DM1:VH	DM1:L	DM1:H	DM1:VH			DM1:F			DM1:F	DM1:F	DM1:L		DM1:VH		
	DM2:L	DM2:VH	DM2:F	DM2:F	DM2:VVH			DM2:L			DM2:L	DM2:H	DM2:F		DM2:VH		
	DM3:H	DM3:F	DM3:VL	DM3:H	DM3:VH			DM3:L			DM3:H	DM3:L	DM3:L		DM3:H		
	DM4:L	DM4:L	DM4:VL	DM4:L	DM4:EH			DM4:L			DM4:H	DM4:H	DM4:L		DM4:VVH		
	DM5:F	DM5:L	DM5:F	DM5:L	DM5:EH			DM5:H			DM5:L	DM5:L	DM5:L		DM5:VH		
CR10	DM1:L	DM1:VL	DM1:L	DM1:F	DM1:VH	DM1:H	DM1:VH	DM1:VH	DM1:VH		DM1:VVH		DM1:H		DM1:EH	DM1:VH	DM1:VH
	DM2:H	DM2:F	DM2:L	DM2:F	DM2:H	DM2:H	DM2:VH	DM2:VVH	DM2:VVH		DM2:H		DM2:H		DM2:H	DM2:H	DM2:VVH
	DM3:L	DM3:F	DM3:H	DM3:L	DM3:H	DM3:VH	DM3:EH	DM3:VH	DM3:VH		DM3:H		DM3:H		DM3:H	DM3:H	DM3:VH
	DM4:L	DM4:L	DM4:F	DM4:F	DM4:H	DM4:VH	DM4:VVH	DM4:VH	DM4:VH		DM4:H		DM4:H		DM4:VVH	DM4:VH	DM4:VH
	DM5:H	DM5:L	DM5:L	DM5:L	DM5:VH	DM5:VVH	DM5:VVH	DM5:VVH	DM5:VH		DM5:VH		DM5:VH		DM5:VVH	DM5:VVH	DM5:VVH
CR11			DM1:F	DM1:F		DM1:H		DM1:H	DM1:H		DM1:H	DM1:L	DM1:H	DM1:VVH	DM1:VVH	DM1:VVH	DM1:F
			DM2:L	DM2:H		DM2:VH		DM2:H	DM2:H		DM2:L	DM2:VL	DM2:F	DM2:H	DM2:VH	DM2:VH	DM2:F
			DM3:H	DM3:H		DM3:H		DM3:VH	DM3:F		DM3:L	DM3:L	DM3:L	DM3:H	DM3:H	DM3:VH	DM3:L
			DM4:H	DM4:H		DM4:H		DM4:H	DM4:H		DM4:VL	DM4:L	DM4:H	DM4:H	DM4:H	DM4:H	DM4:VL
			DM5:VH	DM5:VL		DM5:H		DM5:VH	DM5:H		DM5:F	DM5:L	DM5:F	DM5:VVH	DM5:H	DM5:H	DM5:VL
CR12	DM1:H	DM1:VH	DM1:H			DM1:H		DM1:VH			DM1:VH			DM1:VVH	DM1:VH		
	DM2:H	DM2:VH	DM2:H			DM2:VH		DM2:H			DM2:VH			DM2:H	DM2:H		
	DM3:VH	DM3:H	DM3:VVH			DM3:H		DM3:H			DM3:H			DM3:H	DM3:H		
	DM4:EH	DM4:EH	DM4:VH			DM4:H		DM4:H			DM4:VH			DM4:EH	DM4:VVH		
	DM5:EH	DM5:H	DM5:EH			DM5:H		DM5:VVH			DM5:VVH			DM5:EH	DM5:EH		
CR13						DM1:F		DM1:H			DM1:VVH	DM1:VH	DM1:H	DM1:L	DM1:H		
						DM2:H		DM2:H			DM2:VH	DM2:VH	DM2:F	DM2:F	DM2:F		
						DM3:F		DM3:VH			DM3:VH	DM3:VH	DM3:L	DM3:VL	DM3:L		
						DM4:L		DM4:VVH			DM4:VH	DM4:F	DM4:H	DM4:VL	DM4:VL		
						DM5:H		DM5:VH			DM5:EH	DM5:VVH	DM5:H	DM5:F	DM5:F		
CR14	DM1:VVH	DM1:H			DM1:L	DM1:VVH									DM1:VH		
	DM2:H	DM2:H			DM2:F	DM2:EH									DM2:H		
	DM3:H	DM3:H			DM3:L	DM3:VVH									DM3:H		
	DM4:VH	DM4:VH			DM4:H	DM4:EH									DM4:VH		
	DM5:VVH	DM5:VVH			DM5:F	DM5:EH									DM5:VVH		
CR15								DM1:VH	DM1:VH		DM1:H			DM1:H			
								DM2:VVH	DM2:VVH		DM2:H			DM2:EH			
								DM3:VH	DM3:H		DM3:VH			DM3:VVH			
								DM4:VVH	DM4:VVH		DM4:VH			DM4:EH			
								DM5:F	DM5:H		DM5:H			DM5:EH			
CR16		DM1:L					DM1:H										
		DM2:H					DM2:H										
		DM3:L					DM3:H										
		DM4:F					DM4:H										
		DM5:H					DM5:EH										
CR17								DM1:VH	DM1:H		DM1:VVH			DM1:H	DM1:H		
								DM2:H	DM2:H		DM2:VH			DM2:VH	DM2:L		
								DM3:VH	DM3:VH		DM3:VH			DM3:H	DM3:H		
								DM4:H	DM4:VVH		DM4:VVH			DM4:VVH	DM4:L		
								DM5:VH	DM5:EH		DM5:H			DM5:H	DM5:H		

Table 6.10: The aggregated relationship between the CRs and DRs

CR/DR	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	DR13	DR14	DR15	DR16	DR17
CR1	0.646,0.7 30,0.310, 0.369	0.621,0.711, 0.428,0.481				0.562,0.651, 0.552,0.643		0.749,0.856, 0.175,0.271	0.950,0. 000,0.00 0,0.000		0.866,0.7 92,0.247, 0.303	0.669,0.762, 0.279,0.346		0.873,0.8 33,0.238, 0.286	0.698,0.8 04,0.293, 0.350	0.712,0.8 16,0.231, 0.310	0.556,0.621, 0.487,0.520
CR2	0.913,0.7 63,0.148, 0.227	0.907,0.855, 0.085,0.170	0.905,0.8 37,0.118, 0.199	0.688,0.791, 0.287,0.348	0.702,0.8 08,0.285, 0.343						0.630,0.7 04,0.327, 0.382	0.576,0.618, 0.410,0.436			0.714,0.8 21,0.257, 0.324		0.526,0.562, 0.493,0.525
CR3	0.910,0.6 80,0.213, 0.273	0.911,0.710, 0.162,0.244	0.620,0.6 86,0.336, 0.389	0.613,0.690, 0.404,0.456		0.349,0.386, 0.669,0.771		0.531,0.573, 0.493,0.532							0.698,0.8 04,0.293, 0.350		0.836,0.809, 0.239,0.303
CR4		0.728,0.837, 0.267,0.326		0.513,0.554, 0.513,0.554			0.602,0.6 82,0.436, 0.488	0.484,0.520, 0.536,0.576					0.336,0.389, 0.620,0.686	0.591,0.6 69,0.456, 0.500	0.708,0.8 15,0.272, 0.334		
CR5	0.246,0.3 16,0.718, 0.825			0.691,0.796, 0.305,0.358	0.218,0.2 51,0.393, 0.434	0.280,0.330, 0.643,0.750			0.568,0. 607,0.42 4,0.445			0.513,0.554, 0.513,0.554		0.876,0.8 49,0.142, 0.228	0.723,0.8 30,0.227, 0.305		
CR6		0.661,0.751, 0.291,0.355	0.865,0.7 78,0.238, 0.300		0.370,0.4 23,0.720, 0.833	0.655,0.743, 0.299,0.361	0.702,0.8 08,0.285, 0.343	0.718,0.825, 0.246,0.316	0.702,0. 808,0.28 5,0.343		0.568,0.6 07,0.424, 0.445		0.310,0.369, 0.646,0.730	0.867,0.7 98,0.235, 0.294			
CR7	0.568,0.6 07,0.424, 0.445	0.568,0.607, 0.424,0.445		0.646,0.730, 0.310,0.369	0.620,0.6 86,0.336, 0.389			0.708,0.815, 0.272,0.334	0.865,0. 778,0.23 8,0.300	0.661,0.751, 0.291,0.355	0.859,0.7 22,0.256, 0.318	0.691,0.796, 0.305,0.358	0.620,0.686, 0.336,0.389	0.914,0.7 86,0.138, 0.216	0.944,0.6 58,0.053, 0.106		
CR8			0.865,0.7 84,0.263, 0.315	0.409,0.461, 0.715,0.831	0.259,0.3 11,0.755, 0.863		0.630,0.7 04,0.327, 0.382	0.933,0.512, 0.106,0.160			0.902,0.7 98,0.149, 0.231			0.858,0.7 07,0.271, 0.329	0.630,0.7 04,0.327, 0.382		
CR9	0.452,0.4 88,0.558, 0.601	0.580,0.679, 0.511,0.557	0.400,0.4 22,0.623, 0.707	0.505,0.549, 0.524,0.568	0.913,0.7 63,0.148, 0.227			0.477,0.515, 0.543,0.585			0.513,0.5 54,0.513, 0.554	0.513,0.554, 0.513,0.554	0.383,0.419, 0.588,0.635		0.723,0.8 30,0.227, 0.305		
CR10	0.490,0.5 40,0.540, 0.591	0.394,0.421, 0.610,0.683	0.452,0.4 88,0.558, 0.601	0.457,0.468, 0.545,0.574	0.655,0.7 43,0.299, 0.361	0.689,0.805, 0.214,0.281	0.849,0.8 55,0.152, 0.242	0.732,0.845, 0.161,0.251	0.721,0. 826,0.19 1,0.289		0.698,0.8 04,0.293, 0.350		0.596,0.676, 0.293,0.345	0.873,0.8 33,0.238, 0.286	0.714,0.8 21,0.257, 0.324	0.749,0.856, 0.175,0.271	
CR11			0.596,0.6 72,0.440, 0.478	0.536,0.579, 0.534,0.622		0.620,0.686, 0.336,0.389		0.646,0.730, 0.310,0.369	0.588,0. 635,0.38 3,0.419		0.467,0.5 06,0.584, 0.662	0.336,0.389, 0.620,0.686	0.543,0.580, 0.471,0.500	0.730,0.8 41,0.287, 0.338	0.691,0.7 96,0.305, 0.358	0.702,0.8 08,0.285, 0.343	0.394,0.416, 0.633,0.722
CR12	0.909,0.6 14,0.262, 0.309	0.858,0.707, 0.271,0.329	0.863,0.7 61,0.266, 0.320			0.620,0.686, 0.336,0.389		0.698,0.804, 0.293,0.350			0.723,0.8 30,0.227, 0.305			0.912,0.7 53,0.237, 0.279	0.866,0.7 92,0.247, 0.303		
CR13						0.526,0.562, 0.493,0.525		0.692,0.799, 0.339,0.375			0.870,0.8 16,0.165, 0.254	0.710,0.819, 0.332,0.363	0.566,0.612, 0.441,0.481	0.400,0.4 22,0.623, 0.707	0.484,0.5 17,0.571, 0.648		
CR14	0.743,0.8 52,0.249, 0.309	0.698,0.804, 0.293,0.350			0.493,0.5 25,0.526, 0.562	0.930,0.798, 0.073,0.145									0.714,0.8 21,0.257, 0.324		
CR15								0.730,0.841, 0.329,0.356	0.728,0. 837,0.26 7,0.326		0.646,0.7 30,0.310, 0.369			0.927,0.6 89,0.219, 0.257			
CR16		0.513,0.554, 0.513,0.554					0.852,0.6 08,0.321, 0.368										
CR17								0.669,0.762, 0.279,0.346	0.865,0. 784,0.26 3,0.315		0.746,0.8 55,0.236, 0.301			0.691,0.7 96,0.305, 0.358	0.540,0.5 91,0.490, 0.540		

Table 6.11: Importance weights of CRs

	CRs	Weights of CRs	Rank
CR1	Safety and Security	0.0637	2
CR2	Efficiency	0.0588	10
CR3	Flexibility	0.0609	4
CR4	Adaptability	0.0626	3
CR5	Redundancy	0.0568	13
CR6	Recovery Capability	0.0606	6
CR7	Robustness	0.0649	1
CR8	Predictive Ability	0.0579	11
CR9	Sustainability	0.0573	12
CR10	Innovation	0.0549	15
CR11	Reliability	0.0605	7
CR12	Agility	0.0606	5
CR13	Visibility	0.0538	16
CR14	Collaboration	0.0525	17
CR15	Risk Awareness	0.0588	9
CR16	Resourcefulness	0.0563	14
CR17	Responsiveness	0.0589	8

According to the results, the most crucial requirement for RUL in Istanbul is “Robustness.” This is especially important for ensuring RUL since urban environments are complex and unpredictable. A logistics system's ability to adapt to various challenges, uncertainties, and disruptions is key to ensuring continuous functionality. With factors like traffic congestion, sudden road closures, adverse weather conditions, and other unforeseen events, a robust logistics system ensures that the system can adjust to these dynamic conditions.

The significance of robustness lies in minimizing downtime, allocating resources optimally, improving customer service, and absorbing shocks, all of which are critical in urban logistics where last-mile deliveries and timely services significantly impact customer satisfaction. A robust logistics system also allows compliance with urban

regulations, ensuring that logistics operations align with specific city restrictions and legal requirements.

Table 6.12: Importance weights of DRs for the first stage

	DRs	Weights of DRs	Rank
DR1	Small-Scale Logistics Solutions	0.0543	8
DR2	Hybrid Logistics	0.0632	5
DR3	Dynamic Route Optimization	0.0544	7
DR4	Diversification of Transportation Modes	0.0482	10
DR5	Zero Emission Delivery	0.0475	12
DR6	Collaboration Tools	0.0484	9
DR7	Digitally Enhanced Human Resources	0.0477	11
DR8	Real-Time Data Collection	0.0731	4
DR9	Advanced Safety and Emergency Systems	0.0586	6
DR10	Warehouse Management Systems	0.0460	17
DR11	Traffic Flow Management and Monitoring Systems	0.0763	3
DR12	Fleet Management Systems	0.0473	13
DR13	Intelligent Communication Systems	0.0462	16
DR14	Digital Risk Awareness Systems	0.0998	1
DR15	Urban Logistics as A Service (Ulaas)	0.0956	2
DR16	On-Board Automation	0.0466	15
DR17	Smart Parking Spaces	0.0467	14

After evaluating the CRs, the key practices for RUL as DRs that would meet these requirements were evaluated, and “Digital Risk Awareness Systems” was found to be the most important DR. The effectiveness of Digital Risk Awareness Systems is intrinsically linked to the robustness of RUL. These systems play a crucial role in identifying, assessing, and mitigating potential risks, thereby fortifying RUL operations against uncertainties and disruptions. The robustness of RUL is dependent on the effectiveness of these systems. By leveraging digital risk awareness systems, RUL can proactively identify possible disruptions, assess their potential impact, and take appropriate steps to mitigate risks. This enables RUL to maintain continuous functionality and adaptability in the face of complex and unpredictable urban environments.

As the QFD iteration continues, the weights assigned to DRs at the first stage will be utilized as the weights for CRs in second stage of QFD.

6.2.2. Second Stage of the IVFF-QFD Process

In this section, the technological requirements to meet the DRs of the first stage are evaluated. By benefiting from literature reviews and expert opinions, the DRs² are defined as follows:

Table 6.13: DRs and their explanation for QFD-Second Stage

Technologic solutions for RUL (DRs ²)	Explanation
DR ₁ ² Internet of Things	It enhances RUL by enabling real-time tracking and monitoring of goods and vehicles, optimizing supply chain visibility and responsiveness (Büyüközkan & Ilıcak, 2022).
DR ₂ ² Autonomous Vehicles	Uses advanced technologies such as radar, GPS, sensors, and cameras to detect objects in their surroundings. This enables them to operate without the need for a driver by utilizing real-time data (Büyüközkan & Ilıcak, 2022).
DR ₃ ² Digital Twins	It contributes to RUL by creating virtual replicas of physical logistics systems, allowing for predictive modeling, real-time monitoring, and efficient decision-making (T.C. Ulaştırma ve Altyapı Bakanlığı, 2020).
DR ₄ ² Immersive Interfaces (AR, VR)	It improves RUL by enhancing situational awareness and training. With these technologies, new in-car interfaces can be created that allow information to be displayed to the driver without distraction. It can also lead to the emergence of new generation virtual reality simulations for modeling driver behavior (T.C. Ulaştırma ve Altyapı Bakanlığı, 2020).
DR ₅ ² Unmanned Aerial Vehicles	It plays a role in RUL by providing swift and flexible last-mile delivery options, particularly in congested or hard-to-reach urban areas (Büyüközkan & Ilıcak, 2022).
DR ₆ ² Cloud Computing	It supports RUL by facilitating data storage, processing, and sharing, enabling real-time collaboration and scalability of logistics operations (Büyüközkan & Ilıcak, 2022).
DR ₇ ² 3-D Printing	It enhances RUL by enabling localized and on-demand production, reducing the reliance on centralized supply chains for certain goods (Büyüközkan & Ilıcak, 2022).

Technologic solutions for RUL (DRs ²)		Explanation
DR ₈ ²	Fifth Party Logistics (5PL)	It contributes to RUL by offering comprehensive end-to-end supply chain management solutions, integrating multiple logistics services seamlessly (Istanbul Metropolitan Municipality, 2020b).
DR ₉ ²	Big Data	RUL leverages big data analytics to gain insights into demand patterns, optimize routes, and enhance overall decision-making for more adaptive and efficient operations (Büyükoğkan & Ilıcak, 2022).
DR ₁₀ ²	Artificial Intelligence	AI enhances RUL by automating processes, predicting disruptions, and optimizing resource allocation, contributing to agile and responsive supply chains (Büyükoğkan & Ilıcak, 2022).
DR ₁₁ ²	Blockchain	Blockchain technology ensures RUL through secure, transparent, and traceable transactions, reducing fraud, enhancing trust, and optimizing supply chain processes (Büyükoğkan & Ilıcak, 2022).
DR ₁₂ ²	Physical Internet	It contributes to RUL by optimizing the movement of goods through a standardized and interconnected logistics system (Büyükoğkan & Ilıcak, 2022).
DR ₁₃ ²	Mobile Technologies	It provides real-time communication, tracking, and data access, enabling efficient coordination among stakeholders (Büyükoğkan & Ilıcak, 2022).
DR ₁₄ ²	RFID / Sensor Technology	It enables accurate and real-time tracking of inventory, improving visibility and reducing errors in the supply chain (Büyükoğkan & Ilıcak, 2022).
DR ₁₅ ²	Electric Vehicles/Cargo Bikes	It offers sustainable and flexible transportation options, reducing environmental impact and congestion (Büyükoğkan & Ilıcak, 2022).
DR ₁₆ ²	Driver Assistance Systems	It enhances safety, optimize route planning, and improve overall efficiency in goods transportation (Schau et al., 2015).
DR ₁₇ ²	Robotics	It automates tasks such as sorting, packing, and last-mile delivery, enhancing operational efficiency and adaptability (Brunner et al., 2018).

The computations outlined in Steps 6 through 9 in Section 6.1 were carried out during the second stage of the QFD process. In this stage, the weights of DRs that were determined during the first stage were used as CR² weights. The weights of DR²s were then obtained by creating a relationship matrix between CR² and DR². Following the defuzzification

and normalization procedures, the importance levels and rankings of DR²s were determined, and the results are presented in Table 6.14.

Table 6.14: Importance weights of DR2s for the second stage

	DR ² s	Weights of DR ² s	Rank
DR ₁ ²	Internet of Things	0.0833	1
DR ₂ ²	Autonomous Vehicles	0.0538	8
DR ₃ ²	Digital Twins	0.0655	4
DR ₄ ²	Immersive Interfaces (AR, VR)	0.0528	16
DR ₅ ²	Unmanned Aerial Vehicles	0.0528	12
DR ₆ ²	Cloud Computing	0.0649	5
DR ₇ ²	3-D Printing	0.0528	17
DR ₈ ²	Fifth Party Logistics (5PL)	0.0528	15
DR ₉ ²	Big Data	0.0759	2
DR ₁₀ ²	Artificial Intelligence	0.0676	3
DR ₁₁ ²	Blockchain	0.0590	6
DR ₁₂ ²	Physical Internet	0.0529	11
DR ₁₃ ²	Mobile Technologies	0.0528	13
DR ₁₄ ²	RFID / Sensor Technology	0.0544	7
DR ₁₅ ²	Electric Vehicles/Cargo Bikes	0.0532	9
DR ₁₆ ²	Driver Assistance Systems	0.0531	10
DR ₁₇ ²	Robotics	0.0528	14

In the second stage of QFD, the DRs in the first stage were considered as CRs, and the technological solutions to meet these CRs were presented as DR². The results showed that the most important technological solution is IoT technology. IoT provides real-time monitoring, dynamic route optimization, and predictive maintenance, enabling logistics operators to make informed decisions and adapt to changing conditions. This technology ensures efficient last-mile logistics, enhances end-to-end visibility, and fortifies the resilience of urban logistics and digital risk awareness systems. IoT devices enable continuous monitoring, immediate responses to disruptions, predictive maintenance, and enhanced transparency throughout the supply chain, contributing to the robustness of logistics operations in dynamic urban environments.

6.3. Sensitivity Analysis

Sensitivity analysis is crucial in a QFD as it can assess the impact of customer requirements on design parameters, and guides decision-making in optimizing resources and design. By systematically varying input factors, sensitivity analysis helps prioritize efforts, and continuously improve the product or service design.

To determine the impact of customers' feedback on the design requirements needed for RUL, a sensitivity analysis was conducted in this study. The analysis involved changing the CRs in the first stage, resulting in the creation of 18 different scenarios, while keeping all other variables constant. The weight of the remaining sixteen CRs was fixed at 'EL' from the first to the seventeenth scenario, and the corresponding scenario was assigned to the 'EH' decision. In the eighteenth scenario, all variables were assigned to the EH decision, and the results were evaluated equally. The ranking results are presented in Figure 6.3. It was observed that any change in the voice of customers affected the "how" aspect of the requirements. Although the ranking changes were more significant for the middle-ranked DRs, the rankings of the most important and least important values were less affected than those of the middle-ranked values. The sensitivity analysis was also conducted for the second stage, and the results are presented in Figure 6.4. It was observed that the values remained constant after the first three scenarios, but there were significant changes in all values. This finding highlights the critical influence of customers' feedback when prioritizing RUL requirements.

