**AN INTEGRATED APPROACH FOR SUPPLY CHAIN MANAGEMENT IN HEALTHCARE SYSTEMS FOCUSING ON FACE MASKS AND GLOVES WASTE MANAGEMENT**

(YÜZ MASKELERİ VE ELDİVENLERİN ATIK YÖNETİMİNE ODAKLANAN SAĞLIK SISTEMLERİNDE TEDARİK ZİNCİRİ YÖNETIMİ İÇIN ENTEGRE BİR YAKLAŞIM)

by

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**AHP** : Analytic Hierarchy Process
**ANN** : Artificial Neural Network
**ANP** : Analytic Network Process
**ERP** : Enterprise Resource Planning
**FA** : Firefly Algorithm
**FM** : Face Masks
**HSCM** : Healthcare Supply Chain Management
**HWSCM** : Healthcare Waste Supply Chain Management
**IMW** : Infectious Medical Waste
**MRP** : Material requirements planning
**GIS** : Geographic Information Systems
**MAD** : Mean Absolute Deviation
**MAE** : Mean Absolute Error
**MAPE** : Mean Absolute Percentage Error
**MARE** : Mean Absolute Relative Error
**MCDA** : Multi-Criteria Decision Analysis
**MCDM** : Multi-Criteria Decision Making
**MSE** : Mean Square Error
**MSW** : Municipal Solid Waste
**NAR** : Non-linear Autoregressive
**NGBM** : Non-linear Grey Bernoulli Modelling
**PSCM** : Pharmaceutical Supply Chain Management
**PLS** : Partial Least Squares
**RMS** : Relative Mean Errors
**RMSE** : Root Mean Square Error
$\mathbf{R^2}$ : Coefficient of Determination
**SCM** : Supply Chain Management
**SD** : System Dynamics
**SF-AHP** : Spherical Fuzzy Analytic Hierarchy Process
**SFS** : Spherical Fuzzy Sets

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## ABSTRACT

Healthcare supply chain management has become a critical area of focus, as it encompasses key components such as service quality, inventory optimization, the incorporation of recyclable products, and logistics coordination. Effective management of these elements not only reduces costs but also contributes to the development of sustainable solutions that address environmental, societal, and economic challenges faced by healthcare organizations. The COVID-19 pandemic and other recent crises have highlighted significant vulnerabilities within healthcare systems, prompting policymakers to prioritize the development of comprehensive reforms and policies to strengthen healthcare supply chains. In particular, the extraordinary demands imposed by pandemics and crises necessitate innovative approaches to resource allocation, logistics management, and the handling of complex production and inventory systems.

One of the most pressing challenges emerging from these dynamics is the substantial increase in medical and plastic waste generation, particularly from disposable items such as gloves and face masks. This waste presents a significant environmental challenge, as overall recycling rates remain low despite advancements in waste management technologies. Although gloves and face masks that are not contaminated with clinical waste or hazardous chemicals can be recycled, their widespread use during the pandemic—and their continued use post-pandemic—has not been met with sufficient policy efforts to enhance recycling and reuse strategies. This challenge is especially acute in developing countries, including Turkey, where inefficiencies in managing face mask and glove waste persist. Istanbul, as Turkey’s largest and most populous city, exemplifies the complexities of medical waste management, underscoring a critical gap in the literature and in policy implementation.

This thesis seeks to address this pressing issue by developing a comprehensive and effective waste management policy for disposable face masks and gloves in Istanbul. The research focuses on public waste generation in the post-pandemic period and explores strategies to facilitate the efficient reuse, upcycling, and recycling of these materials. To achieve this, the study employs a multidisciplinary approach that integrates three distinct methodologies: (1) a system dynamics model to simulate and analyse the supply chain of face mask and glove waste management, providing insights into key systemic behaviours and interdependencies; (2) a novel non-linear grey Bernoulli model to forecast trends in medical waste generation in Istanbul and to inform evidence-based policy development; and (3) a spherical multi-criteria decision-making framework to evaluate and prioritise waste management practices based on multiple, often conflicting criteria to be used in the suggested model.

The integration of these methodologies enables the construction of a stock-flow diagram model, which synthesizes insights from empirical data, literature, and methodological findings, as a proposed model. This model offers a comprehensive framework for understanding and managing the life cycle of face mask and glove waste, addressing inefficiencies and proposing actionable solutions tailored to Istanbul's unique context. The study's findings, on the other hand, culminate in a set of detailed policy and strategy recommendations designed to enhance waste management systems focused on face masks and gloves waste in Istanbul. These recommendations emphasize coordinated efforts involving both the Turkish government and the Istanbul municipality, aiming to implement an integrated and sustainable waste management approach.

The proposed model incorporates a range of interrelated variables and their causal interactions, reflecting the complexity of the waste management landscape. By addressing these interactions, the thesis also provides a robust foundation for improving recycling rates, promoting reuse strategies, and mitigating the environmental impacts of medical waste. Ultimately, this research contributes to the broader field of healthcare supply chain management by presenting a scalable and replicable model for managing disposable medical waste, with implications that extend beyond Istanbul to other urban centres facing similar challenges.

# ÖZET

Sağlık sektöründe tedarik zinciri yönetimi, hizmet kalitesi, envanter optimizasyonu, geri dönüştürülebilir ürünlerin entegrasyonu ve lojistik koordinasyonu gibi temel bileşenlerinin kapsadığı problemler nedeniyle günümüzde önemli bir odak alanı haline gelmiştir. Bu unsurların etkin yönetimi, maliyetleri azaltmakla kalmamakta, aynı zamanda da sağlık kuruluşlarının karşılaştığı çevresel, toplumsal ve ekonomik zorlukları ele alan sürdürülebilir çözümlerin geliştirilmesine katkıda bulunmaktadır. Özellikle, geçirilen COVID-19 pandemisi ve son dönemdeki sağlık ile afet boyutlu krizler, sağlık sistemlerindeki önemli kırılganlıkları ortaya koyarak, politika yapıcıları sağlık tedarik zincirlerini güçlendirmek için kapsamlı reformlar ve politikaların geliştirilmesine öncelik vermeye yönlendirmiştir. Aynı zamanda, bu krizlerin getirdiği olağanüstü taleplerin gerçekleştirilmesi, kaynak tahsisinin sağlanması, lojistik yönetimi ve karmaşık üretim ile envanter sistemlerinin ele alınmasında da yenilikçi yaklaşımları gerektirmektedir.