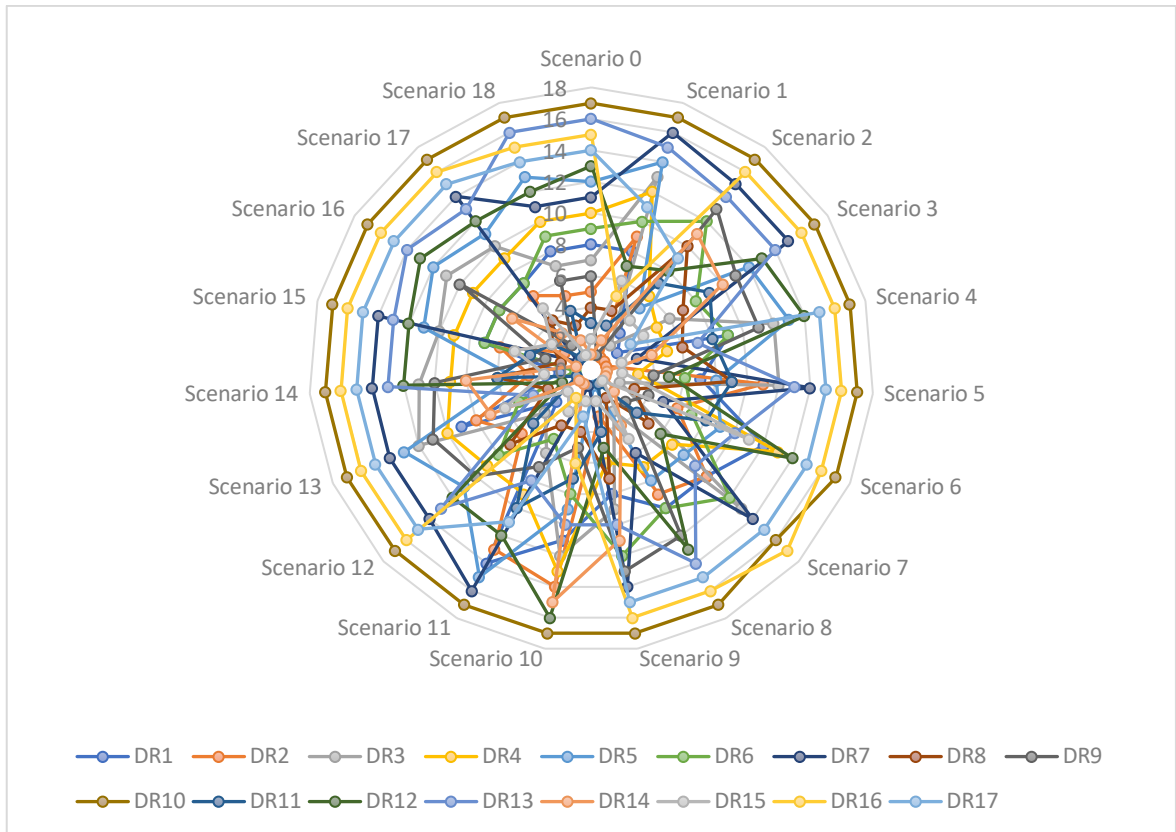


Figure 6.3: Changes in the ranks of DRs with respect to CRs for the first stage

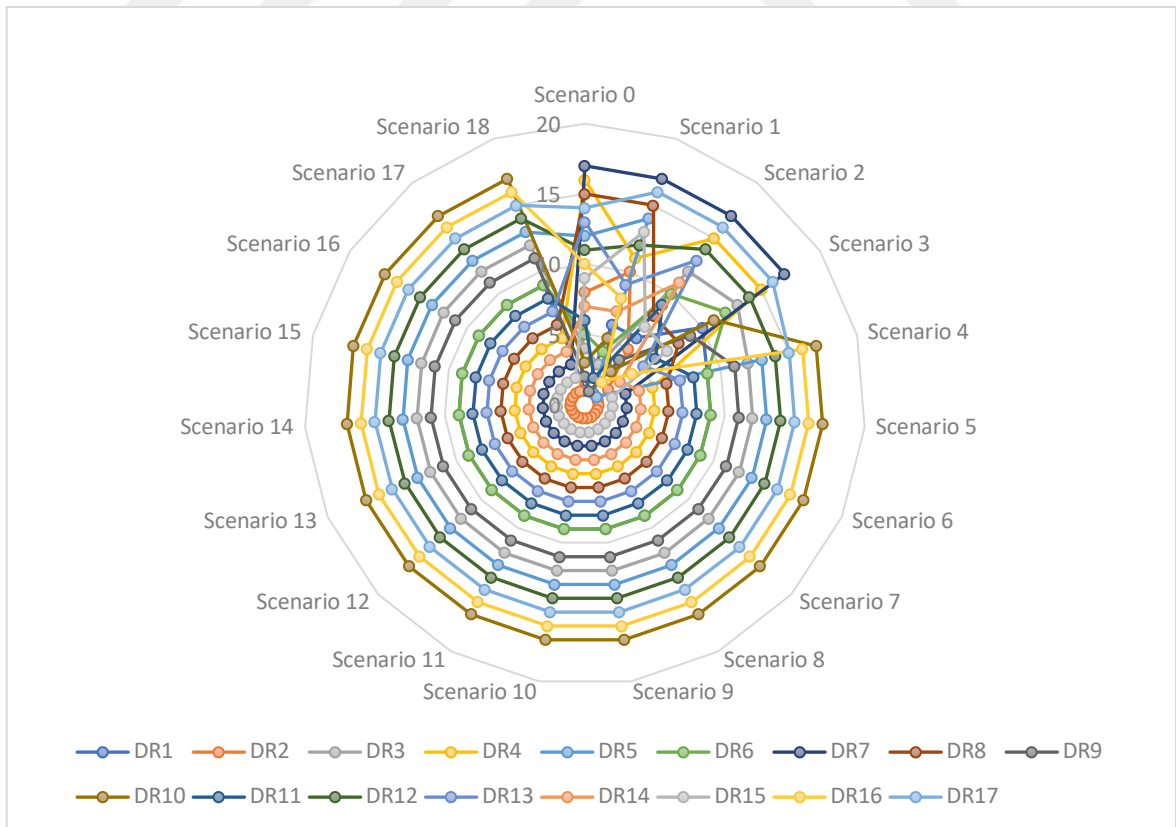


Figure 6.4: Changes in the ranks of DRs with respect to CRs for the second stage

6.4. Concluding Remarks on RUL Technological Infrastructure Design

As cities continue to develop and face unexpected events and disasters, it has become increasingly clear that resilience is crucial. RUL is a key concept for building resilient cities, but it requires successful implementation to be effective. To achieve this, RUL's technological infrastructure must be planned meticulously, and innovative technologies must be integrated into RUL processes. This technological planning is a critical element in future-proofing cities' logistics infrastructures, reducing environmental impacts, and making urban trade more sustainable. Among many different methodologies, QFD stands out as the best choice. It can analytically prioritize technological requirements to plan the technological infrastructure of RUL and provides a framework with unique features to address the complex nature of RUL.

The results of the study showed that the most important resilience requirement is Robustness, the most important key practice is Digital Risk Awareness Systems, and the most important technology is IoT. Having a robust system that can withstand and recover from disruptions is crucial for ensuring the stability and continuity of urban logistics operations. Digital risk awareness systems play a critical role in proactively identifying and mitigating potential risks, which ultimately increases the adaptability and responsiveness of the entire system. The integration of IoT technology further enhances this synergy by providing real-time data from various sources, which allows for a comprehensive understanding of the urban logistics environment. By combining robustness, digital risk awareness systems, and IoT technology in technological planning, we can strengthen the resilience of urban logistics, and create a foundation for adaptable, data-driven, and secure logistics operations that can cope with evolving challenges and uncertainties.

7. RUL TECHNOLOGY PROVIDER SELECTION

The preceding section underscored the pivotal role of IoT technology as the most significant technology for RUL. Contemporary logistics systems, characterized by intricate operations, a rapid work pace, and substantial workload, particularly thrive in complex working environments. The concept of RUL has gained paramount importance worldwide, particularly in the aftermath of the limitations and challenges posed by the COVID-19 pandemic. As a digital technology, IoT plays a pivotal role in mitigating density issues and ensuring efficiency in urban logistics systems. Systems integrated with IoT technology offer real-time visibility and data-based information, leading to cost reduction, heightened customer satisfaction, increased market share, and energy consumption reduction. Within the realm of urban logistics, IoT technology facilitates the effective utilization of truck parking areas, autonomous vehicles, vehicle location detection, traffic flow monitoring, transportation management, real-time monitoring of vehicle, load, and driver statuses, warehouse management, accident reduction, and optimization of the transfer and distribution process, etc. Integrating IoT technology in these areas significantly contributes to the resilience of urban logistics processes.

This section aims to assess the selection of IoT technology providers within the context of urban logistics for the province of Istanbul. The problem is approached using the GDM methodology, and the results are derived from evaluations employing the IVFF-AHP and IVFF-VIKOR methodologies. The following RQs guide this endeavor.

RQ1: What specific criteria and sub-criteria were considered to evaluate and rank IoT service providers in the context of RUL?

RQ2: How can MCDM methods be effectively applied to select the most suitable technology provider for IoT in RUL?

RQ3: What insights and recommendations can be derived in the selection of IoT service providers for RUL?

7.1. Proposed IVFF-MCDM Methodology

In this section, the computational steps of the IVFF-AHP and IVFF-VIKOR methods given in Sections 4.1.1 and 4.1.2 in Chapter 4 are applied for the evaluation of IoT technological provider selection. The flowchart of the proposed methodology is illustrated in Figure 7.1.

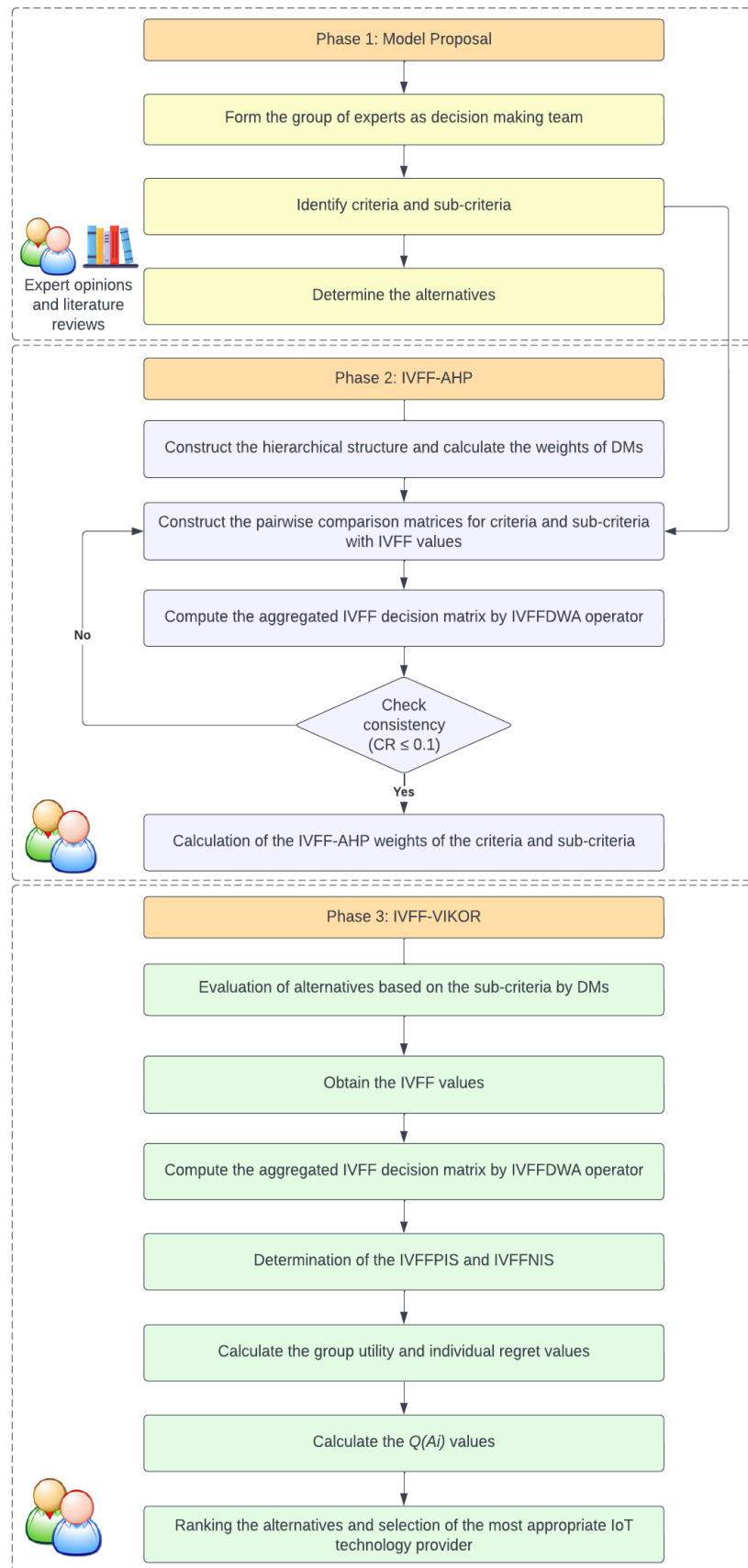


Figure 7.1: The flowchart of the proposed methodology

7.2. Application of the Proposed Methodology

In identifying the most suitable IoT technology providers, it is imperative to first establish the most impactful selection criteria. This section endeavors to delineate the criteria for selecting IoT technology providers by garnering insights from experts employed by IMM, Istanbul IT and Smart City Technologies Inc. (ISBAK), and Istanbul Electronic Telecommunication and Infrastructure Inc. (ISTTELKOM).

Step 1. A group of experts is formed, and the characteristics of the experts are detailed in Table 7.1.

Table 7.1: The characteristics of the DMs

DMs	Institution	Profession	Education	Experience
DM1	ISBAK	Smart City Specialist	Master's degree	5 years
DM2	ISBAK	Consultant	PhD Candidate	>5 years
DM3	ISBAK	Engineer	Bachelor's degree	>5 years
DM4	ISBAK	Engineer	Master's degree	>5 years
DM5	ISTTELKOM	Engineer	Bachelor's degree	3 years

Step 2. With the help of literature review and expert opinions, criteria and alternatives were determined. First, a total of 5 main criteria, 23 sub-criteria and 8 alternatives have been identified and described below. Here, criteria and sub-criteria are assumed to be independent of each other. The hierarchical structure of the problem given in Figure 7.2.

C1: Data Management

C11: Data Processing and Sharing: The IoT provider's capability to efficiently process and share data, ensuring seamless communication and integration within the IoT ecosystem (De Nardis et al., 2022), (Experts view).

C12: Data Visualization: Translating complex datasets into visual representations, such as charts or graphs, to facilitate a more intuitive and comprehensive understanding of patterns, trends, and insights (De Nardis et al., 2022), (Experts view).

C13: Reporting and Dashboards: Providing organized and accessible summaries of key data metrics and performance indicators, often presented through dashboards, to support informed decision-making and monitoring (Medyk, 2017), (Experts view).

C14: Backup Solutions: Implementing strategies and technologies to create duplicate copies of data, safeguarding against loss or corruption, and ensuring data resilience and continuity in the event of unforeseen incidents (S. V. Kumar, 2018).

C2: Cost

C21: Acquisition Cost: This criterion evaluates the initial expenses associated with obtaining and implementing an IoT solution, considering upfront costs such as hardware, software, and licensing fees (Y. Ali & Khan, 2023).

C22: Transition Cost: It assesses the expenses related to the migration or integration of the IoT solution into existing systems, encompassing factors like data transfer, training, and potential disruptions during the implementation process (Medyk, 2017).

C23: Storage Cost: This criterion focuses on the ongoing expenses associated with data storage within the IoT ecosystem, considering the costs related to storage, server maintenance, and scalability as data volumes increase over time (Medyk, 2017).

C24: Maintenance Cost: It evaluates the ongoing expenses required to keep the IoT infrastructure operational, covering aspects such as software updates, hardware maintenance, and troubleshooting, ensuring sustained performance and reliability (Y. Ali & Khan, 2023).

C3: Security

C31: Security Auditability and Access Control: Ensuring the ability to audit and control access to IoT devices and systems, providing transparency and accountability in security measures (Y. Ali & Khan, 2023).

C32: Device Authentication: Verifying the identity of IoT devices to prevent unauthorized access, enhancing the overall security and integrity of the network (Y. Ali & Khan, 2023).

C33: Privacy and Security Standards: Adherence to established standards to safeguard user privacy and maintain robust security practices, ensuring compliance with industry and regulatory guidelines (Medyk, 2017).

C34: Real-Time Detection and Alerting: Capability to promptly detect anomalies or security threats in real-time and provide immediate alerts, facilitating rapid response and mitigation (Y. Ding et al., 2020).

C35: Data Encryption: Implementing strong encryption methods to secure data during transmission and storage, safeguarding sensitive information from unauthorized access or interception (Medyk, 2017).

C4: Platform Capability

C41: Scalability: The ability of the IoT provider to seamlessly expand its services and accommodate the growing volume of connected devices within a network (Y. Ali & Khan, 2023; Medyk, 2017), (Experts view).

C42: Ease of Integration and Deployment: The simplicity and efficiency with which the IoT solutions can be integrated into existing systems and deployed, minimizing disruptions and optimizing implementation (Y. Ali & Khan, 2023), (Experts view).

C43: Protocol Support: The extent to which the IoT provider supports various communication protocols, ensuring compatibility and efficient data exchange across diverse devices and networks (Y. Ali & Khan, 2023), (Experts view).

C44: Usability: The user-friendliness and accessibility of the IoT platform, enabling straightforward navigation, configuration, and management for end-users (Ahmed et al., 2018).

C45: Interoperability (Device Compatibility): The degree to which the IoT provider's devices and systems can seamlessly operate and exchange information with other devices and platforms, ensuring a cohesive and interconnected IoT ecosystem (Y. Ali & Khan, 2023), (Experts view).

C5: Vendor Support & Services

C51: Reputation and Previous Alliance Experiences: Assessing the track record and partnerships of IoT providers to gauge their reliability and performance based on past experiences and industry reputation (Medyk, 2017), (Experts view).

C52: Quality of Technical Support: Evaluating the effectiveness and responsiveness of technical support services provided by IoT vendors to ensure prompt issue resolution and optimal system performance (S. V. Kumar, 2018).

C53: Innovation and R&D Investment: Considering the commitment of IoT providers to innovation and research and development, as it reflects their ability to offer cutting-edge solutions and adapt to emerging technologies (T.C. Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2020).

C54: Timeliness of Vendor Response: Gauging the speed and efficiency with which IoT vendors respond to inquiries or issues, ensuring a timely and effective communication channel for addressing concerns (Ahmed et al., 2018; Medyk, 2017).

C55: Quality of Peer User Community: Examining the strength and engagement of the user community associated with a particular IoT provider, indicating the level of collaboration, shared knowledge, and user satisfaction within the community (Medyk, 2017).

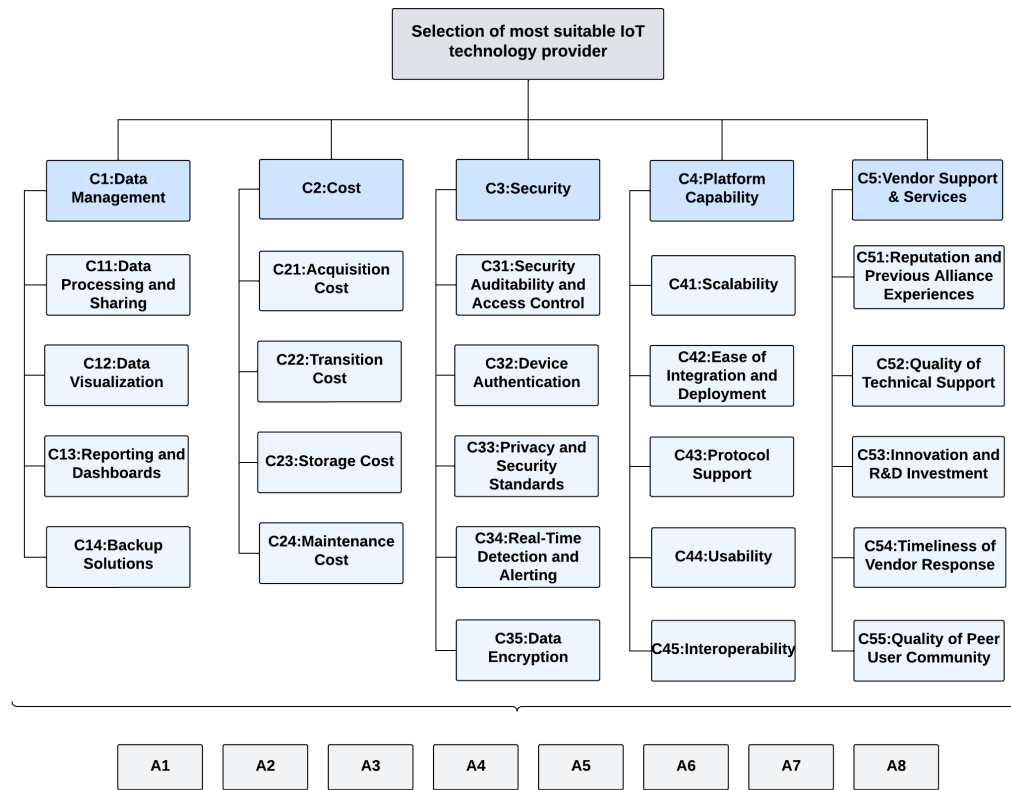


Figure 7.2: The hierarchical model of the IoT technology provider selection

The characteristics of the alternatives are described below:

A1: Founded in 2010. A comprehensive IoT platform, particularly suitable for large-scale smart city projects. Facilitates the connection and management of IoT devices and provides various features for robust IoT solutions. Offers both cloud-based and on-premises deployment options.

A2: Established in 2012. Used in manufacturing, energy, and logistics industries and provides robust IoT solutions, including applications for smart cities. Offers data analytics and business intelligence solutions. Offers both cloud-based and on-premises deployment options.

A3: Established in 2012. Facilitates communication among IoT devices, integrable into various applications for smart cities and have solutions to optimize logistics processes in smart cities. Provides a scalable and secure platform for IoT solutions. Offers both cloud-based and on-premises deployment options.

A4: Established in 2013. Offers customizable solutions for industrial IoT applications. Enables real-time monitoring and optimization of industrial processes and have solutions to optimize logistics processes in smart cities. Offers both cloud-based and on-premises deployment options.

A5: Established in 2013. An industrial IoT platform suitable for smart city applications and enables connection, management, and analysis of IoT devices. Offers both cloud-based and on-premises deployment models.

A6: Established in 2013. Provides artificial intelligence and cognitive computing solutions. Offers a wide range of applications, including healthcare, finance, and manufacturing and utilizes big data analytics and machine learning capabilities. Offers both cloud-based and on-premises deployment options.

A7: Founded in 2016. Integrates industrial IoT, artificial intelligence, and data analytics solutions. Versatile platform suitable for extensive smart city initiatives and supports big data analysis and applications in IoT and energy management. Offers both cloud-based and on-premises deployment options.

A8: Established in 2018. A platform for industrial data collection and analysis. Used in energy management and smart facility management, offering solutions for smart cities and provides comprehensive data infrastructure solutions. Offers both cloud-based and on-premises deployment options.

Step 3. The linguistic terms provided in Table 7.2 were used to determine the importance weights of the five DMs using Equation (4.1.1.1). Table 7.2 presents the resulting importance weights based on the assigned linguistic terms.

Table 7.2: The importance weights of DMs

DMs	Ratings	IVFFNs	Importance weights
DM1	ES	$([0.75, 0.85], [0.05, 0.15])$	$0.235 (w_1)$
DM2	ES	$([0.75, 0.85], [0.05, 0.15])$	$0.235 (w_2)$
DM3	VS	$([0.65, 0.75], [0.15, 0.25])$	$0.148 (w_3)$
DM4	ES	$([0.75, 0.85], [0.05, 0.15])$	$0.235 (w_4)$
DM5	VS	$([0.65, 0.75], [0.15, 0.25])$	$0.148 (w_5)$

Step 4. DMs judgments are obtained through the linguistic scale presented in Table 4.2 in Chapter 4 based on pairwise comparisons. Firstly, DMs evaluated the main criteria, and after that, sub-criteria evaluated by each DM. Due to page limitations, only the evaluations of the main criteria are provided by using IVFFNs are presented in Table 7.3.

Table 7.3: Pairwise comparison matrices for criteria

Criteria	DM1				
	C1	C2	C3	C4	C5
C1	EI	EI	EI	LI	SMI
C2	EI	EI	EI	EI	HI
C3	EI	EI	EI	EI	HI
C4	HI	EI	EI	EI	HI
C5	SLI	LI	LI	LI	EI
	DM2				
	C1	C2	C3	C4	C5
C1	EI	SLI	HI	SLI	EI
C2	SMI	EI	SMI	EI	SMI
C3	LI	SLI	EI	LI	SLI
C4	SMI	EI	HI	EI	SMI
C5	EI	SLI	SMI	SLI	EI
	DM3				
	C1	C2	C3	C4	C5
C1	EI	SLI	SLI	SLI	SLI
C2	SMI	EI	SLI	SLI	SLI
C3	SMI	SMI	EI	SLI	EI
C4	SMI	SMI	SMI	EI	SMI
C5	SMI	SMI	EI	SLI	EI
	DM4				
	C1	C2	C3	C4	C5
C1	EI	HI	HI	LI	SMI
C2	LI	EI	EI	LI	LI
C3	LI	EI	EI	VLI	SLI
C4	HI	HI	VHI	EI	SMI
C5	SLI	HI	SMI	SLI	EI
	DM5				
	C1	C2	C3	C4	C5
C1	EI	HI	SMI	VHI	SMI
C2	LI	EI	LI	EI	LI
C3	SLI	HI	EI	VHI	EI
C4	VLI	EI	VLI	EI	LI
C5	SLI	HI	EI	HI	EI

Step 5. The consistency ratio (CR) is checked for each pairwise comparison matrix, and each was found to be consistent based on the computed CR values. Table 7.3 shows the CR values for criteria.

Step 6. DMs' evaluations are converted into IVFFNs and aggregated using the IVFFDWA operator to obtain the group decision. Here, we consider $\beta = 1$. The aggregated IVFF values concerning the criteria are presented in Table 7.4.