Bu dinamiklerden kaynaklanan en acil sorunlardan biri, özellikle eldiven ve yüz maskesi gibi tek kullanımlık ürünlerden kaynaklanan tıbbi ve plastik atık üretimindeki önemli artıştır. Bu atıklar, atık yönetimi teknolojilerindeki ilerlemelere rağmen genel geri dönüşüm oranlarının düşük kalması nedeniyle ciddi bir çevresel sorun teşkil etmektedir. Klinik atık veya tehlikeli kimyasallarla kontamine olmayan eldiven ve yüz maskeleri geri dönüştürülebilse de, pandemi sırasında ve sonrasında bu ürünlerin yaygın kullanımı, geri dönüşüm ve yeniden kullanım stratejilerini artırmaya yönelik yeterli politika çabalarıyla desteklenememiş ve yüz maskesi ile eldiven atıkları önemli bir sorun haline gelmiştir. Bu sorun, yüz maskesi ve eldiven atıklarının yönetimindeki verimsizliklerin devam ettiği Türkiye de dahil olmak üzere gelişmekte olan ülkelerde özellikle belirgin ve büyüyen bir sorundur. Türkiye'nin en büyük ve en kalabalık şehri olan İstanbul, tıbbi atık yönetiminin karmaşıklıklarına

bir örnek oluşturmakta, literatür ile politika uygulamalarında önemli bir boşluğu vurgulamaktadır.

Bu çalışma, İstanbul'da tek kullanımlık yüz maskeleri ve eldivenler için kapsamlı ve etkili bir atık yönetim politikası geliştirerek; bu acil sorunu ele almayı amaçlamaktadır. Araştırma, pandemi sonrası dönemde kamu kaynaklı atık yönetimine odaklanmakta ve bu atık malzemelerin etkin yeniden kullanımı, ileri dönüşümü ve geri dönüşümünü kolaylaştıracak stratejileri incelemektedir. Bu hedefe ulaşmak için çalışma, üç farklı metodolojiyi entegre eden multidisipliner bir yaklaşım benimsemektedir: (1) yüz maskesi ve eldiven atık yönetiminin tedarik zincirini benzetim metodolojisiyle anlamak ve analiz etmek için bir sistem dinamiği modeli geliştirerek, temel sistem davranışları ve karşılıklı bağımlılıklar hakkında içgörü sağlamak; (2) İstanbul'daki tıbbi atık üretim eğilimlerini tahmin etmek ve kanıta dayalı politika geliştirmeyi bilgilendirmek için yeni bir doğrusal olmayan gri Bernoulli modeli uygulayarak talebi yönetebilmek ve (3) önerilen modelde kullanılmak üzere, birden fazla ve önemli olan kriterlere dayalı atık yönetimi uygulamalarını değerlendirerek önceliklendirmek için küresel kümeleri kullanarak bir çok kriterli karar verme çerçevesi çizmek.

Bu metodolojilerin entegrasyonu, ampirik veriler, literatür ve metodolojik bulgulardan elde edilen içgörüyü sentezleyen bir stok-akış diyagram modeli oluşturmayı mümkün kılmıştır. Bu stok-akış modeli, yüz maskesi ve eldiven atıklarının yaşam döngüsünü anlamak ve yönetmek için kapsamlı bir çerçeve sunmakta, verimsizlikleri ele almakta ve İstanbul'un benzersiz bağlamına uyarlanmış somut çözümler önermektedir. Çalışmanın bulguları ise, İstanbul'da yüz maskesi ve eldiven atıklarına odaklanan atık yönetim sistemlerini geliştirmeye yönelik, ayrıntılı politika ve strateji önerileriyle bitirilmiş olup, bu öneriler; entegre ve sürdürülebilir bir atık yönetimi yaklaşımını uygulamayı hedefleyerek hem yerel hem de merkezi yönetimleri içeren koordineli çabalara vurgu yapmaktadır.

Önerilen model, atık yönetimi alanının karmaşıklığını yansıtan bir dizi birbiriyle ilişkili değişkeni ve bunların nedensel etkileşimlerini içermektedir. Bu etkileşimleri ele alarak, tez aynı zamanda geri dönüşüm oranlarını artırmak, yeniden kullanım stratejilerini teşvik etmek ve tıbbi atıkların çevresel etkilerini karbon salınımı düzeyinde azaltmak için sağlam bir temel sağlamaktadır. Sonuç olarak, bu tez, tek kullanımlık tıbbi atıkların yönetimi için ölçeklenebilir ve tekrarlanabilir bir model sunarak, İstanbul'un ötesinde benzer zorluklarla karşılaşan diğer kentsel merkezlere de uyarlanabilen, sağlık tedarik zinciri yönetimi alanına katkıda bulunmaktadır.

# 1. INTRODUCTION

Supply chain management (SCM) is fundamental to the efficiency and effectiveness of organizational operations, encompassing critical activities such as logistics coordination, inventory control, and operational management. Within this domain, healthcare supply chain management (HSCM) holds particular significance due to its direct impact on patient care and public health outcomes. Despite advancements in SCM practices, HSCM continues to face challenges related to escalating costs, quality assurance, service delivery, and notably, medical waste management.

One of the critical challenges in HSCM is the growing concern over sustainability, particularly environmental sustainability. The rapid industrialization and population growth of the 21st century have intensified production and consumption activities, contributing to environmental degradation and ecological imbalance (Sangodoyin & Ipadeola, 2000; Çelik et al., 2022). In the healthcare sector, improper management of medical waste exacerbates these environmental issues, leading to widespread illnesses and pollution that adversely affect human health (Güleç et al., 2001). Medical waste poses significant risks due to its potential to transmit diseases and contain toxic chemicals (Dehghanifard & Dehghani, 2018). Therefore, integrating effective medical waste management into HSCM is crucial for advancing environmental sustainability efforts (Vasistha et al., 2018; Çetinkaya et al., 2020).

The part COVID-19 pandemic experience has further amplified the challenges associated with medical waste management in developing countries, especially in metropolitan areas like Istanbul, Turkey's largest and most populous city. The widespread use of disposable face masks and gloves during and after the pandemic for the surgical operations and daily healthcare activities has led to a substantial increase in medical and plastic waste, contributing to microplastic pollution and environmental hazards (Abbasi et al., 2020; Selvaranjan et al., 2021). Although these items are recyclable, up-cyclable and reusable if uncontaminated by clinical waste or chemicals, there has been a notable lack of effective policies and strategies to enhance recycling rates and promote reuse, particularly in developing countries like Turkey (Hanedar et al., 2022).

In Istanbul, the management of face mask and glove waste remains inefficient and inadequately addressed, highlighting a critical gap in both policy implementation and academic literature. Deficiencies in waste management practices contribute to environmental contamination and public health risks, emphasizing the need for comprehensive strategies (Eren & Tuzkaya, 2019). Furthermore, the capacity to manage medical waste during crises such as pandemics and natural disasters can be significantly reduced, as the workforce and infrastructure are also affected (Zhao et al., 2021; Klemeš et al., 2020).

Considering these challenges, it is imperative to develop effective planning and integrated assessments of medical waste technologies. Employing appropriate methodologies and tools—such as multi-criteria decision analysis (MCDA), simulation methodologies, and forecasting models—is essential to assist stakeholders in formulating sustainable medical waste management policies (Ciplak, 2015; Coskun, 2022). Understanding the components of healthcare waste focusing on face masks and gloves and their levels of infectiousness is crucial for informed decision-making regarding the adoption of appropriate technologies and strategies (Ciplak & Barton, 2012; Adar & Delice, 2019).

Despite existing efforts, deficiencies in medical waste management for face masks and gloves practices persist in Istanbul, particularly during crisis periods (Balci et al., 2022; Polat, 2022). Gloves and face masks continue to be widely used in public places, generating significant amounts of waste that require proper management. Current disposal methods are limited to incineration and landfilling, which contribute to environmental pollution and economic challenges. The absence of regulations promoting recycling or reuse exacerbates the problem, indicating a pressing need for innovative solutions (Konyalıoğlu et al., 2024a; Konyalıoğlu et al., 2024b). Along with the current literature, scholars highlighted in the context of face masks and gloves waste that accurate forecasting and simulation of medical waste is vital for optimizing storage space, container design and vehicle routes for collection and distribution, thereby improving management efficiency during crises (Cao et al., 2022; Chen et al., 2021; Singh et al., 2022; Zhao et al., 2022). Gloves and face masks are, on the other hand, still used in Istanbul and create an enormous amount of waste under medical waste, indicating that this type of waste should be managed properly. In this vein, the literature highlights the importance of the management of this waste in Istanbul considering the deficiencies of an effective management in Istanbul (Konyalıoğlu et al., 2024a).

Given the recyclability of face masks and gloves and the identified gaps in the existing waste management system, this thesis aims to develop an effective waste management policy for disposable face masks and gloves in Istanbul. The proposed model is designed to be applicable in public places beyond hospital settings and is valid for both crisis and regular periods. The thesis also focuses on public waste generation in the post-pandemic period and explores strategies for efficient reuse, upcycling, and recycling of these materials.

Furthermore, to clearly define the boundaries of this research, the thesis focuses exclusively on face mask and glove waste collected from medical waste bins situated in public areas such as streets and shopping malls in Istanbul. This waste is generated by citizens and is currently not collected with the intention of recycling or reusing. Although the proposed system considers certain variables related to waste collected from hospitals, the operational scope of the thesis is confined to public spaces, emphasizing the enhancement of public benefits. By limiting the study to these contexts, the research aims to develop targeted strategies that address the specific challenges associated with medical waste management in public settings.

To achieve this objective, the study seeks to answer the following research questions:

1. What is the current behaviour of the waste management system as a closed-loop supply chain for face masks and gloves generated in Istanbul?

2. What will be the projected amount of this type of medical waste in the coming years in Istanbul?
3. What are the key determinants for effectively managing face mask and glove waste in Istanbul?
4. Based on the findings, how can a new waste management system for face masks and gloves be proposed?

To address these research questions, the thesis is organized into six primary sections. The first section serves as an introduction, providing an overview of the face mask and glove waste issue in Istanbul and establishing the context and significance of the research. The second section presents a comprehensive literature review, utilizing both systematic and bibliometric methodologies to identify deficiencies in the current waste management system and to highlight the potential for a waste crisis if these issues are not addressed.

The third section outlines the methodology employed in the study. It integrates three distinct approaches to be used in the proposed model:

1. System Dynamics Modelling: To simulate and understand the current state of the waste management system and the supply chain dynamics of face mask and glove waste.
2. Non-linear Grey Bernoulli Model Optimized by the Firefly Algorithm: To forecast medical waste trends in Istanbul and to propose effective policies, including capacity planning influenced by potential crises and waste management strategies.
3. Spherical Multi-Criteria Decision-Making Methodology: To prioritize the determinants within the context of Istanbul's face mask and glove waste management system, enhancing decision-making processes.

The fourth section presents the results corresponding to each methodology, providing detailed analyses and discussions. The fifth section introduces the proposed waste management model, developed by integrating insights from the previous methodologies. This model offers a holistic and integrated approach to elucidate the critical components of face mask and glove waste management in Istanbul, aiming to improve existing systems and policies, especially considering potential crisis periods.

Finally, the sixth section concludes the thesis by summarizing the findings and discussing their implications for policymakers and stakeholders. The proposed model and recommendations are intended to facilitate the effective and efficient management of face masks and gloves waste in Istanbul during both regular and crisis periods, contributing to environmental sustainability and public health.

By addressing a critical gap in waste management practices, this thesis contributes to the broader discourse on environmental sustainability and healthcare supply chain optimization. The research outcomes aim to inform policy development and practical implementation, fostering a more sustainable and efficient approach to medical waste management in urban settings.

# 2. BACKGROUND

This section of the thesis provides a comprehensive background on healthcare waste situation in Turkey as well as the recyclability and reusability of face masks and gloves, based on a literature review that includes various recycling and reuse methods and the technologies employed for their decontamination.