Table 7.4: Aggregated pairwise comparison matrix for criteria

Criteria	C1				C2			
	μ_l	μ_u	ν_l	ν_u	μ_l	μ_u	ν_l	ν_u
C1	0.500	0.500	0.500	0.500	0.585	0.681	0.499	0.542
C2	0.499	0.542	0.585	0.681	0.500	0.500	0.500	0.500
C3	0.427	0.466	0.627	0.719	0.547	0.610	0.497	0.526
C4	0.623	0.717	0.550	0.679	0.586	0.655	0.445	0.456
C5	0.452	0.488	0.558	0.601	0.587	0.687	0.548	0.640
	C3				C4			
	μ_l	μ_u	μ_l	μ_u	μ_l	μ_u	μ_l	μ_u
C1	0.627	0.719	0.427	0.466	0.531	0.673	0.638	0.731
C2	0.497	0.526	0.547	0.610	0.445	0.456	0.586	0.655
C3	0.500	0.500	0.500	0.500	0.548	0.677	0.675	0.790
C4	0.675	0.790	0.548	0.677	0.500	0.500	0.500	0.500
C5	0.529	0.570	0.539	0.624	0.459	0.553	0.610	0.688
	C5							
	μ_l	μ_u	μ_l	μ_u				
C1	0.558	0.601	0.452	0.488				
C2	0.548	0.640	0.587	0.687				
C3	0.539	0.624	0.529	0.570				
C4	0.610	0.688	0.459	0.553				
C5	0.500	0.500	0.500	0.500				

Step 7. The differences matrix between lower and upper points of the membership and non-membership functions was formed based on Equation (4.1.1.3) in Chapter 4.

Step 8. The interval multiplicative matrix was formed based on Equation (4.1.1.4) in Chapter 4.

Step 9. The uncertainty value was obtained.

Step 10. Unnormalized weights were obtained based by Equation (4.1.1.6) in Chapter 4.

Step 11. The normalized weights are calculated by using Equation (4.1.1.7). The obtained final weights are given in Table 7.5 criteria and sub-criteria.

Table 7.5: Final weights of criteria and sub-criteria

Criteria	Weights	Sub-Criteria	Local weights	Global weights
C1	0.2345	C11	0.3308	0.0776
		C12	0.3039	0.0713
		C13	0.2494	0.0585
		C14	0.1159	0.0272
C2	0.1687	C21	0.2815	0.0475
		C22	0.2126	0.0359
		C23	0.2683	0.0453
		C24	0.2376	0.0401
C3	0.1778	C31	0.2749	0.0489
		C32	0.1460	0.0260
		C33	0.2340	0.0416
		C34	0.1946	0.0346
C4	0.2384	C35	0.1505	0.0268
		C41	0.3305	0.0788
		C42	0.1147	0.0273
		C43	0.2109	0.0503
C5	0.1804	C44	0.1257	0.0300
		C45	0.2182	0.0520
		C51	0.2584	0.0466
		C52	0.1566	0.0282
		C53	0.1615	0.0291
		C54	0.2462	0.0444
		C55	0.1773	0.0320

The results show that the most important criterion for the selection of IoT technology provider is “Platform Capability”. It stands out as the most critical criterion when choosing an IoT technology provider because this directly affects the functionality and efficiency of the IoT ecosystem. A powerful platform capability enables seamless connection, management, and analysis of various IoT devices, enabling comprehensive data processing, real-time monitoring and effective use of the IoT. This lays the foundation for building scalable and adaptable solutions and adapts to the dynamic and evolving nature of IoT deployments. Furthermore, “Data Management” emerges as the second most important criterion, as the ability to handle vast volumes of data generated by IoT devices is pivotal. Effective data management ensures the quality, security, and accessibility of information, fostering informed decision-making and enhancing the overall reliability and utility of the IoT system. When the global weights of the sub-criteria are examined, it is seen that the most important criterion is “Scalability”. It is crucial when choosing IoT providers as it enables seamless expansion of the IoT ecosystem to accommodate an ever-increasing number of connected devices, applications, and services. A scalable solution not only optimizes resource usage, but also provides flexibility for future expansions, accommodates variable workloads, and increases cost efficiency. Subsequently, “Data Processing and Sharing” emerges as a second critical sub-criterion. In this way, the increasing volume of data generated by connected devices can be processed in a timely and efficient manner. This is crucial to gaining valuable insights, enabling informed decision-making, and enabling data-driven solutions to drive innovation and efficiency.

After evaluating the IoT technology provider selection criteria, technology providers (alternatives) were evaluated with the IVFF-VIKOR method.

Here, the steps from Step 12 to Step 18 in Section 4.1.2 of Chapter 4 were applied. The final evaluation obtained by IVFF-VIKOR are given in Table 7.6.

Table 7.6: Computed (A_i) , $R(A_i)$ and $Q(A_i)$ values and the ranked order of the alternatives

Alternatives	$S(A_i)$	Order	$R(A_i)$	Order	$Q(A_i)$	Order
A1	0.4959	2	0.0554	2	0.2292	2
A2	0.5297	4	0.0748	6	0.5182	4
A3	0.5003	3	0.0886	8	0.6515	5
A4	0.7255	7	0.0835	7	0.8948	8
A5	0.3893	1	0.0487	1	0.0000	1
A6	0.7557	8	0.0747	5	0.8265	7
A7	0.6337	5	0.0594	3	0.4676	3
A8	0.7111	6	0.0681	4	0.6827	6

Here, the two conditions that explained in VIKOR steps should be checked. According the first condition, $0.2292 - 0.0000 \geq 0.1428 (DQ)$. Hence, the first condition of the method is satisfied. Then, the second condition is checked. Table 7.6 shows that the best alternative is A5 based on $Q(A_i)$ values and it is also the best alternative based on the $S(A_i), R(A_i)$ values. Based on the results, A5 alternative has acceptable stability. This compromise solution is stable within a decision-making process by consensus (for $v = 0.5$). Hence, the ranked order of the strategies are as follows based on the $Q(A_i)$ values:

$$A5 > A1 > A7 > A2 > A3 > A8 > A6 > A4$$

7.3. Comparative Analysis

Here, to compare the effectiveness of the proposed method, a comparative analysis was conducted with IVFF-TOPSIS and IVFF-MARCOS in ranking the strategies. The results obtained with different IVFF-MCDM techniques is presented in Figure 7.3.

It can be observed that the rankings in IVFF-TOPSIS and IVFF-MARCOS are highly similar. In both methodologies, A1 emerged as the most crucial alternative, and this alternative also placed the second position in IVFF-VIKOR. Remarkably, the least prioritized alternative remained consistent across all three methods.

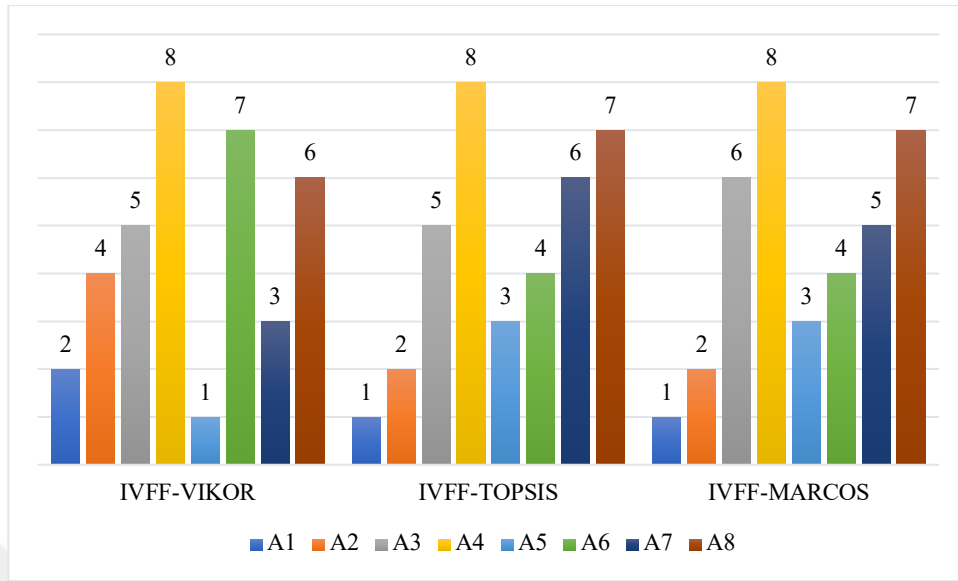


Figure 7.3: Comparison with different IVFF-MCDM techniques

7.4. Sensitivity Analysis

The reliability of the alternative rankings suggested by IVFF-VIKOR is subjected to further scrutiny through a sensitivity analysis. Initially computed for $v = 0.5$, representing the weight assigned to satisfy the majority of alternatives, results can be influenced by altering v values. This variation allows DMs to assess the impact of $Q(A_i)$, $S(A_i)$, $R(A_i)$ values on the compromise ranking list. Consequently, here, a sensitivity analysis is undertaken by adjusting v values and observing the consequent changes in the overall ranking. The outcomes reveal that, even with different v values, the best alternative remains consistent. This observation underscores the robustness and stability of the proposed model.

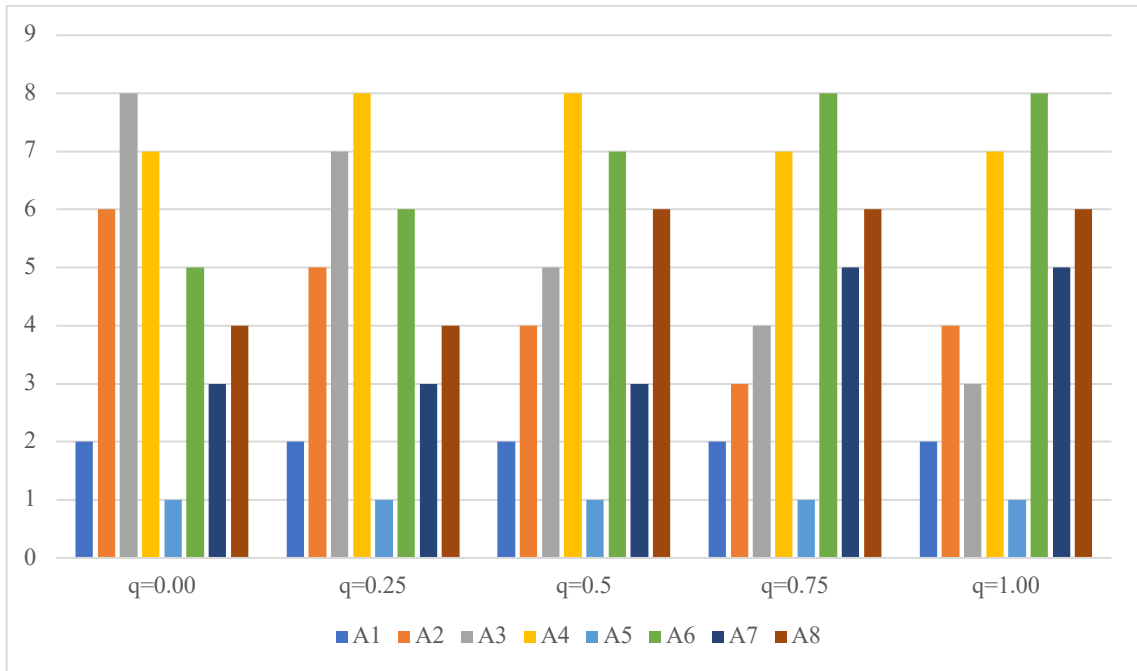


Figure 7.4: Ranking of the alternatives based on different q values

7.5. Concluding Remarks on RUL Technology Provider Selection

This section delves into the problem of selecting an IoT technology provider. The study aims to assign weights to the criteria for selecting an IoT technology provider using IVFF-AHP and IVFF-VIKOR methods. Based on these criteria, the most appropriate technology provider is then chosen. The study has revealed that “Platform Capabilities” is the most important evaluation criterion. This criterion is crucial in determining the overall performance, adaptability, and long-term usability of the chosen IoT technology provider. Among the sub-criteria, “Scalability” was found to be the most important criterion. The scalability capabilities of the platform and its ability to handle the rapidly increasing number of IoT devices and data volume are crucial to the platform’s long-term success and sustainability. A scalable platform can adjust to increasing requirements and growing infrastructure, enabling future expansions and updates. After evaluating the selection criteria, alternatives were prioritized using the IVFF-VIKOR method. As a result of the evaluations, it was seen that the A5 alternative was the best alternative. It is stated that this alternative exceeds expectations, especially when it comes to scalability and usability. This alternative stands out for having a comprehensive set of capabilities for connecting devices, collecting, and analyzing data, and creating applications. It also

includes functionality such as big data analysis, remote monitoring, maintenance prediction. The results obtained in this context will be beneficial for both practitioners and researchers.



8. CONCLUSION AND PERSPECTIVES

UR endeavors to establish robust, adaptable, and sustainable infrastructures capable of withstanding unforeseen events like natural disasters, epidemics, and economic crises. RUL stands as an integral component of this comprehensive resilience initiative. Urban logistics encompasses the transportation, storage, and distribution processes essential for the efficient movement of goods and services within a city. RUL specifically underscores a city's capacity to safeguard supply chains during crisis situations, ensuring rapid recovery and heightened resilience. Through an extensive exploration of UR literature, a noticeable research gap emerged for RUL, motivating the focus of this thesis. The objective is to illuminate the realm of RUL by scrutinizing existing academic and industrial literature, identifying RUL strategies through a current situation analysis, evaluating critical success factors for RUL, planning technological infrastructures, and evaluating technology providers. Decision-making models created for Istanbul province form the core of this thesis, with evaluations guided by expert opinions from the IMM. The contributions of this thesis to the literature are explained as follows:

- While traditional MCDM methods rely on clear, specific, and measurable data, real-world problems are often intricate, multidimensional, and riddled with uncertainties. To address this, Fuzzy Sets emerged as a valuable tool in decision-making, with extensions like IFS, PFS, and FFS introduced over time to tackle diverse aspects of uncertainty. The introduction of IVFFS broadens the scope of uncertainty management. The decision-making problems in this thesis are navigated within the IVFFS framework, offering DMs a potent tool to handle the complexities of uncertainty.
- Upon a thorough literature review, it was observed that there is a notable absence of studies addressing the strategic evaluation of RUL. To identify crucial

strategies for RUL, the initial step involves conducting a comprehensive analysis of the current situation. The most widely used strategic planning tool in the literature, SWOT analysis, can be applied for this purpose. This thesis introduced a pioneering approach to the literature by proposing a novel integrated SWOT-based IVFF-AHP-VIKOR methodology. This contribution not only analyzes RUL factors and strategies specific to Istanbul but also presents novel insights to the literature. Furthermore, it also introduced IVFF-VIKOR in the literature and integrated the IVFFDWA operator with VIKOR and AHP. The outcome of the analysis identifies the most suitable strategy as follows: “ST2- Establish an integrated control center for real-time visibility, facilitating faster decision-making and enhancing the agility of urban logistics processes through the integration of current technologies.”.

- After determining RUL strategies, a thorough analysis was conducted on the critical success factors essential for the successful implementation of RUL. This analysis holds significance in efficiently managing RUL processes and establishing an infrastructure that is robust in the face of crisis situations. Not only does it guide DMs in strategic planning, but it also identifies potential risks and crisis scenarios within logistics processes, ensures preparedness, and charts a roadmap to achieve strategic objectives. In this thesis, a critical success factor evaluation model encompassing four main factors and 21 sub-factors was developed through an extensive literature review and expert opinions. Introducing the IVFF-ISM method aims to provide DMs with increased flexibility in expressing preferences, opinions, and expertise. The study's findings unveiled that the most crucial success factors revolve around managerial and strategy-related factors, along with technological factors.
- The significance of incorporating technology into RUL processes is underscored in both the RUL strategic evaluation and the critical success factors analysis. Within this framework, the thesis extends its focus to technological infrastructure planning for RUL. Introducing the IVFF-QFD method to the literature, a pivotal technology selection was executed through a 2-stage QFD. Initially, RUL key applications were identified, aligning with RUL requirements, followed by a

comprehensive evaluation of technologies applicable to RUL key applications. The study's culmination identified IoT as the most crucial technology.

- Building on the outcomes derived from the technological infrastructure planning section, a comprehensive evaluation of IoT technology providers was conducted in the subsequent phase of the thesis. Drawing insights from expert opinions at the IMM and extensive literature reviews, an evaluation model comprising 5 criteria and 23 sub-criteria was formulated, identifying 8 alternatives. Employing the IVFF-AHP method, the criteria were assessed, followed by the prioritization of alternatives through IVFF-VIKOR. The study's outcome pinpointed the paramount IoT technology provider, ensuring the effective integration of IoT technology in RUL.

While the thesis offers valuable insights into RUL, it is essential to acknowledge its inherent limitations. The four models proposed within the scope of the thesis were developed by reviewing the literature and consulting experts on the subject. Although opinions were received from experts on the subject, the number of experts could be increased. The development of the proposed evaluation models aimed for maximum comprehensiveness, drawing insights from existing literature, industrial reports, and expert opinions. Nevertheless, there exists the potential for further expansion of these models. Additionally, the RUL decision-making models proposed in this thesis were exclusively applied to the context of Istanbul, recognizing that RUL may undergo distinct strategic evaluations in diverse cities.

It is evident that there is a considerable amount of attention given to fuzzy set theory by researchers across the globe. Numerous fuzzy extensions have been introduced in the literature to address specific problems (Kahraman et al., 2016). Among these, FFSs have emerged as a highly robust and pioneering fuzzy extension, and they form the central analytical focus of this thesis. However, in order to enhance the methodological depth of future studies, it may be useful to compare various fuzzy extensions such as hesitant fuzzy sets, neutrosophic fuzzy sets, interval-valued IFSs, and interval-valued PFSs. By taking this approach, researchers can better navigate the complexities of vagueness, hesitation, intuition, and other factors. Additionally, exploring the outcomes of these comparisons

within the realm of MCDM applications has the potential to yield invaluable insights. In this thesis, the evaluations conducted using AHP assumed the evaluation criteria are independent of each other. A perspective for future research can consider any potential interaction or interdependence among these criteria. The utilization of methods such as ANP or DEMATEL could be expanded upon in the analysis. Future research endeavors may delve into identifying potential disruptive factors within the RUL domain, employing an analytical approach to formulate mitigation strategies for their elimination. Generic models could be differentiated and compared for different stakeholders of urban logistics and applied in different areas. Finally, the IVFFDWA operator has been utilized in this thesis to make the aggregation process more flexible. In the future studies, the integration of proposed frameworks with other aggregation operators, such as the Einstein operator or Hamacher operator, could be explored.

REFERENCES

- Abdrabo, M. A., & Hassaan, M. A. (2015). An integrated framework for urban resilience to climate change – Case study: Sea level rise impacts on the Nile Delta coastal urban areas. *Urban Climate*, 14, 554–565. <https://doi.org/10.1016/j.uclim.2015.09.005>
- AbouKorin, S. A. A., Han, H., & Mahran, M. G. N. (2021). Role of urban planning characteristics in forming pandemic resilient cities – Case study of Covid-19 impacts on European cities within England, Germany and Italy. *Cities*, 118, 103324. <https://doi.org/10.1016/j.cities.2021.103324>
- Adedeji, T., Proverbs, D., Xiao, H., Cobbing, P., & Oladokun, V. (2019). Making Birmingham a flood resilient city: Challenges and opportunities. *Water (Switzerland)*, 11(8). Scopus. <https://doi.org/10.3390/w11081699>
- Admiraal, H., & Cornaro, A. (2020). Future cities, resilient cities – The role of underground space in achieving urban resilience. *Underground Space (China)*, 5(3), 223–228. Scopus. <https://doi.org/10.1016/j.undsp.2019.02.001>
- Aghamohagheghi, M., Hashemi, S. M., & Tavakkoli-Moghaddam, R. (2019). A new decision approach for the sustainable transport investment selection based on the generalized entropy and knowledge measure under an interval-valued Pythagorean fuzzy environment. *Scientia Iranica*, 0(0), 0–0. <https://doi.org/10.24200/sci.2019.50131.1529>
- Agrawal, V., Mohanty, R. P., & Agrawal, A. M. (2020). Identification and analysis of enablers of SCM by using MCDM approach. *Benchmarking: An International Journal*, 27(6), 1681–1710. <https://doi.org/10.1108/BIJ-05-2019-0232>
- Aguilar-Barajas, I., Sisto, N. P., Ramirez, A. I., & Magaña-Rueda, V. (2019). Building urban resilience and knowledge co-production in the face of weather hazards: Flash floods in the Monterrey Metropolitan Area (Mexico). *Environmental Science & Policy*, 99, 37–47. <https://doi.org/10.1016/j.envsci.2019.05.021>
- Ahmed, A. I. A., Khan, S., Gani, A., Hamid, S. H. A., & Guizani, M. (2018). Entropy-based Fuzzy AHP Model for Trustworthy Service Provider Selection in Internet of Things. *2018 IEEE 43rd Conference on Local Computer Networks (LCN)*, 606–613. <https://doi.org/10.1109/LCN.2018.8638056>
- Ahmed Elewa, A. K. (2019). Flexible Public Spaces through Spatial Urban Interventions, Towards Resilient Cities. *European Journal of Sustainable Development*, 8(4), 152. <https://doi.org/10.14207/ejsd.2019.v8n4p152>
- Aifandopoulou, G., & Xenou, E. (2019). *Sustainable Urban Logistics Planning*. HORIZON 2020 European project NOVELOG.
- Akben, İ. (2020). *Şehir Lojistiği / City Logistics* (pp. 73–88).
- Akram, M., Ali, G., Alcantud, J., & Riaz, A. (2022). Group decision-making with Fermatean fuzzy soft expert knowledge. *ARTIFICIAL INTELLIGENCE REVIEW*, 55(7), 5349–5389. <https://doi.org/10.1007/s10462-021-10119-8>
- Akram, M., Amjad, U., Alcantud, J., & Santos-Garcia, G. (2022). Complex fermatean fuzzy N-soft sets: A new hybrid model with applications. *JOURNAL OF AMBIENT INTELLIGENCE AND HUMANIZED COMPUTING*. <https://doi.org/10.1007/s12652-021-03629-4>

- Akram, M., & Bibi, R. (2023). Multi-criteria group decision-making based on an integrated PROMETHEE approach with 2-tuple linguistic Fermatean fuzzy sets. *Granular Computing*, 8(5), 917–941. <https://doi.org/10.1007/s41066-022-00359-6>
- Akram, M., Bibi, R., & Ali Al-Shamiri, M. M. (2022). A Decision-Making Framework Based on 2-Tuple Linguistic Fermatean Fuzzy Hamy Mean Operators. *Mathematical Problems in Engineering*.
- Akram, M., Bibi, R., & Deveci, M. (2023). An outranking approach with 2-tuple linguistic Fermatean fuzzy sets for multi-attribute group decision-making. *Engineering Applications of Artificial Intelligence*, 121, 105992. <https://doi.org/10.1016/j.engappai.2023.105992>
- Akram, M., Muhiuddin, G., & Santos-Garcia, G. (2022). An enhanced VIKOR method for multi-criteria group decision-making with complex Fermatean fuzzy sets. *MATHEMATICAL BIOSCIENCES AND ENGINEERING*, 19(7), 7201–7231. <https://doi.org/10.3934/mbe.2022340>
- Akram, M., Niaz, Z., & Feng, F. (2022). Extended CODAS method for multi-attribute group decision-making based on 2-tuple linguistic Fermatean fuzzy Hamacher aggregation operators. *Granular Computing*, 1–26.
- Akram, M., Ramzan, N., & Feng, F. (2022). Extending COPRAS Method with Linguistic Fermatean Fuzzy Sets and Hamy Mean Operators. *JOURNAL OF MATHEMATICS*, 2022. <https://doi.org/10.1155/2022/8239263>
- Akram, M., Ramzan, N., Luqman, A., Santos-García, G., Akram, M., Ramzan, N., Luqman, A., & Santos-García, G. (2023). An integrated MULTIMOORA method with 2-tuple linguistic Fermatean fuzzy sets: Urban quality of life selection application. *AIMS Mathematics*, 8(2), Article math-08-02-147. <https://doi.org/10.3934/math.2023147>
- Akram, M., Shah, S., Al-Shamiri, M., & Edalatpanah, S. (2022a). Extended DEA method for solving multi-objective transportation problem with Fermatean fuzzy sets. *AIMS MATHEMATICS*, 8(1), 924–961. <https://doi.org/10.3934/math.2023045>
- Akram, M., Shah, S., Al-Shamiri, M., & Edalatpanah, S. (2022b). Fractional transportation problem under interval-valued Fermatean fuzzy sets. *AIMS MATHEMATICS*, 7(9), 17327–17348. <https://doi.org/10.3934/math.2022954>
- Akram, M., Shahzadi, G., & Ahmadini, A. (2020). Decision-Making Framework for an Effective Sanitizer to Reduce COVID-19 under Fermatean Fuzzy Environment. *JOURNAL OF MATHEMATICS*, 2020. <https://doi.org/10.1155/2020/3263407>
- Akram, M., Shahzadi, G., & Davvaz, B. (2022). Decision-making model for internet finance soft power and sportswear brands based on sine-trigonometric Fermatean fuzzy information. *SOFT COMPUTING*. <https://doi.org/10.1007/s00500-022-07060-5>
- Akram, M., Shahzadi, S., Shah, S. M. U., & Allahviranloo, T. (2023). An extended multi-objective transportation model based on Fermatean fuzzy sets. *Soft Computing*. <https://doi.org/10.1007/s00500-023-08117-9>
- Alahmadi, R. A., Ganie, A. H., Al-Qudah, Y., Khalaf, M. M., & Ganie, A. H. (2023). Multi-attribute decision-making based on novel Fermatean fuzzy similarity measure and entropy measure. *Granular Computing*, 8(6), 1385–1405. <https://doi.org/10.1007/s41066-023-00378-x>
- Albahri, O. S., Al-Samarraay, M. S., AlSattar, H. A., Alamoodi, A. H., Zaidan, A. A., Albahri, A. S., Zaidan, B. B., & Jasim, A. N. (2023). Rough Fermatean fuzzy decision-based approach for modelling IDS classifiers in the federated learning of