The volume of waste generated by healthcare services in Turkey constitutes a noteworthy proportion of the overall waste produced. Consequently, the effective management and control of healthcare waste necessitate dedicated regulatory frameworks and systems (Birpınar et al., 2009). Especially, the escalating number of private and government hospitals across Istanbul and Turkey contributes to a continuous rise in the generation of medical waste (Eker et al., 2010). Another factor to be taken into consideration is that deficiencies or unsuitability in temporary waste storage areas contribute to the dissemination of medical wastes into the environment, thereby posing significant risks to public health and the ecosystem in Turkey (Eren and Tuzkaya, 2019). Annually, around 22,000 tons of medical waste (MW) are collected in Istanbul, utilizing a developed technology equipment and specialized garments. Furthermore, waste posing epidemic disease risks, such as infectious and pathological materials, undergo incineration rather than sterilization. Accurately estimating the volume of MW and identifying critical factors influencing its generation are crucial for effective management of this hazardous waste in the biggest city of Turkey, Istanbul (Uysal and Tınmaz, 2004; Ceylan et al., 2020). During COVID-19 period, there was a noteworthy surge in the production of Medical Waste (MW) within healthcare institutions, attributed to the COVID-19 epidemic. With the global escalation in the volume and complexity of MW during the COVID-19 pandemic, there was an associated heightened risk of disease transmission, particularly in instances of unsafe transportation and disposal practices in Turkey (Balci et al., 2022). Eren and Tuzkaya (2021) stated that the COVID-19 pandemic has resulted in an increased production of medical waste in Istanbul and if the current trajectory of rising COVID-19 cases persists, there is a potential for even greater challenges posed by medical waste in the days ahead. In this vein, Korkut (2018) reported that over the past 17 years, there has been a notable increase in unit medical waste generation, rising from 0.43 kg/bed-day to 1.68 kg/bed-day in Istanbul. However, the generation of medical waste is assumed to escalate coinciding with the impact of the COVID-19 pandemic in Istanbul (Hanedar et al., 2022). Given the current circumstances, it is imperative to engage in effective planning, conduct an integrated assessment of medical waste technologies, and comprehend the factors influencing the situation for the formulation of sustainable medical waste management policies in Turkey. Employing appropriate methodologies and tools, such as multi-criteria decision analysis (MCDA), becomes crucial in assisting stakeholders and understanding the required policy for medical waste management in Turkey within this sector (Ciplak,2015; Coskun, 2022). Furthermore, achieving an understanding of the components of healthcare waste and their level of infectiousness is crucial for informed decision-making regarding the adoption of appropriate technologies. To comprehensively analyze the entire system, it is of utmost importance to grasp all factors influencing the healthcare waste management system and policies in Turkey (Ciplak and Barton, 2012; Adar and Delice, 2019).

As a subcategory of healthcare waste as mentioned in the previous section, the recyclability of face masks and gloves has garnered significant attention in recent literature, particularly due to the surge in their usage during the COVID-19 pandemic. Several studies have explored optimal strategies for reusing surgical face masks (SFMs) by employing promising disinfection methods, including hydrogen peroxide vapor, ultraviolet radiation, moist heat, dry heat, and ozone gas (Rubio-Romero et al., 2020). These efforts aim to establish safe recycling processes that yield raw materials suitable for reuse in diverse applications.

Recycling SFMs can be approached through two primary methods: primary recycling and secondary (chemical) recycling. Primary recycling involves reusing masks without any pre-treatment, thereby preserving their original structural integrity. In contrast, chemical recycling entails melting and reprocessing SFMs into new products. This method is particularly pertinent given that SFMs are predominantly composed of polypropylene—a thermoplastic petroleum-based polymer known for its robust chemical resistance and low photo-oxidative stability (Maderuelo-Sanz et al., 2022; Selvaranjan et al., 2021; Aragaw, 2020; Kilmartin-Lynch et al., 2021; Saliu et al., 2021).

Similarly, gloves made of nitrile, latex, vinyl, and rubber can be recycled, provided they remain uncontaminated (UniGloves, 2022). The literature identifies several methods for recycling face masks and gloves, including mechanical, thermochemical, and chemical processes. Before initiating these recycling and upcycling processes, it is essential to disinfect the items to ensure safety and compliance with health standards (Hassan et al., 2022). Five disinfection methods are commonly recognized:

1. **Autoclave Disinfection**
2. **Dry Heat Technique**
3. **Microwave/Radio-Wave Disinfection**
4. **Chemical Disinfection**
5. **Ultraviolet (UV) Disinfection**

Economically, all these methods are cost-effective; however, to reduce labor costs and eliminate handling procedures, autoclave disinfection, microwave/radio-wave disinfection, and UV disinfection are suggested as more efficient technologies (Lyu et al., 2024; Ray et al., 2022).

For face masks specifically, four recycling or upcycling methods are prominent in the literature:

1. Mechanical Reprocessing: Physically processing masks to create new materials (Crespo et al., 2021; Cruz Sanchez et al., 2020).

2. Thermochemical Recycling: Using heat and chemical reactions to break down masks into constituent materials (Zhang et al., 2023).
3. Pyrolysis Upcycling: Converting masks into valuable by-products such as fuels, gases, and carbonaceous materials through processes like vacuum pyrolysis, catalytic pyrolysis, co-pyrolysis, and microwave pyrolysis (Yuwen et al., 2023; Zander et al., 2019; Parku et al., 2020; Cao et al., 2022; Park et al., 2023).
4. Chemical Repurposing: Chemically transforming masks into alternative, value-added products (Guselnikova et al., 2022).

Notably, thermochemical recycling can process various types of face masks and convert them into useful products while simultaneously eliminating bacteria and viruses without the need for pre-treatment (Lyu et al., 2024; Ray et al., 2022).

In the context of contaminated gloves, recycling is also feasible. Post-disinfection, gloves can be transformed into materials such as expansive clay soil for pavement subgrade (Zhu et al., 2022), concrete composites (Al biajawi et al., 2024), or asphalt pavement (Gedik et al., 2023). These transformations are achieved through thermochemical or chemical processes, sometimes facilitated by advanced technologies like 3D printing (Mousavi & Deheshani, 2023). Given the significance of recycling gloves after disinfection, it is pertinent to note that in Istanbul, these gloves can be recycled, especially considering that this type of waste is currently not subjected to any recycling procedures (Konyalıoğlu et al., 2024a).

However, it is well-recognized that not all face masks and gloves can undergo recycling and reuse processes. Consequently, some waste will inevitably be directed to landfill operations. In many countries—including those within the European Union—legal dumping is permitted (Gokdemir et al., 2024; Cook et al., 2023). For instance, Germany is recognized as a leader in waste recycling within Europe, distinguished by its comprehensive waste sorting system. During the COVID-19 pandemic, Germany mandated the segregation and collection of all medical waste—excluding sharps and glass—in designated containers as non-recyclable raw materials for disposal in advanced incineration facilities. The country enforces regulations that assign the responsibility of proper waste disposal to hospitals and other healthcare institutions (Attrah et al., 2022).