- IoMT applications. *Neural Computing and Applications*, 35(30), 22531–22549. <https://doi.org/10.1007/s00521-023-08933-y>
- Ali, G., & Ansari, M. (2022). Multiattribute decision-making under Fermatean fuzzy bipolar soft framework. *GRANULAR COMPUTING*, 7(2), 337–352. <https://doi.org/10.1007/s41066-021-00270-6>
- Ali, Y., & Khan, H. U. (2023). IoT platforms assessment methodology for COVID-19 vaccine logistics and transportation: A multi-methods decision making model. *Scientific Reports*, 13(1), Article 1. <https://doi.org/10.1038/s41598-023-44966-y>
- Aliakbari Nouri, F., Khalili Esbouei, S., & Antucheviciene, J. (2015). A Hybrid MCDM Approach Based on Fuzzy ANP and Fuzzy TOPSIS for Technology Selection. *Informatica*, 26(3), 369–388. <https://doi.org/10.15388/Informatica.2015.53>
- Alizadeh-Meghbrazi, M., Tosarkani, B. M., Amin, S. H., Popovic, M. R., & Ahi, P. (2022). Design and optimization of a sustainable and resilient mask supply chain during the COVID-19 pandemic: A multi-objective approach. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-022-02604-z>
- Alkan, N., & Kahraman, C. (2022). Prioritization of Supply Chain Digital Transformation Strategies Using Multi-Expert Fermatean Fuzzy Analytic Hierarchy Process. *Informatica*, 1–33. <https://doi.org/10.15388/22-INFOR493>
- Amirzadeh, M., Sobhaninia, S., Buckman, S. T., & Sharifi, A. (2023). Towards building resilient cities to pandemics: A review of COVID-19 literature. *SUSTAINABLE CITIES AND SOCIETY*, 89, 104326. <https://doi.org/10.1016/j.scs.2022.104326>
- Amirzadeh, M., Sobhaninia, S., & Sharifi, A. (2022). Urban resilience: A vague or an evolutionary concept? *Sustainable Cities and Society*, 81, 103853. <https://doi.org/10.1016/j.scs.2022.103853>
- Amman, M., Rashid, T., & Ali, A. (2023). Fermatean fuzzy multi-criteria decision-making based on Spearman rank correlation coefficient. *Granular Computing*, 8(6), 2005–2019. <https://doi.org/10.1007/s41066-023-00421-x>
- Anelli, D., Tajani, F., & Ranieri, R. (2022). Urban resilience against natural disasters: Mapping the risk with an innovative indicators-based assessment approach. *JOURNAL OF CLEANER PRODUCTION*, 371, 133496. <https://doi.org/10.1016/j.jclepro.2022.133496>
- Arabzad, S. M., Ghorbani, M., Razmi, J., & Shirouyehzad, H. (2015). Employing fuzzy TOPSIS and SWOT for supplier selection and order allocation problem. *International Journal of Advanced Manufacturing Technology*, 76(5–8), 803–818. <https://doi.org/10.1007/s00170-014-6288-3>
- Arafah, Y., Winarso, H., & Suroso, D. S. A. (2018). Towards Smart and Resilient City: A Conceptual Model. *IOP Conference Series: Earth and Environmental Science*, 158, 012045. <https://doi.org/10.1088/1755-1315/158/1/012045>
- Aro, J., Selerio, E., Evangelista, S., Maturan, F., Atibing, N., & Ocampo, L. (2022). Fermatean fuzzy CRITIC-CODAS-SORT for characterizing the challenges of circular public sector supply chains. *OPERATIONS RESEARCH PERSPECTIVES*, 9. <https://doi.org/10.1016/j.orp.2022.100246>
- ARUP. (2014). *City Resilience Index*.
- Arup, Siemens, Chi, H., & City, M. (2015). *Resilient Urban Mobility*.
- ARUP, & The Rockefeller Foundation. (2015). *City Resilience Framework*.
- Atanassov, K. T. (1986). Intuitionistic fuzzy sets. *Fuzzy Sets and Systems*, 20(1), 87–96. [https://doi.org/10.1016/S0165-0114\(86\)80034-3](https://doi.org/10.1016/S0165-0114(86)80034-3)
- Atanassov, K. T. (2012). *On Intuitionistic Fuzzy Sets Theory* (Vol. 283). Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-29127-2>

- Attaullah, Rehman, N., Khan, A., & Santos-García, G. (2023). Fermatean hesitant fuzzy rough aggregation operators and their applications in multiple criteria group decision-making. *Scientific Reports*, 13(1), 6676. <https://doi.org/10.1038/s41598-023-28722-w>
- Aydın, G. T. (2017). *Kent içi lojistik: İstanbul için bir uygulama*. Istanbul Technical University.
- Aydoğan, H., & Ozkir, V. (2024). A Fermatean fuzzy MCDM method for selection and ranking Problems: Case studies. *Expert Systems with Applications*, 237, 121628. <https://doi.org/10.1016/j.eswa.2023.121628>
- Ayyildiz, E. (2022). Fermatean fuzzy step-wise Weight Assessment Ratio Analysis (SWARA) and its application to prioritizing indicators to achieve sustainable development goal-7. *RENEWABLE ENERGY*, 193, 136–148. <https://doi.org/10.1016/j.renene.2022.05.021>
- Babí Almenar, J., Elliot, T., Rugani, B., Philippe, B., Navarrete Gutierrez, T., Sonnemann, G., & Geneletti, D. (2021). Nexus between nature-based solutions, ecosystem services and urban challenges. *Land Use Policy*, 100, 104898. <https://doi.org/10.1016/j.landusepol.2020.104898>
- Bahadur, A. V., & Thornton, H. (2015). Analysing urban resilience: A reality check for a fledgling canon. *International Journal of Urban Sustainable Development*, 7(2), 196–212. <https://doi.org/10.1080/19463138.2015.1060595>
- Bajpai, A., & Misra, S. C. (2021). Barriers to implementing digitalization in the Indian construction industry. *International Journal of Quality & Reliability Management*. <https://doi.org/10.1108/IJQRM-09-2020-0318>
- Banai, R. (2020). Pandemic and the planning of resilient cities and regions. *Cities*, 106, 102929. <https://doi.org/10.1016/j.cities.2020.102929>
- Banica, A., Rosu, L., Muntele, I., & Grozavu, A. (2017). Towards Urban Resilience: A Multi-Criteria Analysis of Seismic Vulnerability in Iasi City (Romania). *Sustainability*, 9(2), Article 2. <https://doi.org/10.3390/su9020270>
- Barak, S., & Javanmard, S. (2020). Outsourcing modelling using a novel interval-valued fuzzy quantitative strategic planning matrix (QSPM) and multiple criteria decision-making (MCDMs). *International Journal of Production Economics*, 222, 107494. <https://doi.org/10.1016/j.ijpe.2019.09.015>
- Barroca, B., Bernardara, P., Girard, S., & Mazo, G. (2015). Considering hazard estimation uncertain in urban resilience strategies. *Natural Hazards and Earth System Sciences*, 15(1), 25–34. <https://doi.org/10.5194/nhess-15-25-2015>
- Bastaminia, A., Rezaei, M. reza, Dastoorpoor, M., & Tazesh, Y. (2016). Evaluation of Urban Resilience to Earthquake A Case Study: Dehdasht City. *International Journal of Ecology & Development*, 31(4), 46–56.
- Beatley, T., & Newman, P. (2013). Biophilic Cities Are Sustainable, Resilient Cities. *Sustainability*, 5(8), 3328–3345. <https://doi.org/10.3390/su5083328>
- Beheshtinia, M. A., Sayadinia, S., & Fathi, M. (2023). Identifying and prioritizing marketing strategies for the building energy management systems using a hybrid fuzzy MCDM technique. *Energy Science & Engineering*, n/a(n/a). <https://doi.org/10.1002/ese3.1584>
- Bellini, E., Bellini, P., Cenni, D., Nesi, P., Pantaleo, G., Paoli, I., & Paolucci, M. (2021). An IoE and Big Multimedia Data Approach for Urban Transport System Resilience Management in Smart Cities. *SENSORS*, 21(2), 435. <https://doi.org/10.3390/s21020435>

- Berte, E., & Panagopoulos, T. (2014). Enhancing city resilience to climate change by means of ecosystem services improvement: A SWOT analysis for the city of Faro, Portugal. *International Journal of Urban Sustainable Development*, 6(2), 241–253. Scopus. <https://doi.org/10.1080/19463138.2014.953536>
- Biswas, S., Chakraborty, R. K., Turan, H. H., & Elsayah, S. (2023). Consideration of uncertainties in a dynamic modeling system integrated with a deep learning based forecasting approach. *CIRP Journal of Manufacturing Science and Technology*, 44, 27–44. <https://doi.org/10.1016/j.cirpj.2023.04.003>
- Biswas, S., Pamucar, D., Kar, S., & Sana, S. (2021). A New Integrated FUCOM-CODAS Framework with Fermatean Fuzzy Information for Multi-Criteria Group Decision-Making. *SYMMETRY-BASEL*, 13(12). <https://doi.org/10.3390/sym13122430>
- Bixler, R. P., Yang, E., Richter, S. M., & Coudert, M. (2021). Boundary crossing for urban community resilience: A social vulnerability and multi-hazard approach in Austin, Texas, USA. *International Journal of Disaster Risk Reduction*, 66, 102613. <https://doi.org/10.1016/j.ijdrr.2021.102613>
- Borie, M., Pelling, M., Ziervogel, G., & Hyams, K. (2019). Mapping narratives of urban resilience in the global south. *Global Environmental Change*, 54, 203–213. <https://doi.org/10.1016/j.gloenvcha.2019.01.001>
- Borsekova, K., Nijkamp, P., & Guevara, P. (2018). Urban resilience patterns after an external shock: An exploratory study. *International Journal of Disaster Risk Reduction*, 31, 381–392. <https://doi.org/10.1016/j.ijdrr.2018.05.012>
- Boschetti, F., Gaffier, C., Moglia, M., Walke, I., & Price, J. (2017). Citizens' perception of the resilience of Australian cities. *Sustainability Science*, 12(3), 345–364. <https://doi.org/10.1007/s11625-017-0429-1>
- Bottero, M., Datola, G., & De Angelis, E. (2020). A System Dynamics Model and Analytic Network Process: An Integrated Approach to Investigate Urban Resilience. *Land*, 9(8), 242. <https://doi.org/10.3390/land9080242>
- Bouraima, M. B., Gore, A., Ayyildiz, E., Yalcin, S., Badi, I., Kiptum, C. K., & Qiu, Y. (2023). Assessing of causes of accidents based on a novel integrated interval-valued Fermatean fuzzy methodology: Towards a sustainable construction site. *Neural Computing and Applications*, 35(29), 21725–21750. <https://doi.org/10.1007/s00521-023-08948-5>
- Brunetta, G., & Salata, S. (2019). Mapping Urban Resilience for Spatial Planning—A First Attempt to Measure the Vulnerability of the System. *Sustainability*, 11(8), 2331. <https://doi.org/10.3390/su11082331>
- Brunner, G., Szebedy, B., Tanner, S., & Wattenhofer, R. (2018). The Urban Last Mile Problem: Autonomous Drone Delivery to Your Balcony. *arXiv:1809.08022 [Cs]*. <http://arxiv.org/abs/1809.08022>
- Bueno, S., Bañuls, V. A., & Gallego, M. D. (2021). Is urban resilience a phenomenon on the rise? A systematic literature review for the years 2019 and 2020 using textometry. *International Journal of Disaster Risk Reduction*, 66, 102588. <https://doi.org/10.1016/j.ijdrr.2021.102588>
- Bunmi Mudashiru, R., Sabtu, N., Abdullah, R., Saleh, A., & Abustan, I. (2022). Optimality of flood influencing factors for flood hazard mapping: An evaluation of two multi-criteria decision-making methods. *Journal of Hydrology*, 612, 128055. <https://doi.org/10.1016/j.jhydrol.2022.128055>

- Bush, J., & Doyon, A. (2019). Building urban resilience with nature-based solutions: How can urban planning contribute? *Cities*, 95, 102483. <https://doi.org/10.1016/j.cities.2019.102483>
- Büyüközkan, G., & Göçer, F. (2018). Digital Supply Chain: Literature review and a proposed framework for future research. *Computers in Industry*, 97, 157–177. <https://doi.org/10.1016/j.compind.2018.02.010>
- Büyüközkan, G., Havle, C. A., & Feyzioglu, O. (2020). A new digital service quality model and its strategic analysis in aviation industry using interval-valued intuitionistic fuzzy AHP. *Journal of Air Transport Management*, 86, 101817. <https://doi.org/10.1016/j.jairtraman.2020.101817>
- Buyukozkan, G., Havle, C. A., & Feyzioglu, O. (2021). Digital competency evaluation of low-cost airlines using an integrated IVIF AHP and IVIF VIKOR methodology. *JOURNAL OF AIR TRANSPORT MANAGEMENT*, 91, 101998. <https://doi.org/10.1016/j.jairtraman.2020.101998>
- Büyüközkan, G., & Ilıcak, Ö. (2019). Integrated SWOT analysis with multiple preference relations: Selection of strategic factors for social media. *Kybernetes*, 48(3), 451–470. <https://doi.org/10.1108/K-12-2017-0512>
- Büyüközkan, G., & Ilıcak, Ö. (2022). Smart urban logistics: Literature review and future directions. *Socio-Economic Planning Sciences*, 81, 101197. <https://doi.org/10.1016/j.seps.2021.101197>
- Büyüközkan, G., Ilıcak, Ö., & Feyzioglu, O. (2022). A review of urban resilience literature. *Sustainable Cities and Society*, 77, 103579. <https://doi.org/10.1016/j.scs.2021.103579>
- Büyüközkan, G., & Mukul, E. (2019). Evaluation of smart city logistics solutions with fuzzy MCDM methods. *Pamukkale University Journal of Engineering Sciences*, 25(9), 1033–1040. <https://doi.org/10.5505/pajes.2019.32956>
- Buyukozkan, G., Mukul, E., & Kongar, E. (2021). Health tourism strategy selection via SWOT analysis and integrated hesitant fuzzy linguistic AHP-MABAC approach. *Socio-Economic Planning Sciences*, 74, 100929. <https://doi.org/10.1016/j.seps.2020.100929>
- Çalik, A., Onifade, S. T., & Alola, A. A. (2023). Evaluating Supply Resilience Performance of an Automotive Industry during Operational Shocks: A Pythagorean Fuzzy AHP-VIKOR-Based Approach. *Systems*, 11(8), Article 8. <https://doi.org/10.3390/systems11080396>
- Camgoz Akdag, H., Zaim, S., Acar, M. F., Demirel, O. F., & Ataman, A. (2012). Product Improvement with Quality Function Deployment (QFD) Technique. *Advanced Materials Research*, 445, 1058–1063. <https://doi.org/10.4028/www.scientific.net/AMR.445.1058>
- Canavera-Herrera, J. S., Tang, J., Nocht, T., & Schooling, J. M. (2022). On the relation between “resilience” and “smartness”: A critical review. *INTERNATIONAL JOURNAL OF DISASTER RISK REDUCTION*, 75, 102970. <https://doi.org/10.1016/j.ijdr.2022.102970>
- Caputo, S., Caserio, M., Coles, R., Jankovic, L., & Gaterell, M. R. (2015). Urban resilience: Two diverging interpretations. *Journal of Urbanism*, 8(3), 222–240. Scopus. <https://doi.org/10.1080/17549175.2014.990913>
- Caragliu, A., Bo, C. D., & Nijkamp, P. (2011). *Smart Cities in Europe Smart Cities in Europe*. 0732. <https://doi.org/10.1080/10630732.2011.601117>
- Cardoso, M. A., Telhado, M. J., Almeida, M. do C., Brito, R. S., Pereira, C., Barreiro, J., & Morais, M. (2020). Following a Step by Step Development of a Resilience

- Action Plan. *Sustainability*, 12(21), Article 21. <https://doi.org/10.3390/su12219017>
- Cariolet, J.-M., Vuillet, M., & Diab, Y. (2019). Mapping urban resilience to disasters – A review. *Sustainable Cities and Society*, 51, 101746. <https://doi.org/10.1016/j.scs.2019.101746>
- Chakraborty, S., & Saha, A. (2022). Selection of optimal lithium ion battery recycling process: A multi-criteria group decision making approach. *JOURNAL OF ENERGY STORAGE*, 55. <https://doi.org/10.1016/j.est.2022.105557>
- Chakraborty, S., & Saha, A. (2023). Novel Fermatean Fuzzy Bonferroni Mean aggregation operators for selecting optimal health care waste treatment technology. *ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE*, 119. <https://doi.org/10.1016/j.engappai.2022.105752>
- Chan, L.-K., & Wu, M.-L. (2002). Quality Function Deployment: A Literature Review. *European Journal of Operational Research*, 143, 463–497. [https://doi.org/10.1016/S0377-2217\(02\)00178-9](https://doi.org/10.1016/S0377-2217(02)00178-9)
- Chander, M., Jain, S. K., & Shankar, R. (2013). Modeling of information security management parameters in Indian organizations using ISM and MICMAC approach. *Journal of Modelling in Management*, 8(2), 171–189. <https://doi.org/10.1108/JM2-10-2011-0054>
- Chang, K.-H., Chung, H.-Y., Wang, C.-N., Lai, Y.-D., & Wu, C.-H. (2023). A New Hybrid Fermatean Fuzzy Set and Entropy Method for Risk Assessment. *Axioms*, 12(1), 58. <https://doi.org/10.3390/axioms12010058>
- Chang, S. E., Mcdaniels, T., Fox, J., Dhariwal, R., & Longstaff, H. (2014). Toward disaster-resilient cities: Characterizing resilience of infrastructure systems with expert judgments. *Risk Analysis*, 34(3), 416–434. Scopus. <https://doi.org/10.1111/risa.12133>
- Chauhan, A., Kaur, H., Yadav, S., & Jakhar, S. K. (2020). A hybrid model for investigating and selecting a sustainable supply chain for agri-produce in India. *Annals of Operations Research*, 290(1–2), 621–642. <https://doi.org/10.1007/s10479-019-03190-6>
- Chelleri, L., Waters, J. J., Olazabal, M., & Minucci, G. (2015). Resilience trade-offs: Addressing multiple scales and temporal aspects of urban resilience. *Environment and Urbanization*, 27(1), 181–198. <https://doi.org/10.1177/0956247814550780>
- Chen, C., Xu, L., Zhao, D., Xu, T., & Lei, P. (2020). A new model for describing the urban resilience considering adaptability, resistance and recovery. *Safety Science*, 128, 104756. <https://doi.org/10.1016/j.ssci.2020.104756>
- Chen, J., Guo, X., Pan, H., & Zhong, S. (2021). What determines city's resilience against epidemic outbreak: Evidence from China's COVID-19 experience. *Sustainable Cities and Society*, 70, 102892. <https://doi.org/10.1016/j.scs.2021.102892>
- Chen, Q., Liu, H., Wang, J., & Shi, H. (2022). New model for occupational health and safety risk assessment based on Fermatean fuzzy linguistic sets and CoCoSo approach. *APPLIED SOFT COMPUTING*, 126. <https://doi.org/10.1016/j.asoc.2022.109262>
- Chen, W.-C., Wang, L.-Y., & Lin, M.-C. (2015). A Hybrid MCDM Model for New Product Development: Applied on the Taiwanese LiFePO₄ Industry. *Mathematical Problems in Engineering*, 2015, 462929. <https://doi.org/10.1155/2015/462929>
- Chen, X., Yu, L., Lin, W., Yang, F., Li, Y., Tao, J., & Cheng, S. (2023). Urban resilience assessment from the multidimensional perspective using dynamic Bayesian

- network: A case study of Fujian Province, China. *Reliability Engineering & System Safety*, 238, 109469. <https://doi.org/10.1016/j.ress.2023.109469>
- Chen, Y., Zhu, M., Zhou, Q., & Qiao, Y. (2021). Research on Spatiotemporal Differentiation and Influence Mechanism of Urban Resilience in China Based on MGWR Model. *International Journal of Environmental Research and Public Health*, 18(3), 1056. <https://doi.org/10.3390/ijerph18031056>
- Cheung, C.-Y., Yoon, H. T., & Chow, A. H. (2015). Optimization of police facility deployment with a case study in Greater London Area. *Journal of Facilities Management*, 13(3), 229–243. <https://doi.org/10.1108/JFM-05-2014-0014>
- Choi, H., & Seo, Y.-A. (2019). The Process of Creating Yongsan Park from the Urban Resilience Perspective. *Sustainability*, 11(5), 1225. <https://doi.org/10.3390/su11051225>
- Chowdhury, Md. M. H., Mahmud, A. K. M. S., Khan, E., Hossain, M., & Barua, Z. (2023). Lessons learnt from COVID-19 vaccine operations and distribution performance: Challenges and resilience strategies. *Asia Pacific Journal of Marketing and Logistics*, 35(9), 2317–2343. <https://doi.org/10.1108/APJML-05-2022-0407>
- Chowdhury, Md. M. H., & Quaddus, M. A. (2015). A multiple objective optimization based QFD approach for efficient resilient strategies to mitigate supply chain vulnerabilities: The case of garment industry of Bangladesh ☆, ☆ ☆☆This manuscript was processed by Associate Editor B. Lev. *Omega*, 57, 5–21. <https://doi.org/10.1016/j.omega.2015.05.016>
- Chu, Z., Cheng, M., & Song, M. (2021). What determines urban resilience against COVID-19: City size or governance capacity? *Sustainable Cities and Society*, 75, 103304. <https://doi.org/10.1016/j.scs.2021.103304>
- CIVITAS. (2015). *Smart choices for cities: Making urban freight logistics more sustainable*.
- Cobbinah, P. B., & Poku-Boansi, M. (2018). Towards resilient cities in Ghana: Insights and strategies. *Futures*, 101, 55–66. <https://doi.org/10.1016/j.futures.2018.06.005>
- Çolak, H., & Lezki, Ş. (2023). Soft Power Effect on Long-Term Buyer-Seller Relationship: A Fuzzy Multi-Criteria Decision-Making Approach and Evidence from the Turkish Smartphone Sector. *Journal of Business-to-Business Marketing*, 30(3), 237–255. <https://doi.org/10.1080/1051712X.2023.2211580>
- Crowe, P. R., & Foley, K. (2017). Exploring urban resilience in practice: A century of vacant sites mapping in Dublin, Edinburgh and Philadelphia. *Journal of Urban Design*, 22(2), 208–228. Scopus. <https://doi.org/10.1080/13574809.2017.1298401>
- da Silva, C. A., dos Santos, E. A., Maier, S. M., & da Rosa, F. S. (2019). Urban resilience and sustainable development policies: An analysis of smart cities in the state of São Paulo. *Revista de Gestão*, 27(1), 61–78. <https://doi.org/10.1108/REGE-12-2018-0117>
- Dachyar, M., & Mahendra, E. A. (2019). Design Factors of Supply Chain Management for Wood Industry SMEs. *Industrial Engineering and Management Systems*, 18(2), 182–194. <https://doi.org/10.7232/iems.2019.18.2.182>
- Dadpour, M., & Shakeri, E. (2017). A Hybrid Model Based on Fuzzy Approach Type II to Select Private Sector in Partnership Projects. *Iranian Journal of Science and Technology-Transactions of Civil Engineering*, 41(2), 175–186. <https://doi.org/10.1007/s40996-017-0047-2>

- Darkwah, R. M., Cobbinah, P. B., & Anokye, P. A. (2018). Contextualising urban resilience in Ghana: Local perspectives and experiences. *Geoforum*, 94, 12–23. <https://doi.org/10.1016/j.geoforum.2018.05.023>
- Datola, G. (2023). Implementing urban resilience in urban planning: A comprehensive framework for urban resilience evaluation. *Sustainable Cities and Society*, 98, 104821. <https://doi.org/10.1016/j.scs.2023.104821>
- Datola, G., Bottero, M., & de Angelis, E. (2021). Enhancing Urban Resilience Capacities: An Analytic Network Process-based Application. *ENVIRONMENTAL AND CLIMATE TECHNOLOGIES*, 25(1), 1270–1283. <https://doi.org/10.2478/rtuect-2021-0096>
- Datola, G., Bottero, M., De Angelis, E., & Romagnoli, F. (2022). Operationalising resilience: A methodological framework for assessing urban resilience through System Dynamics Model. *ECOLOGICAL MODELLING*, 465, 109851. <https://doi.org/10.1016/j.ecolmodel.2021.109851>
- De Nardis, L., Mohammadpour, A., Caso, G., Ali, U., & Di Benedetto, M.-G. (2022). Internet of Things Platforms for Academic Research and Development: A Critical Review. *Applied Sciences*, 12(4), Article 4. <https://doi.org/10.3390/app12042172>
- Delgado-Ramos, G. C., & Guibrune, L. (2017). Assessing the ecological dimension of urban resilience and sustainability. *International Journal of Urban Sustainable Development*, 9(2), 151–169. <https://doi.org/10.1080/19463138.2017.1341890>
- Deliktaş, D., Karagoz, S., Simić, V., & Aydin, N. (2023). A stochastic Fermatean fuzzy-based multi-choice conic goal programming approach for sustainable supply chain management in end-of-life buildings. *Journal of Cleaner Production*, 382, 135305. <https://doi.org/10.1016/j.jclepro.2022.135305>
- Deloitte. (2022). *Building the capacity for change in cities*. https://www2.deloitte.com/content/dam/insights/articles/glob176462_thoughtlab-series1_capacity-for-change/DI_Capacity-for-change.pdf
- Deloitte & Vodafone. (2016). *Akıllı Şehirler Yol Haritası*.
- Deng, Z., & Wang, J. (2021). Evidential Fermatean fuzzy multicriteria decision-making based on Fermatean fuzzy entropy. *INTERNATIONAL JOURNAL OF INTELLIGENT SYSTEMS*, 36(10), 5866–5886. <https://doi.org/10.1002/int.22534>
- Deveci, M., Gokasar, I., Mishra, A. R., Rani, P., & Ye, Z. (2023). Evaluation of climate change-resilient transportation alternatives using fuzzy Hamacher aggregation operators based group decision-making model. *Engineering Applications of Artificial Intelligence*, 119, 105824. <https://doi.org/10.1016/j.engappai.2023.105824>
- Deveci, M., Varouchakis, E. A., Brito-Parada, P. R., Mishra, A. R., Rani, P., Bolgkoranou, M., & Galetakis, M. (2023). Evaluation of risks impeding sustainable mining using Fermatean fuzzy score function based SWARA method. *Applied Soft Computing*, 139, 110220. <https://doi.org/10.1016/j.asoc.2023.110220>
- Dianat, H., Wilkinson, S., Williams, P., & Khatibi, H. (2022). Choosing a holistic urban resilience assessment tool. *International Journal of Disaster Risk Reduction*, 71, 102789. <https://doi.org/10.1016/j.ijdrr.2022.102789>
- Diaz-Sarachaga, J. M., & Jato-Espino, D. (2020). Analysis of vulnerability assessment frameworks and methodologies in urban areas. *Natural Hazards*, 100(1), 437–457. <https://doi.org/10.1007/s11069-019-03805-y>

- Dieleman, H. (2013). Organizational learning for resilient cities, through realizing eco-cultural innovations. *Journal of Cleaner Production*, 50, 171–180. <https://doi.org/10.1016/j.jclepro.2012.11.027>
- Dimic, S., Pamucar, D., Ljubojevic, S., & Dorovic, B. (2016). Strategic Transport Management Models The Case Study of an Oil Industry. *Sustainability*, 8(9), 954. <https://doi.org/10.3390/su8090954>
- Ding, A., Cenci, J., & Zhang, J. (2022). Links between the pandemic and urban green spaces, a perspective on spatial indices of landscape garden cities in China. *SUSTAINABLE CITIES AND SOCIETY*, 85, 104046. <https://doi.org/10.1016/j.scs.2022.104046>
- Ding, Y., Jin, M., Li, S., & Feng, D. (2020). Smart logistics based on the internet of things technology: An overview. *International Journal of Logistics Research and Applications*, 24, 1–23. <https://doi.org/10.1080/13675567.2020.1757053>
- Dixit, A., Suvadashini, P., & Pagare, D. V. (2022). Analysis of barriers to organic farming adoption in developing countries: A grey-DEMATEL and ISM approach. *Journal of Agribusiness in Developing and Emerging Economies*. <https://doi.org/10.1108/JADEE-06-2022-0111>
- Dombi, J. (1982). A general class of fuzzy operators, the demorgan class of fuzzy operators and fuzziness measures induced by fuzzy operators. *Fuzzy Sets and Systems*, 8(2), 149–163. [https://doi.org/10.1016/0165-0114\(82\)90005-7](https://doi.org/10.1016/0165-0114(82)90005-7)
- Dong, X., Shi, T., Zhang, W., & Zhou, Q. (2020). Temporal and Spatial Differences in the Resilience of Smart Cities and Their Influencing Factors: Evidence from Non-Provincial Cities in China. *Sustainability*, 12(4), 1321. <https://doi.org/10.3390/su12041321>
- Du, T. L. T., Bui, D. D., Buurman, J., & Quach, X. T. (2018). Towards adaptive governance for urban drought resilience: The case of Da Nang, Vietnam. *International Journal of Water Resources Development*, 34(4), 597–615. <https://doi.org/10.1080/07900627.2018.1438886>
- Du, Y., Hou, F., Zafar, M., Yu, Q., & Zhai, Y. (2017). A Novel Method for Multiattribute Decision Making with Interval-Valued Pythagorean Fuzzy Linguistic Information: NOVEL METHOD FOR MULTIATTRIBUTE DECISION MAKING. *International Journal of Intelligent Systems*, 32. <https://doi.org/10.1002/int.21881>
- Economist Impact. (2023). *Resilient Cities Index 2023*. https://impact.economist.com/projects/resilient-cities/wp-content/uploads/2023/10/Resilient-Cities_Report.pdf
- Ekmekcioğlu, Ö., Koc, K., Dabanli, I., & Deniz, A. (2022). Prioritizing urban water scarcity mitigation strategies based on hybrid multi-criteria decision approach under fuzzy environment. *Sustainable Cities and Society*, 87, 104195. <https://doi.org/10.1016/j.scs.2022.104195>
- Entemann, C. W. (2002). Fuzzy Logic: Misconceptions and Clarifications. *FUZZY LOGIC*.
- Erdogan, M., & Ayyildiz, E. (2022). Comparison of hospital service performances under COVID-19 pandemics for pilot regions with low vaccination rates. *EXPERT SYSTEMS WITH APPLICATIONS*, 206. <https://doi.org/10.1016/j.eswa.2022.117773>
- Erik Hollnagel, David D. Woods, & Nancy Leveson. (2006). *Resilience engineering: Concepts and precepts*. Aldershot: Ashgate.

- Ervural, B. C., Zaim, S., Demirel, O. F., Aydin, Z., & Delen, D. (2018). An ANP and fuzzy TOPSIS-based SWOT analysis for Turkey's energy planning. *Renewable & Sustainable Energy Reviews*, 82, 1538–1550. <https://doi.org/10.1016/j.rser.2017.06.095>
- Fahmi, A. (2023). Particle swarm optimization selection based on the TOPSIS technique. *Soft Computing*, 27(14), 9225–9245. <https://doi.org/10.1007/s00500-023-08200-1>
- Fahmi, A., Maqbool, Z., Amin, F., & Aslam, M. (2023). Blockchain knowledge selection under the trapezoidal fermatean fuzzy number. *SOFT COMPUTING*, 27(7), 3601–3621. <https://doi.org/10.1007/s00500-022-07611-w>
- Farid, H. M. A., Bouye, M., Riaz, M., & Jamil, N. (2023). Fermatean Fuzzy CODAS Approach with Topology and Its Application to Sustainable Supplier Selection. *Symmetry*, 15(2), Article 2. <https://doi.org/10.3390/sym15020433>
- Feng, X., Xiu, C., Bai, L., Zhong, Y., & Wei, Y. (2020). Comprehensive evaluation of urban resilience based on the perspective of landscape pattern: A case study of Shenyang city. *Cities*, 104, 102722. <https://doi.org/10.1016/j.cities.2020.102722>
- Feofilovs, M., & Romagnoli, F. (2021). Dynamic assessment of urban resilience to natural hazards. *International Journal of Disaster Risk Reduction*, 62, 102328. <https://doi.org/10.1016/j.ijdrr.2021.102328>
- Fetanat, A., Tayebi, M., & Mofid, H. (2023). Water-energy-carbon nexus and sustainability-oriented prioritization of negative emissions technologies for the oil & gas industry: A decision support system under Fermatean fuzzy environment. *Process Safety and Environmental Protection*, 179, 462–483. <https://doi.org/10.1016/j.psep.2023.09.037>
- Friend, R., & Moench, M. (2013). What is the purpose of urban climate resilience? Implications for addressing poverty and vulnerability. *Urban Climate*, 6, 98–113. Scopus. <https://doi.org/10.1016/j.uclim.2013.09.002>
- Fu, H., Hong, N., & Liao, C. (2023). Spatio-temporal patterns of Chinese urban recovery and system resilience under the pandemic new normal. *Cities*, 140, 104385. <https://doi.org/10.1016/j.cities.2023.104385>
- Fu, X., Hopton, M. E., & Wang, X. (2021). Assessment of green infrastructure performance through an urban resilience lens. *Journal of Cleaner Production*, 289, 125146. <https://doi.org/10.1016/j.jclepro.2020.125146>
- Gaber, R. M., El-Kader, M. H. A., & Okba, E. M. (2019). Assessment of urban resilience through the development of an urban resilience assessment model (resilience performance index). *International Journal of Engineering Research and Technology*, 12(12), 2423–2430. Scopus.
- Gafter, L., Tchetchik, A., & Shilo, S. (2022). Urban resilience as a mitigating factor against economically driven out-migration during COVID-19: The case of Eilat, a tourism-based city. *CITIES*, 125, 103636. <https://doi.org/10.1016/j.cities.2022.103636>
- Galderisi, A. (2014). Urban resilience: A framework for empowering cities in face of heterogeneous risk factors. *A/Z ITU Journal of the Faculty of Architecture*, 11(1), 36–58. Scopus.
- Gao, F., Han, M., Wang, S., & Gao, J. (2024). A novel Fermatean fuzzy BWM-VIKOR based multi-criteria decision-making approach for selecting health care waste treatment technology. *Engineering Applications of Artificial Intelligence*, 127, 107451. <https://doi.org/10.1016/j.engappai.2023.107451>

- Gardas, B. B., Raut, R. D., Cheikhrouhou, N., & Narkhede, B. E. (2019). A hybrid decision support system for analyzing challenges of the agricultural supply chain. *Sustainable Production and Consumption*, 18, 19–32. <https://doi.org/10.1016/j.spc.2018.11.007>
- Garg, H., Shahzadi, G., & Akram, M. (2020). Decision-Making Analysis Based on Fermatean Fuzzy Yager Aggregation Operators with Application in COVID-19 Testing Facility. *MATHEMATICAL PROBLEMS IN ENGINEERING*, 2020. <https://doi.org/10.1155/2020/7279027>
- Gavareshki, M. H. K., Hosseini, S. J., & Khajezadeh, M. (2017). A Case Study of Green Supplier Selection Method Using an Integrated ISM-Fuzzy MICMAC Analysis and Multi-Criteria Decision Making. *Industrial Engineering and Management Systems*, 16(4), 562–573. <https://doi.org/10.7232/iems.2017.16.4.562>
- Geetha, S., Narayanamoorthy, S., Kang, D., & Baleanu, D. (2022). An adoptive renewable energy resource selection using Hesitant Pythagorean Fuzzy DEMATEL and VIKOR methods. *Journal of Intelligent & Fuzzy Systems*, 43(4), 4285–4302. <https://doi.org/10.3233/JIFS-201584>
- Gharai, F., Masnavi, M. R., & Hajibandeh, M. (2018). *Urban Local-Spatial Resilience: Developing the Key Indicators and Measures, a Brief Review of Literature*. 15.
- Ghouchani, M., Taji, M., Yaghoubi Roshan, A., & Seifi Chehr, M. (2020). Identification and assessment of hidden capacities of urban resilience. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-020-00752-8>
- Gimenez, R., Labaka, L., & Hernantes, J. (2017). A maturity model for the involvement of stakeholders in the city resilience building process. *Technological Forecasting and Social Change*, 121, 7–16. <https://doi.org/10.1016/j.techfore.2016.08.001>
- Gimenez, R., Labaka, L., & Hernantes, J. (2018). Union means strength: Building city resilience through multistakeholder collaboration. *Journal of Contingencies and Crisis Management*, 26(3), 385–393. <https://doi.org/10.1111/1468-5973.12205>
- Golui, S., Mahapatra, B. S., & Mahapatra, G. S. (2024). A new correlation-based measure on Fermatean fuzzy applied on multi-criteria decision making for electric vehicle selection. *Expert Systems with Applications*, 237, 121605. <https://doi.org/10.1016/j.eswa.2023.121605>
- Gonzales, G., Costan, F., Suladay, D., Gonzales, R., Enriquez, L., Costan, E., Atibing, N., Aro, J., Evangelista, S., Maturan, F., Selerio, E., & Ocampo, L. (2022). Fermatean Fuzzy DEMATEL and MMDE Algorithm for Modelling the Barriers of Implementing Education 4.0: Insights from the Philippines. *APPLIED SCIENCES-BASEL*, 12(2). <https://doi.org/10.3390/app12020689>
- Gonzales, R., Almacen, R., Gonzales, G., Costan, F., Suladay, D., Enriquez, L., Costan, E., Atibing, N., Aro, J., Evangelista, S., Maturan, F., Selerio, E., & Ocampo, L. (2022). Priority Roles of Stakeholders for Overcoming the Barriers to Implementing Education 4.0: An Integrated Fermatean Fuzzy Entropy-Based CRITIC-CODAS-SORT Approach. *COMPLEXITY*, 2022. <https://doi.org/10.1155/2022/7436256>
- Görçün, Ö. F., Aytekin, A., Selçuk Korucuk, & Tirkolae, E. B. (2023). Evaluating and selecting sustainable logistics service providers for medical waste disposal treatment in the healthcare industry. *Journal of Cleaner Production*, 408, 137194. <https://doi.org/10.1016/j.jclepro.2023.137194>
- Görçün, Ö. F., Pamucar, D., & Biswas, S. (2023). The blockchain technology selection in the logistics industry using a novel MCDM framework based on Fermatean

- fuzzy sets and Dombi aggregation. *Information Sciences*, 635, 345–374. <https://doi.org/10.1016/j.ins.2023.03.113>
- Gordon, B. L., Quesnel, K. J., Abs, R., & Ajami, N. K. (2018). A case-study based framework for assessing the multi-sector performance of green infrastructure. *Journal of Environmental Management*, 223, 371–384. <https://doi.org/10.1016/j.jenvman.2018.06.029>
- Gracias, J. S., Parnell, G. S., Specking, E., Pohl, E. A., & Buchanan, R. (2023). Smart Cities—A Structured Literature Review. *Smart Cities*, 6(4), Article 4. <https://doi.org/10.3390/smartcities6040080>
- Greater London Authority. (2020). *London City Resilience Strategy 2020*.
- Grinberger, A. Y., & Felsenstein, D. (2016). Dynamic agent based simulation of welfare effects of urban disasters. *Computers, Environment and Urban Systems*, 59, 129–141. <https://doi.org/10.1016/j.compenvurbsys.2016.06.005>
- Gul, M. (2020). Application of Pythagorean fuzzy AHP and VIKOR methods in occupational health and safety risk assessment: The case of a gun and rifle barrel external surface oxidation and colouring unit. *International Journal of Occupational Safety and Ergonomics*, 26(4), 705–718. <https://doi.org/10.1080/10803548.2018.1492251>
- Gul, M., & Ak, M. (2022). Occupational Risk Assessment for Flight Schools: A 3,4-Quasirung Fuzzy Multi-Criteria Decision Making-Based Approach. *SUSTAINABILITY*, 14(15). <https://doi.org/10.3390/su14159373>
- Gul, M., Lo, H., & Yucesan, M. (2021). Fermatean fuzzy TOPSIS-based approach for occupational risk assessment in manufacturing. *COMPLEX & INTELLIGENT SYSTEMS*, 7(5), 2635–2653. <https://doi.org/10.1007/s40747-021-00417-7>
- Gül, S. (2021). Fermatean fuzzy set extensions of SAW, ARAS, and VIKOR with applications in COVID-19 testing laboratory selection problem. *Expert Systems*, 38(8), e12769. <https://doi.org/10.1111/exsy.12769>
- Gundogdu, F. K., Duleba, S., Moslem, S., & Aydin, S. (2021). Evaluating public transport service quality using picture fuzzy analytic hierarchy process and linear assignment model. *APPLIED SOFT COMPUTING*, 100, 106920. <https://doi.org/10.1016/j.asoc.2020.106920>
- Gupta, A. K., & Goyal, H. (2021). Framework for implementing big data analytics in Indian manufacturing: ISM-MICMAC and Fuzzy-AHP approach. *Information Technology & Management*, 22(3), 207–229. <https://doi.org/10.1007/s10799-021-00333-9>
- Gürevin, S., & Seçkin, Y. Ç. (2013). Resilient cities and adaptation to climate change: Chicago metropolitan area as a case study. *A/Z ITU Journal of the Faculty of Architecture*, 10(2), 15–32. Scopus.
- Hao, T., Zheng, X., Wang, H., Xu, K., & Yu, Y. (2023). Development of a method for weight determination of disaster-causing factors and quantitative risk assessment for tailings dams based on causal coupling relationships. *STOCHASTIC ENVIRONMENTAL RESEARCH AND RISK ASSESSMENT*, 37(2), 749–775. <https://doi.org/10.1007/s00477-022-02316-w>
- Harrison, C., Eckman, B., Hamilton, R., & Hartswick, P. (2010). *Foundations for Smarter Cities*. 54(4), 1–16.
- Hassankhani, M., Alidadi, M., Sharifi, A., & Azhdari, A. (2021). Smart City and Crisis Management: Lessons for the COVID-19 Pandemic. *International Journal of Environmental Research and Public Health*, 18(15), Article 15. <https://doi.org/10.3390/ijerph18157736>

- Havle, C. A., Feyzioglu, O., & Buyukozhan, G. (2021). An integrated SWOT based fuzzy AHP and fuzzy MARCOS methodology for digital transformation strategy analysis in airline industry. *Journal of Air Transport Management*, 97, 102142. <https://doi.org/10.1016/j.jairtraman.2021.102142>
- Heinzlef, C., Robert, B., Hémond, Y., & Serre, D. (2020). Operating urban resilience strategies to face climate change and associated risks: Some advances from theory to application in Canada and France. *Cities*, 104, 102762. <https://doi.org/10.1016/j.cities.2020.102762>
- Henstra, D. (2012). Toward the Climate-Resilient City: Extreme Weather and Urban Climate Adaptation Policies in Two Canadian Provinces. *Journal of Comparative Policy Analysis: Research and Practice*, 14(2), 175–194. <https://doi.org/10.1080/13876988.2012.665215>
- Hernantes, J., Maraña, P., Gimenez, R., Sarriegi, J. M., & Labaka, L. (2019). Towards resilient cities: A maturity model for operationalizing resilience. *Cities*, 84, 96–103. <https://doi.org/10.1016/j.cities.2018.07.010>
- Herrera-Viedma, E., Palomares, I., Li, C.-C., Cabrerizo, F. J., Dong, Y., Chiclana, F., & Herrera, F. (2021). Revisiting Fuzzy and Linguistic Decision Making: Scenarios and Challenges for Making Wiser Decisions in a Better Way. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 51(1), 191–208. <https://doi.org/10.1109/TSMC.2020.3043016>
- Hezam, I. M., Mishra, A. R., Rani, P., & Alshamrani, A. (2023). Assessing the barriers of digitally sustainable transportation system for persons with disabilities using Fermatean fuzzy double normalization-based multiple aggregation method. *Applied Soft Computing*, 133, 109910. <https://doi.org/10.1016/j.asoc.2022.109910>
- Hezam, I. M., Rani, P., Mishra, A. R., & Alshamrani, A. (2023). Assessment of autonomous smart wheelchairs for disabled persons using hybrid interval-valued Fermatean fuzzy combined compromise solution method. *Sustainable Energy Technologies and Assessments*, 57, 103169. <https://doi.org/10.1016/j.seta.2023.103169>
- Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, 4(1), 1–23. <https://doi.org/10.1146/annurev.es.04.110173.000245>
- Hooshangi, N., Mahdizadeh Gharakhanlou, N., & Ghaffari Razin, S. R. (2023). Evaluation of potential sites in Iran to localize solar farms using a GIS-based Fermatean Fuzzy TOPSIS. *Journal of Cleaner Production*, 384, 135481. <https://doi.org/10.1016/j.jclepro.2022.135481>
- Hsieh, C. Y., Wee, H., & Chen, A. (2016). Resilient logistics to mitigate supply chain uncertainty: A case study of an automotive company. *Scientia Iranica*, 23, 2287–2296. <https://doi.org/10.24200/sci.2016.3957>
- Huang, G., Li, D., Zhu, X., & Zhu, J. (2021). Influencing factors and their influencing mechanisms on urban resilience in China. *Sustainable Cities and Society*, 74, 103210. <https://doi.org/10.1016/j.scs.2021.103210>
- Huang, Y.-J., Cheng, S., Yang, F.-Q., & Chen, C. (2022). Analysis and Visualization of Research on Resilient Cities and Communities Based on VOSviewer. *INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH*, 19(12), 7068. <https://doi.org/10.3390/ijerph19127068>
- Hudec, O. (2017). Cities of Resilience: Integrated Adaptive Planning. *Quality Innovation Prosperity*, 21(1), 106. <https://doi.org/10.12776/qip.v21i1.776>

- Ilieva, G., & Yankova, T. (2022). Extension of Interval-Valued Fermatean Fuzzy TOPSIS for Evaluating and Benchmarking COVID-19 Vaccines. *MATHEMATICS*, 10(19). <https://doi.org/10.3390/math10193514>
- İnaç, H. (2012). *Urban logistics analysis in Istanbul and evaluation of solution suggestions with Analytical Hierarchy Process (AHP)*.
- Istanbul Metropolitan Municipality. (2015). *2015-2019 Stratejik Plan*.
- Istanbul Metropolitan Municipality. (2018). *AMBITION, VISION & ROADMAP SMART PUBLIC TRANSPORT ISTANBUL*. https://roadmapsforenergy.eu/wp-content/uploads/2017/final_city_reports/20170912_D6.4_Final_City_Report_Smart_Mobility_Public_Transport_Istanbul.pdf
- Istanbul Metropolitan Municipality. (2020a). *2020-2024 Stratejik Plan*.
- Istanbul Metropolitan Municipality. (2020b). *Istanbul Vision 2050 Strategy Document*. Istanbul Metropolitan Municipality. <https://vizyon2050.istanbul/upload/content/ebooken.pdf>
- Iturriza, M., Hernantes, J., & Labaka, L. (2019). Coming to Action: Operationalizing City Resilience. *Sustainability*, 11(11), 3054. <https://doi.org/10.3390/su11113054>
- Iturriza, M., Labaka, L., Hernantes, J., & Abdelgawad, A. (2020). Shifting to climate change aware cities to facilitate the city resilience implementation. *Cities*, 101, 102688. <https://doi.org/10.1016/j.cities.2020.102688>
- Jabareen, Y. (2013). Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk. *Cities*, 31, 220–229. <https://doi.org/10.1016/j.cities.2012.05.004>
- Jamali, A., Robati, M., Nikoomaram, H., Farsad, F., & Aghamohammadi, H. (2023). Urban Resilience Assessment Using Hybrid MCDM Model Based on DEMATEL-ANP Method (DANP). *Journal of the Indian Society of Remote Sensing*, 51(4), 893–915. <https://doi.org/10.1007/s12524-023-01670-8>
- Jan, A., Khan, A., Khan, W., & Afridi, M. (2021). A novel approach to MADM problems using Fermatean fuzzy Hamacher prioritized aggregation operators. *SOFT COMPUTING*, 25(22), 13897–13910. <https://doi.org/10.1007/s00500-021-06308-w>
- Jana, S., & Mahanta, J. (2023). Boundary of a fuzzy set and its application in GIS: A review. *Artificial Intelligence Review*, 56(7), 6477–6507. <https://doi.org/10.1007/s10462-022-10331-0>
- Javidroozi, V., Shah, H., Amini, A., & Cole, A. (2014). *Smart City as an Integrated Enterprise: A Business Process Centric Framework Addressing Challenges in Systems Integration*. July. <https://doi.org/10.13140/RG.2.1.2561.1921>
- Jeevaraj, S. (2021). Ordering of interval-valued Fermatean fuzzy sets and its applications. *Expert Systems with Applications*, 185, 115613. <https://doi.org/10.1016/j.eswa.2021.115613>
- Jiskani, I. M., Shah, S. A. A., Qingxiang, C., Zhou, W., & Lu, X. (2020). A multi-criteria based SWOT analysis of sustainable planning for mining and mineral industry in Pakistan. *Arabian Journal of Geosciences*, 13(21), 1108. <https://doi.org/10.1007/s12517-020-06090-3>
- Joshi, B. P. (2019). Pythagorean fuzzy average aggregation operators based on generalized and group-generalized parameter with application in MCDM problems. *International Journal of Intelligent Systems*, 34(5), 895–919. Scopus. <https://doi.org/10.1002/int.22080>