Overall, all the identified systems via the literature and the current technologies of recycling and reusing concerning face masks and gloves, it’s evident that there is a gap in Turkey, especially in Istanbul to use these recycling and reusing operations in the current situation. Related to the importance of this matter, it can be also stated that there is no facility in Turkey for recycling but incineration. In Istanbul, medical waste management is conducted through specialized facilities operated by İSTAÇ, the city's environmental management company. Medical waste, including face masks and gloves, is transported to İSTAÇ's medical waste incineration and sterilization plants. Upon arrival, all waste undergoes radiation screening as a preliminary safety measure. The disposal process involves incinerating the waste at temperatures between 850 and 1000 degrees Celsius, effectively neutralizing harmful pathogens and reducing the waste volume. Strict hygiene protocols are meticulously followed throughout the disposal process to prevent contamination and ensure environmental safety. Furthermore, the vehicles used for transporting medical waste are thoroughly disinfected after unloading and before commencing subsequent collection cycles, adhering to high standards of cleanliness and reducing the risk of cross-contamination (Anadolu Ajansı, 2021).

# 3. LITERATURE REVIEW

The literature review section of this thesis encompasses 168 studies conducted between 2005 and 2024. It aims to identify gaps in the existing literature by examining not only healthcare supply chain management, healthcare waste supply chain management, and pharmaceutical supply chain management, but also the management of face mask and glove waste.

In this thesis, two integrated methods for reviewing the literature are employed: systematic analysis and bibliometric analysis, as recommended by scholars (Nightingale, 2009; Cocchia, 2014; Donthu et al., 2021). These methods were selected based on their advantages and their prevalent use in the existing literature.

The literature review is conducted in four distinct sections. Firstly, the scope of the research is defined to establish the boundaries and objectives guiding the literature review process. Secondly, articles are systematically screened from various databases, including Google Scholar, Web of Science (WoS), and EBSCO, to ensure the inclusion of relevant studies. Thirdly, the methodologies and themes employed in the selected articles are identified to facilitate a comprehensive bibliometric analysis. Lastly, the existing research gaps are evaluated, and the research questions that this thesis aims to address are formulated accordingly.

Figure 3.1 presents a detailed flowchart of the literature review process employed in this thesis.

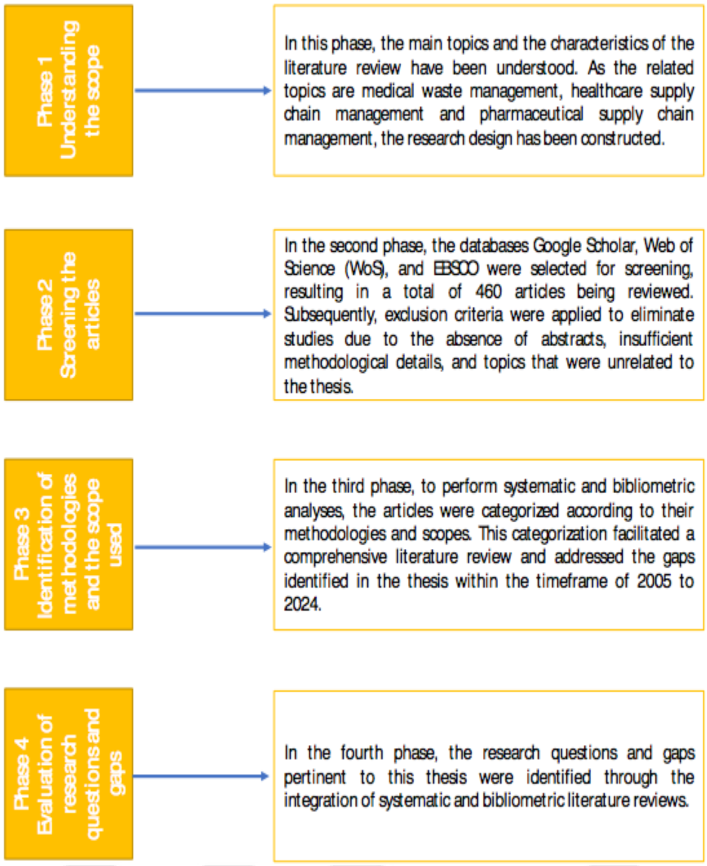


Figure 3.1: The flowchart of the literature review-PRISMA flowchart

As mentioned in the Figure 3.1., Google Scholar, EBSCO, and Web of Science (WoS) were utilized to collect data for the studies. Furthermore, the collected data were visualized using graphs to facilitate comparisons (Fetscherin & Usunier, 2012). These datasets were subsequently imported into VOSviewer for bibliometric analysis. Table 3.1 details the article collection process, including the time periods and topics used for filtering.

Table 3.1: Data Query for literature review

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|---|---|
| Keywords Used for this Review | “Healthcare Supply Chain Management”, “Healthcare Waste Supply Chain Management”, “COVID-19 pandemic and supply chain management”, “Medical Waste Management” |
| Topics | “Title and Abstract” |
| Paper Type | Book Chapters and Articles |
| Language | English |
| Timeline | 2005-2024 |
| Categories | Logistics, Supply Chain Management, Management and Manufacturing and Waste Management |

In the subsequent sections, each component of the literature review is systematically summarized through categorization. Following this, a bibliometric analysis is conducted based on various criteria, including publication year, research scope, topics, countries of origin of the articles, journals, and methodologies—encompassing both the approaches and the solutions to the identified problems utilized in the studies. This comprehensive analysis enables the thesis to systematically identify gaps within the existing literature.

### 3.1. Systematic Literature Review

This section of the thesis conducts a systematic literature review to examine how current research addresses the topics of “Healthcare Supply Chain Management,” “Healthcare Waste Supply Chain Management,” “COVID-19 Pandemic and Supply Chain Management,” and “Medical Waste Management” within the period from 2005 to 2024. Consequently, the studies are analysed chronologically to provide a timeline-based investigation.