- Kabak, M. (2013). A Fuzzy DEMATEL-ANP Based Multi Criteria Decision Making Approach For Personnel Selection. *Journal of Multiple-Valued Logic and Soft Computing*, 20(5–6), 571–593.
- Kabak, M., Dagdeviren, M., & Burmaoglu, S. (2016). A hybrid SWOT-FANP model for energy policy making in Turkey. *Energy Sources Part B-Economics Planning and Policy*, 11(6), 487–495. <https://doi.org/10.1080/15567249.2012.673692>
- Kahraman, C., Demirel, N. Ç., & Demirel, T. (2007). Prioritization of e-Government strategies using a SWOT-AHP analysis: The case of Turkey. *European Journal of Information Systems*, 16(3), 284–298. <https://doi.org/10.1057/palgrave.ejis.3000679>
- Kahraman, C., Öztayşi, B., & Çevik, S. (2016). A Comprehensive Literature Review of 50 Years of Fuzzy Set Theory. *International Journal of Computational Intelligence Systems*, 9. <https://doi.org/10.1080/18756891.2016.1180817>
- Kakati, P., Senapati, T., Moslem, S., & Pilla, F. (2024). Fermatean fuzzy Archimedean Heronian Mean-Based Model for estimating sustainable urban transport solutions. *Engineering Applications of Artificial Intelligence*, 127, 107349. <https://doi.org/10.1016/j.engappai.2023.107349>
- Kang, H.-Y., Lee, A. H. I., Chang, C.-C., & Kang, M.-S. (2012). A Model for Selecting Technologies in New Product Development. *Mathematical Problems in Engineering*, 2012, 358129. <https://doi.org/10.1155/2012/358129>
- Kannan, G., Pokharel, S., & Kumar, P. S. (2009). A hybrid approach using ISM and fuzzy TOPSIS for the selection of reverse logistics provider. *Resources Conservation and Recycling*, 54(1), 28–36. <https://doi.org/10.1016/j.resconrec.2009.06.004>
- Kao, F., Huang, S., & Lo, H. (2022). A Rough-Fermatean DEMATEL Approach for Sustainable Development Evaluation for the Manufacturing Industry. *INTERNATIONAL JOURNAL OF FUZZY SYSTEMS*, 24(7), 3244–3264. <https://doi.org/10.1007/s40815-022-01334-8>
- Karuppiah, K., & Sankaranarayanan, B. (2023). An integrated multi-criteria decision-making approach for evaluating e-waste mitigation strategies. *Applied Soft Computing*, 144, 110420. <https://doi.org/10.1016/j.asoc.2023.110420>
- Karuppiah, K., Sankaranarayanan, B., Ali, S., AlArjani, A., & Mohamed, A. (2022). Causality analytics among key factors for green economy practices: Implications for sustainable development goals. *FRONTIERS IN ENVIRONMENTAL SCIENCE*, 10. <https://doi.org/10.3389/fenvs.2022.933657>
- Karuppiah, K., Sankaranarayanan, B., Ali, S. M., & Bhalaji, R. K. A. (2023). Decision modeling of the challenges to human–robot collaboration in industrial environment: A real world example of an emerging economy. *Flexible Services and Manufacturing Journal*, 35(4), 1007–1037. <https://doi.org/10.1007/s10696-022-09474-7>
- Kaytez, F. (2022). Evaluation of priority strategies for the expansion of installed wind power capacity in Turkey using a fuzzy analytic network process analysis. *Renewable Energy*, 196, 1281–1293. <https://doi.org/10.1016/j.renene.2022.07.043>
- Keshavarz-Ghorabae, M., Amiri, M., Hashemi-Tabatabaei, M., Zavadskas, E., & Kaklauskas, A. (2020). A New Decision-Making Approach Based on Fermatean Fuzzy Sets and WASPAS for Green Construction Supplier Evaluation. *MATHEMATICS*, 8(12). <https://doi.org/10.3390/math8122202>
- Khan, A. U., & Ali, Y. (2023). Enhancement of resilience and quality of cold supply chain under the disruptions caused by COVID-19: A case of a developing country.

- Australian Journal of Management*, 48(2), 341–365.
<https://doi.org/10.1177/03128962221095596>
- Khanam, S., Siddiqui, J., & Talib, F. (2015). Modelling the TQM enablers and IT resources in the ICT industry: An ISM-MICMAC approach. *International Journal of Information Systems and Management (IJISAM)*, 1, 195–218.
<https://doi.org/10.1504/IJISAM.2015.072290>
- Khatibi, H., Wilkinson, S., Eriwata, G., Sweya, L., Baghersad, M., Dianat, H., Ghaedi, K., & Javanmardi, A. (2022). An integrated framework for assessment of smart city resilience. *Environment and Planning B: Urban Analytics and City Science*, 49, 239980832210924. <https://doi.org/10.1177/23998083221092422>
- Khezeli, M., Najafi, E., Molana, M. H., & Seidi, M. (2023). A sustainable and resilient supply chain (RS-SCM) by using synchronisation and load-sharing approach: Application in the oil and gas refinery. *International Journal of Systems Science: Operations & Logistics*, 10(1), 2198055.
<https://doi.org/10.1080/23302674.2023.2198055>
- Kiba-janiak, M. (2016). Key success factors for city logistics from the perspective of various groups of stakeholders. 12(6), 557–569.
<https://doi.org/10.1016/j.trpro.2016.02.011>
- Kim, D., & Lim, U. (2016). Urban Resilience in Climate Change Adaptation: A Conceptual Framework. *Sustainability*, 8(4), 405.
<https://doi.org/10.3390/su8040405>
- Kim, D., & Song, S.-K. (2018). Measuring changes in urban functional capacity for climate resilience: Perspectives from Korea. *Futures*, 102, 89–103.
<https://doi.org/10.1016/j.futures.2018.05.001>
- Kirişçi, M. (2023). Data analysis for panoramic X-ray selection: Fermatean fuzzy type correlation coefficients approach. *Engineering Applications of Artificial Intelligence*, 126, 106824. <https://doi.org/10.1016/j.engappai.2023.106824>
- Kirisci, M., Demir, I., & Simsek, N. (2022). Fermatean fuzzy ELECTRE multi-criteria group decision-making and most suitable biomedical material selection. *ARTIFICIAL INTELLIGENCE IN MEDICINE*, 127.
<https://doi.org/10.1016/j.artmed.2022.102278>
- Kirişçi, M., & Simsek, N. (2023). A novel kernel principal component analysis with application disaster preparedness of hospital: Interval-valued Fermatean fuzzy set approach. *The Journal of Supercomputing*, 79(17), 19848–19878.
<https://doi.org/10.1007/s11227-023-05395-w>
- Kita, S. M. (2017). Urban vulnerability, disaster risk reduction and resettlement in Mzuzu city, Malawi. *International Journal of Disaster Risk Reduction*, 22, 158–166.
<https://doi.org/10.1016/j.ijdrr.2017.03.010>
- Kocak, B., Yardimci, A. H., Yuzkan, S., Keles, A., Altun, O., Bulut, E., Bayrak, O. N., & Okumus, A. A. (2023). Transparency in Artificial Intelligence Research: A Systematic Review of Availability Items Related to Open Science in Radiology and Nuclear Medicine. *Academic Radiology*, 30(10), 2254–2266.
<https://doi.org/10.1016/j.acra.2022.11.030>
- Korucuk, S., Aytekin, A., Ecer, F., Karamasa, C., & Zavadskas, E. (2022). Assessing Green Approaches and Digital Marketing Strategies for Twin Transition via Fermatean Fuzzy SWARA-COPRAS. *AXIOMS*, 11(12).
<https://doi.org/10.3390/axioms11120709>
- Kumar, P., & Kumar Singh, R. (2022). Strategic framework for developing resilience in Agri-Food Supply Chains during COVID 19 pandemic. *International Journal of*

- Logistics Research and Applications*, 25(11), 1401–1424. <https://doi.org/10.1080/13675567.2021.1908524>
- Kumar, R., Khepar, J., Yadav, K., Kareri, E., Alotaibi, S. D., Viriyasitavat, W., Gulati, K., Kotecha, K., & Dhiman, G. (2022). A Systematic Review on Generalized Fuzzy Numbers and Its Applications: Past, Present and Future. *Archives of Computational Methods in Engineering*, 29(7), 5213–5236. <https://doi.org/10.1007/s11831-022-09779-8>
- Kumar, S., Sharma, D., Rao, S., Lim, W. M., & Mangla, S. K. (2022). Past, present, and future of sustainable finance: Insights from big data analytics through machine learning of scholarly research. *Annals of Operations Research*. <https://doi.org/10.1007/s10479-021-04410-8>
- Kumar, S. V. (2018). *A Survey on Choosing the Right IOT Technology Platform*. <https://www.semanticscholar.org/paper/A-Survey-on-Choosing-the-Right-IOT-Technology-Kumar/b3121655cb745d5dcc5a1822c75a6f1aed49cd5f>
- Kutlu Gündoğdu, F., & Kahraman, C. (2020). A novel spherical fuzzy analytic hierarchy process and its renewable energy application. *Soft Computing*, 24(6), 4607–4621. <https://doi.org/10.1007/s00500-019-04222-w>
- Kutty, A. A., Kucukvar, M., Onat, N. C., Ayvaz, B., & Abdella, G. M. (2023). Measuring sustainability, resilience and livability performance of European smart cities: A novel fuzzy expert-based multi-criteria decision support model. *Cities*, 137, 104293. <https://doi.org/10.1016/j.cities.2023.104293>
- Kutty, A. A., Wakjira, T. G., Kucukvar, M., Abdella, G. M., & Onat, N. C. (2022). Urban resilience and livability performance of European smart cities: A novel machine learning approach. *JOURNAL OF CLEANER PRODUCTION*, 378, 134203. <https://doi.org/10.1016/j.jclepro.2022.134203>
- Labaka, L., Maraña, P., Giménez, R., & Hernantes, J. (2019). Defining the roadmap towards city resilience. *Technological Forecasting and Social Change*, 146, 281–296. <https://doi.org/10.1016/j.techfore.2019.05.019>
- Lai, H., Liao, H., Long, Y., & Zavadskas, E. (2022). A Hesitant Fermatean Fuzzy CoCoSo Method for Group Decision-Making and an Application to Blockchain Platform Evaluation. *INTERNATIONAL JOURNAL OF FUZZY SYSTEMS*, 24(6), 2643–2661. <https://doi.org/10.1007/s40815-022-01319-7>
- Lak, A., Hakimian, P., & Sharifi, A. (2021). An evaluative model for assessing pandemic resilience at the neighborhood level: The case of Tehran. *Sustainable Cities and Society*, 75, 103410. <https://doi.org/10.1016/j.scs.2021.103410>
- Lak, A., Hasankhan, F., & Garakani, S. A. (2020). Principles in practice: Toward a conceptual framework for resilient urban design. *Journal of Environmental Planning and Management*, 0(0), 1–33. <https://doi.org/10.1080/09640568.2020.1714561>
- Lam, J. S. L., & Bai, X. (2016). A quality function deployment approach to improve maritime supply chain resilience. *Transportation Research Part E: Logistics and Transportation Review*, 92, 16–27. <https://doi.org/10.1016/j.tre.2016.01.012>
- Lamba, K., & Singh, S. P. (2018). Modeling big data enablers for operations and supply chain management. *International Journal of Logistics Management*, 29(2), 629–658. <https://doi.org/10.1108/IJLM-07-2017-0183>
- Lanlan, J., Sarker, M. N. I., Ali, I., Firdaus, R. B. R., & Hossin, M. A. (2023). Vulnerability and resilience in the context of natural hazards: A critical conceptual analysis. *ENVIRONMENT DEVELOPMENT AND SUSTAINABILITY*. <https://doi.org/10.1007/s10668-023-03440-5>

- Lee, H.-C., & Chang, C.-T. (2018). Comparative analysis of MCDM methods for ranking renewable energy sources in Taiwan. *Renewable and Sustainable Energy Reviews*, 92, 883–896. <https://doi.org/10.1016/j.rser.2018.05.007>
- Li, G., Kou, C., Wang, Y., & Yang, H. (2020). System dynamics modelling for improving urban resilience in Beijing, China. *Resources, Conservation and Recycling*, 161, 104954. <https://doi.org/10.1016/j.resconrec.2020.104954>
- Li, J., Jiang, Y., Zhai, M., Gao, J., Yao, Y., & Li, Y. (2023). Construction and application of sponge city resilience evaluation system: A case study in Xi'an, China. *Environmental Science and Pollution Research*, 30(22), 62051–62066. <https://doi.org/10.1007/s11356-023-26357-y>
- Li, L., Uyttenhove, P., & Van Eetvelde, V. (2020). Planning green infrastructure to mitigate urban surface water flooding risk – A methodology to identify priority areas applied in the city of Ghent. *Landscape and Urban Planning*, 194, 103703. <https://doi.org/10.1016/j.landurbplan.2019.103703>
- Li, Z., Zhang, X., Ma, Y., Feng, C., & Hajiyev, A. (2019). A multi-criteria decision making method for urban flood resilience evaluation with hybrid uncertainties. *International Journal of Disaster Risk Reduction*, 36, 101140. <https://doi.org/10.1016/j.ijdrr.2019.101140>
- Liang, W., Zhang, X., & Liu, M. (2015). The Maximizing Deviation Method Based on Interval-Valued Pythagorean Fuzzy Weighted Aggregating Operator for Multiple Criteria Group Decision Analysis. *Discrete Dynamics in Nature and Society*, 2015, 1–15. <https://doi.org/10.1155/2015/746572>
- Lin, L.-Z., & Lu, C.-F. (2013). Fuzzy Group Decision-Making in the Measurement of Ecotourism Sustainability Potential. *Group Decision and Negotiation*, 22(6), 1051–1079. <https://doi.org/10.1007/s10726-012-9305-7>
- Liu, D., Liu, Y., & Chen, X. (2019). Fermatean fuzzy linguistic set and its application in multicriteria decision making. *INTERNATIONAL JOURNAL OF INTELLIGENT SYSTEMS*, 34(5), 878–894. <https://doi.org/10.1002/int.22079>
- Liu, D., Liu, Y., & Wang, L. (2019). Distance measure for Fermatean fuzzy linguistic term sets based on linguistic scale function: An illustration of the TODIM and TOPSIS methods. *INTERNATIONAL JOURNAL OF INTELLIGENT SYSTEMS*, 34(11), 2807–2834. <https://doi.org/10.1002/int.22162>
- Liu, L., Lei, Y., Zhuang, M., & Ding, S. (2022). The impact of climate change on urban resilience in the Beijing-Tianjin-Hebei region. *SCIENCE OF THE TOTAL ENVIRONMENT*, 827, 154157. <https://doi.org/10.1016/j.scitotenv.2022.154157>
- Liu, P., Rani, P., & Mishra, A. (2022). COPRAS method based on interval-valued hesitant Fermatean fuzzy sets and its application in selecting desalination technology. *APPLIED SOFT COMPUTING*, 119. <https://doi.org/10.1016/j.asoc.2022.108570>
- Liu, S.-C., Peng, F.-L., Qiao, Y.-K., & Zhang, J.-B. (2021). Evaluating disaster prevention benefits of underground space from the perspective of urban resilience. *International Journal of Disaster Risk Reduction*, 58, 102206. <https://doi.org/10.1016/j.ijdrr.2021.102206>
- Liu, X., Li, S., Xu, X., & Luo, J. (2021). Integrated natural disasters urban resilience evaluation: The case of China. *NATURAL HAZARDS*, 107(3), 2105–2122. <https://doi.org/10.1007/s11069-020-04478-8>
- Liu, Y., Liu, J., & Qin, Y. (2020). Pythagorean fuzzy linguistic Muirhead mean operators and their applications to multiattribute decision-making. *International Journal of Intelligent Systems*, 35(2), 300–332. Scopus. <https://doi.org/10.1002/int.22212>

- Liu, Y., Liu, W., Zhang, X., Lin, Y., Zheng, G., Zhao, Z., Cheng, H., Gross, L., Li, X., Wei, B., & Su, F. (2023). Nighttime light perspective in urban resilience assessment and spatiotemporal impact of COVID-19 from January to June 2022 in mainland China. *Urban Climate*, 50, 101591. <https://doi.org/10.1016/j.uclim.2023.101591>
- Liu, Z., Ma, R., & Wang, H. (2022). Assessing urban resilience to public health disaster using the rough analytic hierarchy process method: A regional study in China. *Journal of Safety Science and Resilience*, 3(2), 93–104. <https://doi.org/10.1016/j.jnlssr.2021.12.003>
- Lu, P., & Stead, D. (2013). Understanding the notion of resilience in spatial planning: A case study of Rotterdam, The Netherlands. *Cities*, 35, 200–212. <https://doi.org/10.1016/j.cities.2013.06.001>
- Luo, S., & Liu, J. (2022). An innovative index system and HFFS-MULTIMOORA method based group decision-making framework for regional green development level evaluation. *EXPERT SYSTEMS WITH APPLICATIONS*, 189. <https://doi.org/10.1016/j.eswa.2021.116090>
- Luqman, A., & Shahzadi, G. (2023). Multi-attribute decision-making for electronic waste recycling using interval-valued Fermatean fuzzy Hamacher aggregation operators. *Granular Computing*, 8(5), 991–1012. <https://doi.org/10.1007/s41066-023-00363-4>
- Mabrouk, M., & Haoying, H. (2023). Urban resilience assessment: A multicriteria approach for identifying urban flood-exposed risky districts using multiple-criteria decision-making tools (MCDM). *International Journal of Disaster Risk Reduction*, 91, 103684. <https://doi.org/10.1016/j.ijdrr.2023.103684>
- Mahdiraji, H. A., Yafitayan, F., Abbasi-Kamardi, A., Jafari-Sadeghi, V., Sahut, J.-M., & Dana, L.-P. (2023). A synthesis of boundary conditions with adopting digital platforms in SMEs: An intuitionistic multi-layer decision-making framework. *The Journal of Technology Transfer*. <https://doi.org/10.1007/s10961-023-10028-8>
- Maihemuti, S., Wang, W., Wu, J., & Wang, H. (2022). New energy power system operation security evaluation based on the SWOT analysis. *Scientific Reports*, 12(1), Article 1. <https://doi.org/10.1038/s41598-022-16444-4>
- Majewska, A., Denis, M., Jarecka-Bidzinska, E., Jaroszewicz, J., & Krupowicz, W. (2022). Pandemic resilient cities: Possibilities of repairing Polish towns and cities during COVID-19 pandemic. *LAND USE POLICY*, 113, 105904. <https://doi.org/10.1016/j.landusepol.2021.105904>
- Making urban freight logistics more sustainable*. (n.d.).
- Makki, A. A., & Alqahtani, A. Y. (2022). Modeling the Enablers to FinTech Innovation in Saudi Arabia: A Hybrid Approach Using ISM and ANP. *Systems*, 10(5), 181. <https://doi.org/10.3390/systems10050181>
- Mao, D., Yang, H., Zhang, S., Sun, H., & Wang, X. (2023). Adaptive Behavioral Dynamics in Public Open Spaces During the COVID-19 Pandemic: A Technological Perspective on Urban Resilience. *Journal of the Knowledge Economy*, 1–27. <https://doi.org/10.1007/s13132-023-01591-4>
- Marana, P., Labaka, L., & Sarriegi, J. M. (2018). A framework for public-private-people partnerships in the city resilience-building process. *Safety Science*, 110, 39–50. <https://doi.org/10.1016/j.ssci.2017.12.011>
- Maraña, P., Labaka, L., & Sarriegi, J. M. (2020). We need them all: Development of a public private people partnership to support a city resilience building process.

- Technological Forecasting and Social Change*, 154, 119954. <https://doi.org/10.1016/j.techfore.2020.119954>
- Mardani, A., Saraji, M. K., Mishra, A. R., & Rani, P. (2020). A novel extended approach under hesitant fuzzy sets to design a framework for assessing the key challenges of digital health interventions adoption during the COVID-19 outbreak. *Applied Soft Computing*, 96, 106613. <https://doi.org/10.1016/j.asoc.2020.106613>
- Masnavi, M. R., Gharai, F., & Hajibandeh, M. (2019). Exploring urban resilience thinking for its application in urban planning: A review of literature. *International Journal of Environmental Science and Technology*, 16(1), 567–582. <https://doi.org/10.1007/s13762-018-1860-2>
- Mateen, M. H., Al-Dayel, I., & Alsuraiheed, T. (2023). Fermatean Fuzzy Fairly Aggregation Operators with Multi-Criteria Decision-Making. *Axioms*, 12(9), Article 9. <https://doi.org/10.3390/axioms12090865>
- McCartney, G., Pinto, J., & Liu, M. (2021). City resilience and recovery from COVID-19: The case of Macao. *Cities*, 112, 103130. <https://doi.org/10.1016/j.cities.2021.103130>
- McGill, R. (2020). Urban resilience – An urban management perspective. *Journal of Urban Management*, 9(3), 372–381. <https://doi.org/10.1016/j.jum.2020.04.004>
- Medyk, S. (2017). *Partner Selection and Value Network Analysis for Internet of Things Vendors – Defining a Smart City Strategic Alliance* [fi=Ylempi AMK-opinnäytetyö|sv=Högre YH-examensarbete|en=Master's thesis]. Metropolia Ammattikorkeakoulu. <http://www.theseus.fi/handle/10024/126826>
- Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning*, 147, 38–49. <https://doi.org/10.1016/j.landurbplan.2015.11.011>
- Megahed, N. A., & Ghoneim, E. M. (2020). Antivirus-built environment: Lessons learned from Covid-19 pandemic. *Sustainable Cities and Society*, 61, 102350. <https://doi.org/10.1016/j.scs.2020.102350>
- Mierzejewska, L., & Wdowicka, M. (2018). City Resilience vs. Resilient City: Terminological Intricacies and Concept Inaccuracies. *Quaestiones Geographicae*, 37(2), 7–15. <https://doi.org/10.2478/quageo-2018-0018>
- Milenkovic, M., Glavic, D., & Mladenovic, M. N. (2018). Decision-Support Framework for Selecting the Optimal Road Toll Collection System. *Journal of Advanced Transportation*, 4949565. <https://doi.org/10.1155/2018/4949565>
- Mishra, A., Bullet, P., & Pandey, K. (2022). Fermatean fuzzy CRITIC-EDAS approach for the selection of sustainable third-party reverse logistics providers using improved generalized score function. *JOURNAL OF AMBIENT INTELLIGENCE AND HUMANIZED COMPUTING*, 13(1), 295–311. <https://doi.org/10.1007/s12652-021-02902-w>
- Mishra, A. R., Chen, S.-M., & Rani, P. (2023). Multicriteria decision making based on novel score function of Fermatean fuzzy numbers, the CRITIC method, and the GLDS method. *Information Sciences*, 623, 915–931. <https://doi.org/10.1016/j.ins.2022.12.031>
- Mishra, A. R., Rani, P., Deveci, M., Gokasar, I., Pamucar, D., & Govindan, K. (2023). Interval-valued Fermatean fuzzy heronian mean operator-based decision-making method for urban climate change policy for transportation activities. *Engineering Applications of Artificial Intelligence*, 124, 106603. <https://doi.org/10.1016/j.engappai.2023.106603>