#### 3.1.1. Healthcare Supply Chain Management

Zheng et al. (2006) applied a strategic framework between healthcare, SCM and business activities in e-adoption of healthcare supply chain management in order to see the efficiencies of HSCMs. In 2008, Kumar et al. used time series analysis and other similar approaches in order to facilitate a cost reduction in logistics of HSCM.

Mustaffa and Potter (2009) evaluated the performance of inventory management in clinics including wholesalers and the distribution network in Malaysia. Samuel et al. (2010) assessed HSCM by the aid of system dynamics simulation modelling and concluded that there is a bullwhip effect in healthcare supply chain management practices. Turhan and Vayvay (2009) designed a service-oriented architecture by vendor managed inventory approach in healthcare supply chain management systems. A literature review study by de Vries and Huijsman (2011) using a qualitative approach showed that HSCM studies are increasing year by year because of its effective usage in terms of sustainability. Yap and Tan(2012) proposed a conceptual framework for HSCM utilizing examples of practices and performances in Malaysia. Pishvaee et al. (2014) developed a probabilistic programming model for improving an HSC network for medical needles and syringe by the aid of computational analysis. Another study published in 2014 by Abukhousa et al. reviewed the latest studies about simulation and modelling approach utilization in healthcare supply chain area in a decision support view. Furthermore, Kammoun et al. (2014) systematically highlighted discrete event simulation applications in supply chain management in hospitals by the aid of the latest. studies in the literature. Kritchanchai (2014) schematized operational framework of healthcare supply chain management in order to emphasize the national health problems in Thailand. Additionally, a fishbone diagram was utilized by Lenin (2014) used in order to visualize the weaknesses of HSCM in United Arabic Emirates and to and measure quality performance. Next year, Chong et al. (2015) used neural networks and statistical analysis in order to assess Radio Frequency Identification (RFID) systems adoption by the users which were nurses and physicians.

In 2016, Kwon et al. enlightens the strategic areas and developable efficiency in costs where supply chain management in healthcare is included whilst improving the quality in operations in healthcare. Another study published in 2016 by Azadeh et al. used a mathematical approach for optimization of the HSC including supply chains' efficiency measuring. Sabegh et al. (2017) proposed an integrated genetic algorithm and neural network approach for minimization of total manufacturing cost and of environmental effects due to production and transportation. Chikul et al. (2017)

performed a scenario analysis based on Best-Worst Case approach for utilization of RFID and Automated Guided Vehicles (AGV) system technologies in HSCM compared to manual practices. At the same year, Alotaibi and Mehmood (2017) presented a literature review about the big data utilization, role and efficiency in healthcare supply chains. Imran et al. (2018) used interactive multi-objective programming in fuzzy mode for the optimization of HSCM. Mathur et al. (2018) explored the efficiency and effectiveness of HSCM based on a large database of published data. Ageron et al. (2018) evaluated HSCM and logistic systems by considering the latest challenges and developments in HSCM area. Kritchanchai et al. (2018) used Analytic Hierarchy process for healthcare logistic performance in supply chains by KPIs.

A recent study by Khorasani et al. (2020) was a systematic review and meta-analysis lean SCM in healthcare. Another literature review by Moons et al. (2019) classified SC systems based on the logistics systems' performance. Scavarda et al. (2019) framed the practices, policies by integrating the theory of healthcare supply chain management for enlightening the exact process and the barriers by the aid of literature review. Lucchese et al. (2020) developed a hybrid model including facility location model and location routing model for minimizing logistics costs in healthcare supply chains whilst adopting the simulation approach. Alizadeh et al. (2020) tried to redesign reverse and forward supply chain networks for medical supply chains in order to minimize biological risks and maximize profit by using a mixed integer linear programming which is also a part of De Novo Programming.

### 3.1.2. Healthcare Waste Supply Chain Management

Shinee et al. (2008) characterized medical and hospital waste management in Mongolia by using data collection and analyzed by grouping them according to their types, quantities and facilities. Chaerul et al. (2008) used system dynamics modelling in order to better manage the supply chain management of waste in hospitals for minimizing the risks coming from infectious waste. On the other hand, Ananth et al. (2010) developed a healthcare waste management system in 12 countries compared to the current status of healthcare waste management. Dursun et al. (2011) tried to assess healthcare waste treatment alternatives by using a fuzzy approach in a hierarchical structure considering ideal and anti-ideal solution for treatment of these types of waste. Again, in 2011, Ho evaluated two waste disposal companies in medical area in order to compare and determine the optimal one by using fuzzy AHP. On the other hand, Next year, Abed-Elmdoust and Kerachian (2012) used evidential reasoning approach for the purpose of assessing hospital medical solid waste and used Dempster-Shafer theory for aggregating waste assessment criteria. For healthcare waste management, Chauhan and Singh (2016) used a multi-criteria decision-making method in a hybrid way for evaluating sustainable area of healthcare waste facility of disposal. Wang et al. (2019) proposed a mixed integer nonlinear modelling for reverse logistic network design of closed loop supply chain of healthcare waste collection and flow while firstly forecasting waste amount of this type of waste. Kargar et al. (2020a) tried to optimize medical waste quantity and redesign reverse supply chain of medical waste in the region of Iran via a possibilist mathematical programming by considering total costs and the optimal treatment technology option of this type of waste.

Pharmaceutical/drug waste is also categorised under healthcare waste, which is investigated in the literature by scholars.  Regarding the specialized HSCM of pharmaceuticals, Kim (2005) used a case study in order to optimize the inventory control. Woosley and Wiley-Patton (2009) examined PSCM with optimization of inventories. On the other hand, Sousa et al. (2011) published an article in financial area by using mixed integer linear programming model for maximizing net present value while minimizing the costs of globally working PSCM. Baboli et al. (2011) modelled a replenishment policy in PSC based on centralized and decentralized modellings for seeking the best quantity and replenishment policy. Kelle et al. (2012) used dynamic programming and general multi-product (s,S) model in order to optimize PSC in a hospital in operational level decisions including stocks, holding costs and inventory levels based on service level and the availability of spaces for stocks . Uthayakumar and Priyan (2013) assessed an optimization tool in pursuance of the evaluation of inventory strategies in pharmaceutical supply chains by using a two-echelon inventory model and solved this model by a Lagragian method. Priyan and Uthayakumar (2014) developed their model compared to their study published in 2013 by adding different rates and costs hospital's expiry date and holding cost in pharmaceutical network by a fuzzy stochastic approach. Mehralian et al. (2015) used essentially fuzzy TOPSIS with data collection for modelling and developing SCM in pharmaceutical area. Mousazadeh et al. (2015) designed PSC via robust possibilistic programming as bi-objective mixed integer linear programming in order to provide the minimization of total cost while optimizing material flows. On the other hand, Weraikat et al. (2016) used centralized model for a green reverse supply chain management for pharmaceuticals and solved this model by Lagragian relaxation with the aim of coordinating the collection of unwanted medical goods from customers. Vishwakarma et al. (2016) used fuzzy AHP to analyze PSCM and found the main risks of Indian PSC. Settanni et al. (2017) evaluated the studies on PSC in the literature from the perspective of operations research and models that have been used in the studies. Another study which is published in 2017 by Nematollahi et al. (2017) expressed a model in two-echelon pharmaceutical supply chains by taking into consideration economic and social collaborative decision making structures in order to maximize net profit by minimizing lead times under stochastic demand. Martins et al. (2017) presented a hybrid approach of simulation and optimization in the form of mixed integer programming and discrete event simulation for the purpose of redesigning pharmaceutical wholesaler network and minimizing the costs. Moreover, Mehralian et al. (2017) used AHP method, performed by 44 interviewers, for understanding the relationship and prioritize related factors in pharmaceutical supply chain management. Clauson et al. (2018) investigated the effects of blockchain opportunities and functionality in healthcare systems, including pharmaceutical supply chains and medical devices supplies by an extended literature review. Savadkoohi et al. (2018) used possibilistic programming approach in the form of mixed integer linear programming in order to model location and inventory multi periodically in pharmaceutical supply chains. Furthermore, Merkuryeva et al. (2018) made a scenario analysis based on pharmaceutical supply chain management by regression analysis and genetic programming approaches. Nematollahi et al. (2018) used multi-objective coordination model for maximizing respective self-interests at two level pharmaceutical supply chain under stochastic demand and solved by ε-constraint method. Forghani et al. (2018) used an integrated approach mixed integer linear programming, PCA and TOPSIS in order to evaluate suppliers based on decision making and optimization approaches in pharmaceutical supply chains. Furthermore, Beldek et al. (2019) tried to give a perspective about supply chain management in healthcare by the aid of a systematic literature review in pharmaceutical and medical sector.

Kees et al. (2019) used a fuzzy goal programming approach in public hospitals' drug supply chain logistic as an optimization model including the flows of economic and physical. Roshan et al. (2019) proposed a mixed integer nonlinear modelling including fuzzy and crisp numbers with the aim of minimizing total costs of network, demand which is not met and maximizing the social responsibility satisfaction in pharmaceutical supply chains. Viegas et al. (2019) made a classificatory analysis and review of pharmaceutical supply chain studies in the literature and based on questionnaire. Singh and Goh (2019) used mixed integer linear programming by intuitionistic fuzzy numbers with the aim of scalarizing operators in pharmaceutical supply chains. Franco et Lizarazo (2020) formulated a mixed integer model for pharmaceutical supply chain networks in hospitals and used simulation-optimization approach for management in tactical and operative decisions. The second part of the study has been modelled with bi-objective optimization models in order to minimize the amount of expired medicines and maximize expiration dates.

Moreover, Tat et al. (2020) developed a hybrid decentralized and centralized model for avoiding of governmental penalties and ensuring patient service level while decreasing the amount of pharmaceutical waste in pharmaceutical supply chains. Also, Akbarpour et al. (2020) proposed multi objective model for perishable pharmaceutical drugs' supply chains under uncertain demand by developing this chain's effectiveness and efficiency. Gómez and Espana (2020) evaluated operational risks in pharmaceutical supply chains and illustrated the relations by using fuzzy QFD.

Another study published in 2020 by Chen et al. used Kano's model and quantitative analysis in questionnaire forms to evaluate the perceptions of logistics services and supply chains in pharmaceutical services. Zandkarimkhani et al. (2020) aimed to minimize the total cost in perishable pharmaceutical supply chain networks by using fuzzy chance constrained programming and goal programming under stochastic demand.

Alshemari et al. (2020) showed a detailed literature review on pharmaceutical waste, circular economy management of this type of waste and supply chain management of pharmaceutical waste. Also, Argiyantari et al. (2020), at the same year, investigated the studies in the literature in the framework of pharmaceutical supply chain transformation based on Lean principle.

### 3.1.3. Medical Waste Applications in the Literature and COVID-19 Effect

When considered in a way of systematic literature review for the medical waste management, even though the number of studies conducted in Turkey seems limited, around the world, medical waste management studies still increase, which indicates numerous studies within the field of medical waste management exist in the literature. To start, Aung et al. (2019) focused on evaluating medical waste management in accordance with World Health Organization guidelines. Their model, developed for this purpose, was implemented across eight diverse hospitals in Myanmar, encompassing both public and private institutions. Data collection involved surveys, interviews, and observations, with multi-criteria decision-making methods employed to determine relevant waste management criteria. Stringent control measures are imperative for hazardous waste, encompassing adherence to regulations, laws, as well as leveraging experiential insights and technological advancements (Aung et al., 2019).

Zamparas et al. (2019) delved into the management of infectious waste in Greece. Their study involved a comparative analysis of related regulations across European Union countries, utilizing a multi-criteria model. The Analytic Hierarchy Process was applied from an environmental standpoint, with official data serving as input, and environmental management criteria yielding the most favorable outcomes (Zamparas et al., 2019).

Examining the biomedical waste generated during the Covid-19 pandemic, Ilyas et al. (2020) identified key sources such as facemasks, testing kits, personal protective equipment, and gloves. The effective management of these waste streams is critical to curb the rapid spread of diseases. The study evaluated various applications under policy frameworks to recommend appropriate methods for the proper disposal of hazardous medical waste (Ilyas et al., 2020).

Sangkham (2020) conducted a medical waste study in the Asian region during the pandemic, underscoring the importance of adhering to guidelines and standards for hazardous waste disposal to mitigate environmental and social impacts. Tirkolaee et al. (2021) focused on infectious waste management during the Covid-19 pandemic, utilizing a mixed-integer linear programming model. This model addressed the disruption in regular waste management caused by the pandemic, aiming to minimize infection risks, travel times, and deviations from time windows. The study applied this model in Iran, presenting diverse scenario results for managerial recommendations (Tirkolaee et al., 2021). Singh et al. (2022) conducted a meta-analysis examining waste management in the context of the Covid-19 pandemic across different countries. Their investigation sought to understand the current state of medical waste management considering diverse socioeconomic and environmental parameters. In another contribution to medical waste, Janik-Karpinska et al. (2023) explored various medical waste types to emphasize the significance of waste management for human health and environmental safety. Their paper presented information on different management principles to offer a comprehensive overview of healthcare waste on a global scale, considering its potential harm to the population through various pathways (Janik-Karpinska et al., 2023).