- Mishra, A., & Rani, P. (2021). Multi-criteria healthcare waste disposal location selection based on Fermatean fuzzy WASPAS method. *COMPLEX & INTELLIGENT SYSTEMS*, 7(5), 2469–2484. <https://doi.org/10.1007/s40747-021-00407-9>
- Mishra, A., Rani, P., Saha, A., Hezam, I., Pamucar, D., Marinovic, M., & Pandey, K. (2022). Assessing the Adaptation of Internet of Things (IoT) Barriers for Smart Cities' Waste Management Using Fermatean Fuzzy Combined Compromise Solution Approach. *IEEE ACCESS*, 10, 37109–37130. <https://doi.org/10.1109/ACCESS.2022.3164096>
- Mishra, A., Rani, P., Saha, A., Senapati, T., Hezam, I., & Yager, R. (2022). Fermatean fuzzy copula aggregation operators and similarity measures-based complex proportional assessment approach for renewable energy source selection. *COMPLEX & INTELLIGENT SYSTEMS*, 8(6), 5223–5248. <https://doi.org/10.1007/s40747-022-00743-4>
- Mishra, S., Singh, S. P., Johansen, J., Cheng, Y., & Farooq, S. (2019). Evaluating indicators for international manufacturing network under circular economy. *Management Decision*, 57(4), 811–839. <https://doi.org/10.1108/MD-05-2018-0565>
- Moeuf, A., Lamouri, S., Pellerin, R., Tamayo-Giraldo, S., Tobon-Valencia, E., & Eburdy, R. (2020). Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs. *International Journal of Production Research*, 58(5), 1384–1400. <https://doi.org/10.1080/00207543.2019.1636323>
- Moghadas, M., Asadzadeh, A., Vafeidis, A., Fekete, A., & Kötter, T. (2019). A multi-criteria approach for assessing urban flood resilience in Tehran, Iran. *International Journal of Disaster Risk Reduction*, 35, 101069. <https://doi.org/10.1016/j.ijdrr.2019.101069>
- Mohammadi, N., & Sakhteh, S. (2023). Start-up accelerator value chain: A systematic literature review. *Management Review Quarterly*, 73(2), 661–694. <https://doi.org/10.1007/s11301-021-00257-2>
- Moktadir, Md. A., & Ren, J. (2023a). Leveraging environmental, social, and governance strategies for sustainable tannery solid waste management towards achieving sustainable development goals. *Sustainable Development*, n/a(n/a). <https://doi.org/10.1002/sd.2812>
- Moktadir, Md. A., & Ren, J. (2023b). Modeling challenges for Industry 4.0 implementation in new energy systems towards carbon neutrality: Implications for impact assessment policy and practice in emerging economies. *Resources, Conservation and Recycling*, 199, 107246. <https://doi.org/10.1016/j.resconrec.2023.107246>
- Molavi, M. (2018). Measuring Urban Resilience to Natural Hazards. *TeMA - Journal of Land Use, Mobility and Environment*, 11(2), 195–212. <https://doi.org/10.6092/1970-9870/5485>
- Mondal, A., Roy, S., & Pamucar, D. (2023). Regret-based three-way decision making with possibility dominance and SPA theory in incomplete information system. *EXPERT SYSTEMS WITH APPLICATIONS*, 211. <https://doi.org/10.1016/j.eswa.2022.118688>
- Moraci, F., Errigo, M., Fazia, C., Burgio, G., & Foresta, S. (2018). Making Less Vulnerable Cities: Resilience as a New Paradigm of Smart Planning. *Sustainability*, 10(3), 755. <https://doi.org/10.3390/su10030755>

- Mouratidis, K. (2022). COVID-19 and the compact city: Implications for well-being and sustainable urban planning. *Science of The Total Environment*, 811, 152332. <https://doi.org/10.1016/j.scitotenv.2021.152332>
- Mukeshimana, M. C., Zhao, Z.-Y., & Nshimiyimana, J. P. (2021). Evaluating strategies for renewable energy development in Rwanda: An integrated SWOT – ISM analysis. *Renewable Energy*, 176, 402–414. <https://doi.org/10.1016/j.renene.2021.05.104>
- Narayanamoorthy, S., Parthasarathy, T., Pragathi, S., Shanmugam, P., Baleanu, D., Ahmadian, A., & Kang, D. (2022). The novel augmented Fermatean MCDM perspectives for identifying the optimal renewable energy power plant location. *SUSTAINABLE ENERGY TECHNOLOGIES AND ASSESSMENTS*, 53. <https://doi.org/10.1016/j.seta.2022.102488>
- Nasrollahi, M., Fathi, M. R., Sobhani, S. M., Khosravi, A., & Noorbakhsh, A. (2021). Modeling resilient supplier selection criteria in desalination supply chain based on fuzzy DEMATEL and ISM. *International Journal of Management Science and Engineering Management*, 16(4), 264–278. <https://doi.org/10.1080/17509653.2021.1965502>
- National Institute of Urban Affairs & The Energy and Resources Institute. (2020). *MAINSTREAMING URBAN RESILIENCE: Lessons from Indian Cities*.
- Niu, W., Rong, Y., Yu, L., & Huang, L. (2022). A Novel Hybrid Group Decision Making Approach Based on EDAS and Regret Theory under a Fermatean Cubic Fuzzy Environment. *Mathematics*, 10(17), 3116. <https://doi.org/10.3390/math10173116>
- Nowicka, K. (2014). Smart City logistics on cloud computing model. *Procedia - Social and Behavioral Sciences*, 151, 266–281. <https://doi.org/10.1016/j.sbspro.2014.10.025>
- Oke, A. E., O. Aghimien, D., I. Akinradewo, O., & O. Aigbavboa, C. (2020). Improving resilience of cities through smart city drivers. *Construction Economics and Building*, 20(2). <https://doi.org/10.5130/AJCEB.v20i2.6647>
- Olazabal, M., & Pascual, U. (2016). Use of fuzzy cognitive maps to study urban resilience and transformation. *Environmental Innovation and Societal Transitions*, 18, 18–40. <https://doi.org/10.1016/j.eist.2015.06.006>
- Opricovic, S., & Tzeng, G.-H. (2004). Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research*, 156(2), 445–455. [https://doi.org/10.1016/S0377-2217\(03\)00020-1](https://doi.org/10.1016/S0377-2217(03)00020-1)
- Otay, İ., & Kahraman, C. (2022). A novel circular intuitionistic fuzzy AHP&VIKOR methodology: An application to a multi-expert supplier evaluation problem. *Pamukkale University Journal of Engineering Sciences*, 28(1), 194–207. <https://doi.org/10.5505/pajes.2021.90023>
- Ozuduru, B. H., Varol, C., & Yalciner Ercoskun, O. (2014). Do shopping centers abate the resilience of shopping streets? The co-existence of both shopping venues in Ankara, Turkey. *Cities*, 36, 145–157. <https://doi.org/10.1016/j.cities.2012.10.003>
- Pan, J.-S., Hu, P., Snášel, V., & Chu, S.-C. (2023). A survey on binary metaheuristic algorithms and their engineering applications. *Artificial Intelligence Review*, 56(7), 6101–6167. <https://doi.org/10.1007/s10462-022-10328-9>
- Pan, Y., Zeng, S., Chen, W., & Gu, J. (2023). Service quality evaluation of crowdsourcing logistics platform based on Fermatean fuzzy TODIM and regret theory. *Engineering Applications of Artificial Intelligence*, 123, 106385. <https://doi.org/10.1016/j.engappai.2023.106385>

- Papapostolou, A., Karakosta, C., Apostolidis, G., & Doukas, H. (2020). An AHP-SWOT-Fuzzy TOPSIS Approach for Achieving a Cross-Border RES Cooperation. *Sustainability*, 12(7), 2886. <https://doi.org/10.3390/su12072886>
- Parizi, S. M., Taleai, M., & Sharifi, A. (2021). Integrated methods to determine urban physical resilience characteristics and their interactions. *Natural Hazards*, 109(1), 725–754. <https://doi.org/10.1007/s11069-021-04855-x>
- Peng, X., & Dai, J. (2020). A bibliometric analysis of neutrosophic set: Two decades review from 1998 to 2017. *Artificial Intelligence Review*. <https://doi.org/10.1007/s10462-018-9652-0>
- Peng, X., & Selvachandran, G. (2019). Pythagorean fuzzy set: State of the art and future directions. *Artificial Intelligence Review*, 52(3), 1873–1927. Scopus. <https://doi.org/10.1007/s10462-017-9596-9>
- Pieroni, A., Scarpato, N., Nunzio, L. D., Fallucchi, F., & Raso, M. (2018). *Smarter City: Smart Energy Grid based on Blockchain Technology Smarter City: Smart Energy Grid based on Blockchain Technology*. February. <https://doi.org/10.18517/ijaseit.8.1.4954>
- Piltan, M., & Sowlati, T. (2016). A multi-criteria decision support model for evaluating the performance of partnerships. *Expert Systems with Applications*, 45, 373–384. <https://doi.org/10.1016/j.eswa.2015.10.002>
- Pizzo, B. (2015). Problematizing resilience: Implications for planning theory and practice. *Cities*, 43, 133–140. <https://doi.org/10.1016/j.cities.2014.11.015>
- POLIS, and Rupprecht Consult - Forschung & Beratung GmbH (eds). (2021). *Topic Guide: Planning for more resilient and robust urban mobility*. <https://civitas.eu/resources/topic-guide-planning-for-more-resilient-and-robust-urban-mobility>
- Powley, E. H. (2009). Reclaiming resilience and safety: Resilience activation in the critical period of crisis. *Human Relations*, 62(9), 1289–1326. <https://doi.org/10.1177/0018726709334881>
- Qi, G., Atef, M., & Yang, B. (2024). Fermatean fuzzy covering-based rough set and their applications in multi-attribute decision-making. *Engineering Applications of Artificial Intelligence*, 127, 107181. <https://doi.org/10.1016/j.engappai.2023.107181>
- Qin, H., Peng, Q., Ma, X., & Zhan, J. (2023). A new multi-attribute decision making approach based on new score function and hybrid weighted score measure in interval-valued Fermatean fuzzy environment. *Complex & Intelligent Systems*, 9(5), 5359–5376. <https://doi.org/10.1007/s40747-023-01021-7>
- Qiu, D., Lv, B., & Chan, C. M. L. (2022). How Digital Platforms Enhance Urban Resilience. *Sustainability*, 14(3), Article 3. <https://doi.org/10.3390/su14031285>
- Rahimirad, Z., & Sadabadi, A. A. (2023). Green hydrogen technology development and usage policymaking in Iran using SWOT analysis and MCDM methods. *International Journal of Hydrogen Energy*, 48(40), 15179–15194. <https://doi.org/10.1016/j.ijhydene.2023.01.035>
- Rajak, S., Mathiyazhagan, K., Agarwal, V., Sivakumar, K., Kumar, V., & Appolloni, A. (2022). Issues and analysis of critical success factors for the sustainable initiatives in the supply chain during COVID- 19 pandemic outbreak in India: A case study. *Research in Transportation Economics*, 93, 101114. <https://doi.org/10.1016/j.retrec.2021.101114>
- Ramsey, M. M., Muñoz-Erickson, T. A., Mélendez-Ackerman, E., Nytch, C. J., Branoff, B. L., & Carrasquillo-Medrano, D. (2019). Overcoming barriers to knowledge

- integration for urban resilience: A knowledge systems analysis of two-flood prone communities in San Juan, Puerto Rico. *Environmental Science & Policy*, 99, 48–57. <https://doi.org/10.1016/j.envsci.2019.04.013>
- Rani, P., & Mishra, A. (2021). Fermatean fuzzy Einstein aggregation operators-based MULTIMOORA method for electric vehicle charging station selection. *EXPERT SYSTEMS WITH APPLICATIONS*, 182. <https://doi.org/10.1016/j.eswa.2021.115267>
- Rani, P., & Mishra, A. (2022). Interval-valued fermatean fuzzy sets with multi-criteria weighted aggregated sum product assessment-based decision analysis framework. *NEURAL COMPUTING & APPLICATIONS*, 34(10), 8051–8067. <https://doi.org/10.1007/s00521-021-06782-1>
- Rani, P., Mishra, A., Deveci, M., & Antucheviciene, J. (2022). New complex proportional assessment approach using Einstein aggregation operators and improved score function for interval-valued Fermatean fuzzy sets. *COMPUTERS & INDUSTRIAL ENGINEERING*, 169. <https://doi.org/10.1016/j.cie.2022.108165>
- Rani, P., Mishra, A., Saha, A., Hezam, I., & Pamucar, D. (2022). Fermatean fuzzy Heronian mean operators and MEREC-based additive ratio assessment method: An application to food waste treatment technology selection. *INTERNATIONAL JOURNAL OF INTELLIGENT SYSTEMS*, 37(3), 2612–2647. <https://doi.org/10.1002/int.22787>
- Rao, C. N., & Sujatha, M. (2023). A consensus-based Fermatean fuzzy WASPAS methodology for selection of healthcare waste treatment technology selection. *Decision Making: Applications in Management and Engineering*, 6(2), Article 2. <https://doi.org/10.31181/dmame622023621>
- RazaviToosi, S. L., & Samani, J. M. (2019). A Fuzzy Group Decision Making Framework Based on ISM-FANP-FTOPSIS for Evaluating Watershed Management Strategies. *Water Resources Management*, 33(15), 5169–5190. <https://doi.org/10.1007/s11269-019-02423-4>
- Rehman, O. ur, & Ali, Y. (2021). Enhancing healthcare supply chain resilience: Decision-making in a fuzzy environment. *The International Journal of Logistics Management*, 33(2), 520–546. <https://doi.org/10.1108/IJLM-01-2021-0004>
- Restemeyer, B., Woltjer, J., & van den Brink, M. (2015). A strategy-based framework for assessing the flood resilience of cities – A Hamburg case study. *Planning Theory & Practice*, 16(1), 45–62. <https://doi.org/10.1080/14649357.2014.1000950>
- Rezaei, H., Macioszek, E., Derakhshesh, P., Houshyar, H., Ghabouli, E., Bakhshi Lomer, A. R., Ghanbari, R., & Esmailzadeh, A. (2023). A Spatial Decision Support System for Modeling Urban Resilience to Natural Hazards. *Sustainability*, 15(11), Article 11. <https://doi.org/10.3390/su15118777>
- Rezvani, S. M., de Almeida, N. M., Falcão, M. J., & Duarte, M. (2022). Enhancing urban resilience evaluation systems through automated rational and consistent decision-making simulations. *Sustainable Cities and Society*, 78, 103612. <https://doi.org/10.1016/j.scs.2021.103612>
- Ribeiro, P. J. G., & Pena Jardim Gonçalves, L. A. (2019). Urban resilience: A conceptual framework. *Sustainable Cities and Society*, 50, 101625. <https://doi.org/10.1016/j.scs.2019.101625>
- Rodríguez-Izquierdo, E., Cid, A., García-Meneses, P. M., Peña-Sanabria, K. A., Lerner, A. M., Matus-Kramer, A., & Escalante, A. E. (2022). From resilience attributes to city resilience. *Landscape and Urban Planning*, 226, 104485. <https://doi.org/10.1016/j.landurbplan.2022.104485>

- Romero-Lankao, P., Gnatz, D. M., & Sperling, J. B. (2016). Examining urban inequality and vulnerability to enhance resilience: Insights from Mumbai, India. *Climatic Change*, 139(3–4), 351–365. <https://doi.org/10.1007/s10584-016-1813-z>
- Rong, Y., Yu, L., Niu, W., Liu, Y., Senapati, T., & Mishra, A. (2022). MARCOS approach based upon cubic Fermatean fuzzy set and its application in evaluation and selecting cold chain logistics distribution center. *ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE*, 116. <https://doi.org/10.1016/j.engappai.2022.105401>
- Rose, Bell, Autry, & Cherry. (2017). Urban Logistics: Establishing Key Concepts and Building a Conceptual Framework for Future Research. *Transportation Journal*, 56(4), 357. <https://doi.org/10.5325/transportationj.56.4.0357>
- Ruan, C., & Chen, X. (2023). Probabilistic Interval-Valued Fermatean Hesitant Fuzzy Set and Its Application to Multi-Attribute Decision Making. *Axioms*, 12(10), Article 10. <https://doi.org/10.3390/axioms12100979>
- Ruan, J., Chen, Y., & Yang, Z. (2021). Assessment of temporal and spatial progress of urban resilience in Guangzhou under rainstorm scenarios. *International Journal of Disaster Risk Reduction*, 66, 102578. <https://doi.org/10.1016/j.ijdrr.2021.102578>
- S., J., Gokasar, I., Deveci, M., Delen, D., Zaidan, B. B., Wen, X., Shang, W.-L., & Kou, G. (2023). Adoption of energy consumption in urban mobility considering digital carbon footprint: A two-phase interval-valued Fermatean fuzzy dominance methodology. *Engineering Applications of Artificial Intelligence*, 126, 106836. <https://doi.org/10.1016/j.engappai.2023.106836>
- Saaty, T. L. (2006). The Analytic Network Process. In T. L. Saaty & L. G. Vargas (Eds.), *Decision Making with the Analytic Network Process: Economic, Political, Social and Technological Applications with Benefits, Opportunities, Costs and Risks* (pp. 1–26). Springer US. https://doi.org/10.1007/0-387-33987-6_1
- Saha, A., Pamucar, D., Gorcun, O. F., & Mishra, A. R. (2023). Warehouse site selection for the automotive industry using a fermatean fuzzy-based decision-making approach. *EXPERT SYSTEMS WITH APPLICATIONS*, 211, 118497. <https://doi.org/10.1016/j.eswa.2022.118497>
- Saikia, B., Dutta, P., & Talukdar, P. (2023). An advanced similarity measure for Pythagorean fuzzy sets and its applications in transportation problem. *Artificial Intelligence Review*. <https://doi.org/10.1007/s10462-023-10421-7>
- Sajjad, M., Chan, J. C. L., & Chopra, S. S. (2021). Rethinking disaster resilience in high-density cities: Towards an urban resilience knowledge system. *Sustainable Cities and Society*, 69, 102850. <https://doi.org/10.1016/j.scs.2021.102850>
- Samarakkody, A., Amaratunga, D., & Haigh, R. (2022). Characterising Smartness to Make Smart Cities Resilient. *SUSTAINABILITY*, 14(19), 12716. <https://doi.org/10.3390/su141912716>
- Samarakkody, A., Amaratunga, D., & Haigh, R. (2023). Technological Innovations for Enhancing Disaster Resilience in Smart Cities: A Comprehensive Urban Scholar's Analysis. *Sustainability*, 15(15), Article 15. <https://doi.org/10.3390/su151512036>
- Saracoglu, B. O., Ohunakin, O. S., Adelekan, D. S., Gill, J., Atiba, O. E., Okokpujie, I. P., & Atayero, A. A. (2018). A framework for selecting the location of very large photovoltaic solar power plants on a global/supergrid. *Energy Reports*, 4, 586–602. <https://doi.org/10.1016/j.egyr.2018.09.002>

- Saraji, M., Streimikiene, D., & Kyriakopoulos, G. (2021). Fermatean Fuzzy CRITIC-COPRAS Method for Evaluating the Challenges to Industry 4.0 Adoption for a Sustainable Digital Transformation. *SUSTAINABILITY*, 13(17). <https://doi.org/10.3390/su13179577>
- Sathyan, R., Palanisamy, P., Suresh, G., & Navin, M. (2022). Modelling the drivers of responsiveness of automotive supply chain using an integrated fuzzy DEMATEL-ISM approach. *Journal of Global Operations and Strategic Sourcing*. <https://doi.org/10.1108/JGOSS-05-2022-0039>
- Schau, V., Rossak, W., Hempel, H., & Späthe, S. (2015). *Smart City Logistik Erfurt (SCL): ICT-Support for managing Fully Electric Vehicles in the Domain of Inner City Freight Traffic A Look at an ongoing Federal Project in the City of Erfurt, Germany*. <https://doi.org/10.1109/IEOM.2015.7093862>
- Seikh, M. R., & Mandal, U. (2023). Interval-valued Fermatean fuzzy Dombi aggregation operators and SWARA based PROMETHEE II method to bio-medical waste management. *Expert Systems with Applications*, 226, 120082. <https://doi.org/10.1016/j.eswa.2023.120082>
- Seker, S., & Aydin, N. (2023). Fermatean fuzzy based Quality Function Deployment methodology for designing sustainable mobility hub center. *Applied Soft Computing*, 134, 110001. <https://doi.org/10.1016/j.asoc.2023.110001>
- Senapati, T., & Yager, R. (2019a). Fermatean fuzzy weighted averaging/geometric operators and its application in multi-criteria decision-making methods. *ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE*, 85, 112–121. <https://doi.org/10.1016/j.engappai.2019.05.012>
- Senapati, T., & Yager, R. R. (2019b). Some New Operations Over Fermatean Fuzzy Numbers and Application of Fermatean Fuzzy WPM in Multiple Criteria Decision Making. *Informatica*, 30(2), 391–412. <https://doi.org/10.15388/Informatica.2019.211>
- Senapati, T., & Yager, R. R. (2020). Fermatean fuzzy sets. *Journal of Ambient Intelligence and Humanized Computing*, 11(2), 663–674. <https://doi.org/10.1007/s12652-019-01377-0>
- Serbanica, C., & Constantin, D. L. (2023). Misfortunes never come singly. A holistic approach to urban resilience and sustainability challenges. *Cities*, 134, 104177. <https://doi.org/10.1016/j.cities.2022.104177>
- Serre, D., & Heinzllef, C. (2018). Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks. *International Journal of Disaster Risk Reduction*, 30, 235–243. <https://doi.org/10.1016/j.ijdrr.2018.02.018>
- Sha, L., & Shao, Y. (2023). Fermatean Hesitant Fuzzy Choquet Integral Aggregation Operators. *IEEE Access*, 11, 38548–38562. <https://doi.org/10.1109/ACCESS.2023.3267512>
- Shahbandarzadeh, H., & Ghorbanpour, A. (2011). The Applying ISM/ANP Approach for Appropriate Location Selection of Health Centers. *Iranian Journal of Management Studies*, 4(2), 5–28. <https://doi.org/10.22059/ijms.2011.23470>
- Shahzadi, G., Luqman, A., & Karaaslan, F. (2023). A decision-making technique under interval-valued Fermatean fuzzy Hamacher interactive aggregation operators. *Soft Computing*. <https://doi.org/10.1007/s00500-023-08479-0>
- Shahzadi, G., Muhiuddin, G., Butt, M., & Ashraf, A. (2021). Hamacher Interactive Hybrid Weighted Averaging Operators under Fermatean Fuzzy Numbers. *JOURNAL OF MATHEMATICS*, 2021. <https://doi.org/10.1155/2021/5556017>

- Shamout, S., Boarin, P., & Wilkinson, S. (2021). The shift from sustainability to resilience as a driver for policy change: A policy analysis for more resilient and sustainable cities in Jordan. *SUSTAINABLE PRODUCTION AND CONSUMPTION*, 25, 285–298. <https://doi.org/10.1016/j.spc.2020.08.015>
- Shamsuddin, S. (2020). Resilience resistance: The challenges and implications of urban resilience implementation. *Cities*, 103, 102763. <https://doi.org/10.1016/j.cities.2020.102763>
- Shardeo, V., Patil, A., & Madaan, J. (2020). Critical Success Factors for Blockchain Technology Adoption in Freight Transportation Using Fuzzy ANP-Modified TISM Approach. *International Journal of Information Technology & Decision Making*, 19(6), 1549–1580. <https://doi.org/10.1142/S0219622020500376>
- Sharifi, A. (2020). Urban Resilience Assessment: Mapping Knowledge Structure and Trends. *Sustainability*, 12(15), 5918. <https://doi.org/10.3390/su12155918>
- Sharifi, A., Chelleri, L., Fox-Lent, C., Grafakos, S., Pathak, M., Olazabal, M., Moloney, S., Yumagulova, L., & Yamagata, Y. (2017). Conceptualizing Dimensions and Characteristics of Urban Resilience: Insights from a Co-Design Process. *Sustainability*, 9(6), 1032. <https://doi.org/10.3390/su9061032>
- Sharma, M., & Sehrawat, R. (2020). A hybrid multi-criteria decision-making method for cloud adoption: Evidence from the healthcare sector. *Technology in Society*, 61, 101258. <https://doi.org/10.1016/j.techsoc.2020.101258>
- Shaw, M., Majumdar, A., & Govindan, K. (2022). Barriers of social sustainability: An improved interpretive structural model of Indian textile and clothing supply chain. *Sustainable Development*, 30(6), 1616–1633. <https://doi.org/10.1002/sd.2331>
- Sheffi, Y. (2008). *Resilience: What it is and how to achieve it*. 5.
- Shi, C., Guo, N., Gao, X., & Wu, F. (2022). How carbon emission reduction is going to affect urban resilience. *JOURNAL OF CLEANER PRODUCTION*, 372, 133737. <https://doi.org/10.1016/j.jclepro.2022.133737>
- Shit, C., & Ghorai, G. (2021). Multiple attribute decision-making based on different types of Dombi aggregation operators under Fermatean fuzzy information. *Soft Computing*, 25(22), 13869–13880. <https://doi.org/10.1007/s00500-021-06252-9>
- Simic, V., Ahmad, W., Dikshit, S., Bin-Mohsin, B., Sadim, M., & Anjum, M. (2023). Optimizing Material Selection with Fermatean Fuzzy Hybrid Aggregation Operators. *Axioms*, 12(10), Article 10. <https://doi.org/10.3390/axioms12100984>
- Simic, V., Gokasar, I., Deveci, M., & Isik, M. (2022). Fermatean Fuzzy Group Decision-Making Based CODAS Approach for Taxation of Public Transit Investments. *IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT*. <https://doi.org/10.1109/TEM.2021.3109038>
- Simic, V., Ivanovic, I., Doric, V., & Torkayesh, A. (2022). Adapting Urban Transport Planning to the COVID-19 Pandemic: An Integrated Fermatean Fuzzy Model. *SUSTAINABLE CITIES AND SOCIETY*, 79. <https://doi.org/10.1016/j.scs.2022.103669>
- Simic, V., Torkayesh, A., & Maghsoodi, A. (2022). Locating a disinfection facility for hazardous healthcare waste in the COVID-19 era: A novel approach based on Fermatean fuzzy ITARA-MARCOS and random forest recursive feature elimination algorithm. *ANNALS OF OPERATIONS RESEARCH*. <https://doi.org/10.1007/s10479-022-04822-0>
- Sinaga, R., Prastowo, Simangunsong, B. C. H., Liebman, A., & Tambunan, A. H. (2019). Analysis of barriers in supplying electricity using interpretative structural

- modeling. *Energy Strategy Reviews*, 25, 11–17.
<https://doi.org/10.1016/j.esr.2019.04.011>
- Singh, S., Agrawal, V., & Mohanty, R. P. (2022). Multi-criteria decision analysis of significant enablers for a competitive supply chain. *Journal of Advances in Management Research*, 19(3), 414–442. <https://doi.org/10.1108/JAMR-09-2021-0322>
- Singh, S., & Misra, S. C. (2018). Migration of PLM systems to cloud. *International Journal of Communication Systems*, 31(18), e3815.
<https://doi.org/10.1002/dac.3815>
- Snep, R. P. H., Voeten, J. G. W. F., Mol, G., & Van Hattum, T. (2020). Nature Based Solutions for Urban Resilience: A Distinction Between No-Tech, Low-Tech and High-Tech Solutions. *Frontiers in Environmental Science*, 8. Scopus.
<https://doi.org/10.3389/fenvs.2020.599060>
- Solangi, Y. A., Tan, Q., Mirjat, N. H., & Ali, S. (2019). Evaluating the strategies for sustainable energy planning in Pakistan: An integrated SWOT-AHP and Fuzzy-TOPSIS approach. *Journal of Cleaner Production*, 236, 117655.
<https://doi.org/10.1016/j.jclepro.2019.117655>
- Sony, M., Antony, J., Mc Dermott, O., & Garza-Reyes, J. A. (2021). An empirical examination of benefits, challenges, and critical success factors of industry 4.0 in manufacturing and service sector. *Technology in Society*, 67, 101754.
<https://doi.org/10.1016/j.techsoc.2021.101754>
- Sousa, J. F. D. (2015). *Urban Logistics Integrated in a Multimodal Mobility System*. September. <https://doi.org/10.1109/ITSC.2015.23>
- Stead, D. (2014). Urban planning, water management and climate change strategies: Adaptation, mitigation and resilience narratives in the Netherlands. *International Journal of Sustainable Development & World Ecology*, 21(1), 15–27.
<https://doi.org/10.1080/13504509.2013.824928>
- Su, Y.-S. (2017). Rebuild, retreat or resilience: Urban flood vulnerability analysis and simulation in Taipei. *International Journal of Disaster Resilience in the Built Environment*, 8(2), 110–122. <https://doi.org/10.1108/IJDRBE-11-2015-0055>
- Suárez, M., Gómez-Baggethun, E., Benayas, J., & Tilbury, D. (2016). Towards an Urban Resilience Index: A Case Study in 50 Spanish Cities. *Sustainability*, 8(8), 774.
<https://doi.org/10.3390/su8080774>
- Sun, S. (2023). The availability improvement of CNC machine tool based on DEMATEL–ISM–QFD integration method. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 17(1), 69–77.
<https://doi.org/10.1007/s12008-022-01122-6>
- Tabibian, M., & Movahed, S. (2016). Towards Resilient and Sustainable Cities: A Conceptual Framework. *Scientia Iranica*, 23(5), 2081–2093.
<https://doi.org/10.24200/sci.2016.2273>
- Tabibian, M., & Rezapour, M. (2016). Assessment of urban resilience; a case study of Region 8 of Tehran city, Iran. *Scientia Iranica*, 23(4), 1699–1707.
<https://doi.org/10.24200/sci.2016.2240>
- Tan, J., Liu, Y., Senapati, T., Garg, H., & Rong, Y. (2022). An extended MABAC method based on prospect theory with unknown weight information under Fermatean fuzzy environment for risk investment assessment in B&R. *JOURNAL OF AMBIENT INTELLIGENCE AND HUMANIZED COMPUTING*.
<https://doi.org/10.1007/s12652-022-03769-1>

- Tavana, M., Zareinejad, M., Di Caprio, D., & Kaviani, M. A. (2016). An integrated intuitionistic fuzzy AHP and SWOT method for outsourcing reverse logistics. *Applied Soft Computing*, 40, 544–557. <https://doi.org/10.1016/j.asoc.2015.12.005>
- T.C. Çevre, Şehircilik ve İklim Değişikliği Bakanlığı. (2020). *Nesnelerin İnterneti: Akıllı Şehirler Kapasite Geliştirme ve Rehberlik Projesi*.
- T.C. Ulaştırma ve Altyapı Bakanlığı. (2020). *Ulusal Akıllı Ulaşım Sistemleri Strateji Belgesi ve 2020-2023 Eylem Planı*. <https://www.uab.gov.tr/uploads/announcements/ulusal-akilli-ulasim-sistemleri-strateji-belgesi-v/ulusal-akilli-ulas-im-sistemleri-strateji-belgesi-ve-2020-2023-eylem-planı.pdf>
- The Rockefeller Foundation. (2019). *Resilient Cities, Resilient Lives Learning from the 100RC Network*.
- The Rockefeller Foundation. (2020). *Urban Resilience*. 100 Resilient Cities. <http://www.100resilientcities.org/resources/>
- Therias, A., & Rafiee, A. (2023). City digital twins for urban resilience. *INTERNATIONAL JOURNAL OF DIGITAL EARTH*, 16(2), 4164–4190. <https://doi.org/10.1080/17538947.2023.2264827>
- Therrien, M., Usher, S., & Matyas, D. (2020). Enabling strategies and impeding factors to urban resilience implementation: A scoping review. *Journal of Contingencies and Crisis Management*, 28(1), 83–102. <https://doi.org/10.1111/1468-5973.12283>
- Titz, A., & Chiotha, S. S. (2019). Pathways for Sustainable and Inclusive Cities in Southern and Eastern Africa through Urban Green Infrastructure? *Sustainability*, 11(10), 2729. <https://doi.org/10.3390/su11102729>
- Tortorella, G., Kurnia, S., Trentin, M., Oliveira, G. A., & Setti, D. (2022). Industry 4.0: What is the relationship between manufacturing strategies, critical success factors and technology adoption? *Journal of Manufacturing Technology Management*, 33(8), 1407–1428. <https://doi.org/10.1108/JMTM-02-2022-0088>
- UN-Habitat. (2021). *Urban economic recovery and resilience*.
- UN-Habitat. (2022). *Future Cities Advisory Outlook 2022: Building New Urban Resilience*. https://unhabitat.org/sites/default/files/2023/03/future_cities_advisory_outlook_2022_building_new_urban_resilience_abridged_version_1.pdf
- United Nations Development Programme. (2022). *Helping communities weather the socio-economic downturn: BUILDING URBAN RESILIENCE*. <https://www.undp.org/sites/g/files/zskgke326/files/2023-02/UNDP-Building-Urban-Resilience-2022.pdf>
- United Nations Office for Disaster Risk Reduction. (2013). *Making Cities Resilient: Summary for Policymakers*.
- Urban Sustainability Directors Network. (n.d.). *Getting Smart About Smart Cities*.
- Vale, L. J. (2014). The politics of resilient cities: Whose resilience and whose city? *Building Research and Information*, 42(2), 191–201. Scopus. <https://doi.org/10.1080/09613218.2014.850602>
- Verma, R. (2021). A Decision-Making Approach Based on New Aggregation Operators under Fermatean Fuzzy Linguistic Information Environment. *AXIOMS*, 10(2). <https://doi.org/10.3390/axioms10020113>
- Vona, M., Harabaglia, P., & Murgante, B. (2016). Thinking about resilient cities: Studying Italian earthquakes. *Proceedings of the Institution of Civil Engineers -*

- Urban Design and Planning*, 169(4), 185–199.
<https://doi.org/10.1680/udap.14.00007>
- Wamsler, C., Brink, E., & Rivera, C. (2013). Planning for climate change in urban areas: From theory to practice. *Journal of Cleaner Production*, 50, 68–81.
<https://doi.org/10.1016/j.jclepro.2012.12.008>
- Wang, C., Sun, Y., Lim, M. K., Ghadimi, P., & Azadnia, A. H. (2023). An analysis of barriers for successful implementation of municipal solid waste management in Beijing: An integrated DEMATEL-MMDE-ISM approach. *Industrial Management & Data Systems*, ahead-of-print(ahead-of-print).
<https://doi.org/10.1108/IMDS-08-2022-0464>
- Wang, D., Li, J., & Liu, Y. (2023). Evaluating barriers and strategies to green energy innovations for sustainable development: Developing resilient energy systems. *Frontiers in Energy Research*, 11.
<https://www.frontiersin.org/articles/10.3389/fenrg.2023.1201692>
- Wang, H., Liu, Z., & Zhou, Y. (2023). Assessing urban resilience in China from the perspective of socioeconomic and ecological sustainability. *Environmental Impact Assessment Review*, 102, 107163.
<https://doi.org/10.1016/j.eiar.2023.107163>
- Wang, H., Wang, X., & Wang, L. (2019). Multicriteria Decision Making Based on Archimedean Bonferroni Mean Operators of Hesitant Fermatean 2-Tuple Linguistic Terms. *COMPLEXITY*, 2019. <https://doi.org/10.1155/2019/5705907>
- Wang, J., & Foley, K. (2021). Assessing the performance of urban open space for achieving sustainable and resilient cities: A pilot study of two urban parks in Dublin, Ireland. *Urban Forestry & Urban Greening*, 62, 127180.
<https://doi.org/10.1016/j.ufug.2021.127180>
- Wang, K.-L., Jiang, W., & Miao, Z. (2023). Impact of high-speed railway on urban resilience in China: Does urban innovation matter? *Socio-Economic Planning Sciences*, 87, 101607. <https://doi.org/10.1016/j.seps.2023.101607>
- Wang, L. (2022). Exploring a knowledge map for urban resilience to climate change. *Cities*, 131, 104048. <https://doi.org/10.1016/j.cities.2022.104048>
- Wang, L., Xue, X., Zhang, Y., & Luo, X. (2018). Exploring the Emerging Evolution Trends of Urban Resilience Research by Scientometric Analysis. *International Journal of Environmental Research and Public Health*, 15(10), 2181.
<https://doi.org/10.3390/ijerph15102181>
- Wang, W., Han, X., Ding, W., Wu, Q., Chen, X., & Deveci, M. (2023). A Fermatean fuzzy Fine–Kinney for occupational risk evaluation using extensible MARCOS with prospect theory. *Engineering Applications of Artificial Intelligence*, 117, 105518. <https://doi.org/10.1016/j.engappai.2022.105518>
- Wang, X., Wang, C., & Shi, J. (2023). Evaluation of urban resilience based on Service-Connectivity-Environment (SCE) model: A case study of Jinan city, China. *International Journal of Disaster Risk Reduction*, 95, 103828.
<https://doi.org/10.1016/j.ijdrr.2023.103828>
- Wang, Y., Ma, X., Qin, H., Sun, H., & Wei, W. (2023). Hesitant Fermatean fuzzy Bonferroni mean operators for multi-attribute decision-making. *Complex & Intelligent Systems*. <https://doi.org/10.1007/s40747-023-01203-3>
- Wang, Y., Xu, L., & Solangi, Y. A. (2020). Strategic renewable energy resources selection for Pakistan: Based on SWOT-Fuzzy AHP approach. *SUSTAINABLE CITIES AND SOCIETY*, 52, 101861. <https://doi.org/10.1016/j.scs.2019.101861>

- Wang, Z., Fu, H., & Zhou, L. (2023). Multiple urban resilience evaluation of resource-based cities' sustainable transformation effect. *Resources, Conservation and Recycling*, 191, 106912. <https://doi.org/10.1016/j.resconrec.2023.106912>
- Wardekker, A. (2021). Contrasting the framing of urban climate resilience. *Sustainable Cities and Society*, 75, 103258. <https://doi.org/10.1016/j.scs.2021.103258>
- Wardekker, A., Wilk, B., Brown, V., Uittenbroek, C., Mees, H., Driessen, P., Wassen, M., Molenaar, A., Walda, J., & Runhaar, H. (2020). A diagnostic tool for supporting policymaking on urban resilience. *Cities*, 101, 102691. <https://doi.org/10.1016/j.cities.2020.102691>
- Warfield, J. N. (1974). Developing Interconnection Matrices in Structural Modeling. *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-4(1), 81–87. <https://doi.org/10.1109/TSMC.1974.5408524>
- Wei, D., Meng, D., Rong, Y., Liu, Y., Garg, H., & Pamucar, D. (2022). Fermatean Fuzzy Schweizer-Sklar Operators and BWM-Entropy-Based Combined Compromise Solution Approach: An Application to Green Supplier Selection. *ENTROPY*, 24(6). <https://doi.org/10.3390/e24060776>
- Wei, G., Wang, J., Wei, C., Wei, Y., & Zhang, Y. (2019). Dual Hesitant Pythagorean Fuzzy Hamy Mean Operators in Multiple Attribute Decision Making. *IEEE Access*, 7, 86697–86716. <https://doi.org/10.1109/ACCESS.2019.2924974>
- Weichselgartner, J., & Kelman, I. (2014). Challenges and opportunities for building urban resilience. *A/Z ITU Journal of the Faculty of Architecture*, 11(1), 20–35. Scopus.
- Wicaksono, T., & Illés, C. B. (2022). From resilience to satisfaction: Defining supply chain solutions for agri-food SMEs through quality approach. *PLOS ONE*, 17(2), e0263393. <https://doi.org/10.1371/journal.pone.0263393>
- Wu, C., Cenci, J., Wang, W., & Zhang, J. (2022). Resilient City: Characterization, Challenges and Outlooks. *Buildings*, 12(5), Article 5. <https://doi.org/10.3390/buildings12050516>
- Xia, C., & Zhai, G. (2022). The spatiotemporal evolution pattern of urban resilience in the Yangtze River Delta urban agglomeration based on TOPSIS-PSO-ELM. *SUSTAINABLE CITIES AND SOCIETY*, 87, 104223. <https://doi.org/10.1016/j.scs.2022.104223>
- Xu, B. (2020). Methods for evaluating the computer network security with fuzzy number intuitionistic fuzzy dual Hamy mean operators. *Journal of Intelligent & Fuzzy Systems*, 39(3), 4427–4441. <https://doi.org/10.3233/JIFS-200414>
- Xu, H., Li, Y., & Wang, L. (2020). Resilience Assessment of Complex Urban Public Spaces. *International Journal of Environmental Research and Public Health*, 17(2), 524. <https://doi.org/10.3390/ijerph17020524>
- Xu, H., & Xue, B. (2017). Key indicators for the resilience of complex urban public spaces. *Journal of Building Engineering*, 12, 306–313. <https://doi.org/10.1016/j.jobe.2017.06.018>
- Xu, X., & Zou, P. X. W. (2020). Analysis of factors and their hierarchical relationships influencing building energy performance using interpretive structural modelling (ISM) approach. *Journal of Cleaner Production*, 272, 122650. <https://doi.org/10.1016/j.jclepro.2020.122650>
- Xun, X., & Yuan, Y. (2020). Research on the urban resilience evaluation with hybrid multiple attribute TOPSIS method: An example in China. *Natural Hazards*, 103(1), 557–577. <https://doi.org/10.1007/s11069-020-04000-0>

- Yager, R. R. (2013). Pythagorean fuzzy subsets. *2013 Joint IFSA World Congress and NAFIPS Annual Meeting (IFSA/NAFIPS)*, 57–61. <https://doi.org/10.1109/IFSA-NAFIPS.2013.6608375>
- Yaman Galantini, Z. D., & Tezer, A. (2018). Resilient urban planning process in question: Istanbul case. *International Journal of Disaster Resilience in the Built Environment*, 00–00. <https://doi.org/10.1108/IJDRBE-10-2016-0038>
- Yang, J. L., Chiu, H. N., Tzeng, G.-H., & Yeh, R. H. (2008). Vendor selection by integrated fuzzy MCDM techniques with independent and interdependent relationships. *Information Sciences*, 178(21), 4166–4183. <https://doi.org/10.1016/j.ins.2008.06.003>
- Yang, M., Jiao, M., & Zhang, J. (2022). Research on Urban Resilience and Influencing Factors of Chengdu-Chongqing Economic Circle. *Sustainability*, 14(17), Article 17. <https://doi.org/10.3390/su141710585>
- Yang, S., & Chong, Z. (2021). Smart city projects against COVID-19: Quantitative evidence from China. *Sustainable Cities and Society*, 70, 102897. <https://doi.org/10.1016/j.scs.2021.102897>
- Yang, S., Pan, Y., & Zeng, S. (2022). Decision making framework based Fermatean fuzzy integrated weighted distance and TOPSIS for green low-carbon port evaluation. *ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE*, 114. <https://doi.org/10.1016/j.engappai.2022.105048>
- Yang, Y., Zhang, C., Zhao, Q., & Zhang, Y. (2024). A sustainability evaluation framework for the urban energy Internet using the Fermatean fuzzy Aczel-Alsina hybrid MCDM method. *Expert Systems with Applications*, 238, 122115. <https://doi.org/10.1016/j.eswa.2023.122115>
- Yao, F., & Wang, Y. (2020). Towards resilient and smart cities: A real-time urban analytical and geo-visual system for social media streaming data. *Sustainable Cities and Society*, 63, 102448. <https://doi.org/10.1016/j.scs.2020.102448>
- Yuan, Z., & Hu, W. (2023). Urban resilience to socioeconomic disruptions during the COVID-19 pandemic: Evidence from China. *International Journal of Disaster Risk Reduction*, 91, 103670. <https://doi.org/10.1016/j.ijdr.2023.103670>
- Zanjirani, D. M., Hashemkhani Zolfani, S., & Prentkovskis, O. (2019). L.A.R.G. supplier selection based on integrating house of quality, Taguchi loss function and M.O.P.A. *Economic Research-Ekonomska Istraživanja*, 32(1), 1944–1964. <https://doi.org/10.1080/1331677X.2019.1635036>
- Zeb, A., Khan, A., Juniad, M., & Izhar, M. (2022). Fermatean fuzzy soft aggregation operators and their application in symptomatic treatment of COVID-19 (case study of patients identification). *JOURNAL OF AMBIENT INTELLIGENCE AND HUMANIZED COMPUTING*. <https://doi.org/10.1007/s12652-022-03725-z>
- Zeng, S., Chen, W., Gu, J., & Zhang, E. (2023). An Integrated EDAS Model for Fermatean Fuzzy Multi-Attribute Group Decision Making and Its Application in Green-Supplier Selection. *Systems*, 11(3), Article 3. <https://doi.org/10.3390/systems11030162>
- Zeng, S., Gu, J., & Peng, X. (2023). Low-carbon cities comprehensive evaluation method based on Fermatean fuzzy hybrid distance measure and TOPSIS. *Artificial Intelligence Review*, 56(8), 8591–8607. <https://doi.org/10.1007/s10462-022-10387-y>
- Zeng, S., Pan, Y., & Jin, H. (2022). Online Teaching Quality Evaluation of Business Statistics Course Utilizing Fermatean Fuzzy Analytical Hierarchy Process with

- Aggregation Operator. *SYSTEMS*, 10(3).
<https://doi.org/10.3390/systems10030063>
- Zeng, X., Yu, Y., Yang, S., Lv, Y., & Sarker, M. N. I. (2022). Urban Resilience for Urban Sustainability: Concepts, Dimensions, and Perspectives. *SUSTAINABILITY*, 14(5), 2481. <https://doi.org/10.3390/su14052481>
- Zhai, G., Li, S., & Chen, J. (2015). Reducing Urban Disaster Risk by Improving Resilience in China from a Planning Perspective. *Human and Ecological Risk Assessment: An International Journal*, 21(5), 1206–1217. <https://doi.org/10.1080/10807039.2014.955385>
- Zhang, F., & Xu, S. (2016). Multiple Attribute Group Decision Making Method Based on Utility Theory Under Interval-Valued Intuitionistic Fuzzy Environment. *Group Decision and Negotiation*, 25(6), 1261–1275. <https://doi.org/10.1007/s10726-016-9473-y>
- Zhang, J., & Wang, T. (2023). Urban resilience under the COVID-19 pandemic: A quantitative assessment framework based on system dynamics. *Cities*, 136, 104265. <https://doi.org/10.1016/j.cities.2023.104265>
- Zhang, J., Yang, X., & Lu, D. (2023). Evaluation of Urban Resilience Based on Trio Spaces: An Empirical Study in Northeast China. *Buildings*, 13(7), Article 7. <https://doi.org/10.3390/buildings13071695>
- Zhang, M., Yang, Y., Li, H., & van Dijk, M. P. (2020). Measuring Urban Resilience to Climate Change in Three Chinese Cities. *Sustainability*, 12(22), 9735. <https://doi.org/10.3390/su12229735>
- Zhang, X., & Li, H. (2018). Urban resilience and urban sustainability: What we know and what do not know? *Cities*, 72, 141–148. <https://doi.org/10.1016/j.cities.2017.08.009>
- Zhang, X., Mao, F., Gong, Z., Hannah, D. M., Cai, Y., & Wu, J. (2023). A disaster-damage-based framework for assessing urban resilience to intense rainfall-induced flooding. *Urban Climate*, 48, 101402. <https://doi.org/10.1016/j.uclim.2022.101402>
- Zhang, X., Song, J., Peng, J., & Wu, J. (2019). Landslides-oriented urban disaster resilience assessment—A case study in ShenZhen, China. *Science of The Total Environment*, 661, 95–106. <https://doi.org/10.1016/j.scitotenv.2018.12.074>
- Zhang, X., & Xu, Z. (2014). Extension of TOPSIS to multiple criteria decision making with pythagorean fuzzy sets. *International Journal of Intelligent Systems*, 29(12), 1061–1078. Scopus. <https://doi.org/10.1002/int.21676>
- Zhao, R., Fang, C., Liu, J., & Zhang, L. (2022). The evaluation and obstacle analysis of urban resilience from the multidimensional perspective in Chinese cities. *SUSTAINABLE CITIES AND SOCIETY*, 86, 104160. <https://doi.org/10.1016/j.scs.2022.104160>
- Zhao, Z.-Y., Chen, Y.-L., & Li, H. (2019). What affects the development of renewable energy power generation projects in China: ISM analysis. *Renewable Energy*, 131, 506–517. <https://doi.org/10.1016/j.renene.2018.07.063>
- Zheng, Y., Xie, X.-L., Lin, C.-Z., Wang, M., & He, X.-J. (2018). Development as adaptation: Framing and measuring urban resilience in Beijing. *Advances in Climate Change Research*, 9(4), 234–242. <https://doi.org/10.1016/j.accre.2018.12.002>
- Zhou, F., & Chen, T.-Y. (2022). A hybrid approach combining AHP with TODIM for blockchain technology provider selection under the Pythagorean fuzzy scenario.

- Artificial Intelligence Review*, 55(7), 5411–5443. <https://doi.org/10.1007/s10462-021-10128-7>
- Zhou, L.-P., Wan, S.-P., & Dong, J.-Y. (2021). A Fermatean Fuzzy ELECTRE Method for Multi-Criteria Group Decision-Making. *Informatica*, 33(1), 181–224. <https://doi.org/10.15388/21-INFOR463>
- Zhou, Q., Zhu, M., Qiao, Y., Zhang, X., & Chen, J. (2021). Achieving resilience through smart cities? Evidence from China. *Habitat International*, 111, 102348. <https://doi.org/10.1016/j.habitatint.2021.102348>
- Zhu, S., Li, D., & Feng, H. (2019). Is smart city resilient? Evidence from China. *Sustainable Cities and Society*, 50, 101636. <https://doi.org/10.1016/j.scs.2019.101636>
- Zhu, S., Li, D., Feng, H., Gu, T., Hewage, K., & Sadiq, R. (2020). Smart city and resilient city: Differences and connections. *WIREs Data Mining and Knowledge Discovery*, 10(6). <https://doi.org/10.1002/widm.1388>
- Zimmermann, M., Aucamp, F., & Polit, D. J. (2019). *Resilient cities, thriving cities: The evolution of urban resilience*. ICLEI.
- Zou, Y. (2023). Urban resilience, digital technologies, and the economic recovery of a city from the pandemic. *Public Administration Review*, n/a(n/a). <https://doi.org/10.1111/puar.13678>

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Büyüközkan, G., Ilıcak, Ö., & Feyzioğlu, O. (2022). A review of urban resilience literature. *Sustainable Cities and Society*, 77, 103579.

Büyüközkan, G., & Ilıcak, Ö. (2022). Smart urban logistics: Literature review and future directions. *Socio-Economic Planning Sciences*, 81, 101197.