On the other hand, in the literature, there are a few studies about COVID-19 effect on healthcare waste management and healthcare SCM in the world during COVID-

19 pandemic. It is also a fact that there is a little of studies about HSCM but investigating especially the face mask policies in each country leads us to understand how the effective policy of waste management should be managed. During COVID-19 outbreak, Firstly, Akarsu et al. (2021) evaluated disposable face masks as environmental threat and tried to estimate the used face mask amount during COVID-19 pandemic by explaining why microplastic waste results in plastic pollution. Ammendolia et al. (2021) evaluated personal protective equipment, such as gloves, face masks as an alerting source of pollution in Toronto and proposed a new strategy for municipal collection policies. Abbasi et al. (2020) explained their concerns about high production and use of face masks, which results in a high rate of microplastic pollution during COVID-19 pandemic in Arabian Peninsula by computing the amount of face masks which are used in each of the country of Arabian Peninsula. Aragaw (2020) studied face masks, which are used to control COVID-19 transmission, pollution and concluded that face mask threatens environmental sustainability and face mask pollution is an issue that needs to be focused on in order to eradicate the problem. Eikenberry et al. (2020) tried to model the face mask utility and to understand how the face masks are used to avoid from COVID-19 pandemic by the aid of stochastic differential equations while concluding that face mask use decreases the transmission of the virus between citizens. Feng et al. (2020) compared face mask policies of countries during COVID-19 pandemic and many of countries suggest face mask use in public area even if citizens are symptomatic or asymptomatic in order to prevent risks. Furthermore, Worby and Chang (2020) evaluated the distribution allocation of face masks since the resources become limited and supply-demand balance deteriorates during COVID-19 pandemic. Sarkodie and Owusu (2020) observed the quantity of wastes during lockdowns and concluded that it dramatically increases as production and consumption increase parallelly. Sangkham (2020) states that medical waste generation during COVID-19 pandemic can be found as given in formulas for countries and estimated the waste generation through the outbreak.

Furthermore, Nzediegwu and Chang (2020) stated that solid waste including gloves, face masks and aprons, which is not properly managed potentially and rapidly spreads COVID-19 pandemic in developing countries. Another example, Govindan et al. (2020) tried to develop a decision support system in order to better manage the demand in healthcare during pandemic based on the point of view of physicians and fuzzy interference system. Kulkarni and Anantharama (2020) evaluated municipal solid waste management with opportunities, challenges and threats during COVID-19 pandemic with a real data in terms of collection, disposal and treatment services.

About COVID-19 pandemic, Nikolopoulos et al. (2020) simulated supply chains for services and medical products in order to forecast by machine and deep learning algorithms during COVID-19 pandemic days. Leite at al. (2020) expressed the quality measurements across healthcare operations and supply chain during COVID-19 pandemic for the demand, supply and source allocations for better managing the vital goods and medicals supply. Sharma et al. (2020) evaluated solid waste management during COVID-19 pandemic and their changes of compositions. Klemeš et al. (2020) tried to analyze plastic waste footprint, including contaminated waste, and how to minimize plastic waste during COVID-19 period and after the outbreak. Furthermore, Ilyas et al. (2020) investigated disinfection technologies and strategies of medical waste in order to analyze health risk of contaminated waste and proposed a new policy for biomedical waste. Kargar et al. (2020b) used a revised multi-choice goal programming approach in order to minimize medical waste logistic cost and negative effects during COVID-19 pandemic. Ma et al. (2020) proposed a guideline for medical waste management in case of emergency in China with MSW examples.

Benson et al. (2021) tried to forecast personal protection equipment, including gloves, face shields and surgical masks in Africa and analyzed their environmental effects especially in Nigeria during COVID-19 pandemic. Furthermore, Thind et al. (2021) assessed environmental effects of biomedical waste management system in India, including incineration operations and their effectiveness. Van Fan et al. (2021) analyzed municipal solid waste management strategies and the effects of COVID-19 pandemic on waste management while in some cities, waste is increasing and, in some cities, it is decreasing with different rates. Das et al. (2021) have conducted a literature review for healthcare waste management during COVID-19 pandemic for analyzing possible scenarios in the world. Manupati et al. (2021) used a Fuzzy VIKOR method in order to select the best possible alternative for healthcare waste disposal techniques during COVID-19 pandemic.

Moreover, Yang et al. (2021) analyzed highly contaminated healthcare waste, including face masks, gloves and shields, in Wuhan according to their types and compared them with other cities in China. At the same year, Tirkolaee et al. (2021) used a fuzzy weighed goal programming approach with the aim of determining the optimal and sustainable policy for medical waste management in a real case during COVID-19 pandemic. Hantoko et al. (2021) discussed the waste management operations during outbreak for proposing new approaches to the challenges of waste disposal, especially for contaminated waste. Zhao et al. (2021) performed a life cycle assessment for medical waste in China in order to compare environmental impacts of emergency disposals with scenario analysis and to recommend new policies. At the same area, Torkashvand et al. (2021) proposed another guideline for municipal solid waste management, including medical and healthcare waste, with the help of current literature during COVID-19 pandemic. Maalouf and Maalouf (2021) analyzed the COVID-19 pandemic effects on medical waste management in Lebanon and concluded that medical waste should be properly managed since the infectious waste rate has rapidly increased. Thakur (2021) proposed an integrated PESTEL analysis and fuzzy MICMAC method with clustering for inform hospitals about medical waste management's treatment during COVID-19 period. Zhao et al. (2022) used MILP modelling for producing renewable fuels by using PPE waste during Covid-19 period and applied this model in New-York. Yogiswari et al. (2022) studied environmental cost analysis for medical waste management during COVID-19 period in Indonesia by using a qualitative approach. Ranjbari et al. (2022) tried to scrutinize a systematic literature review on medical waste management by considering COVID-19 effect. Harussani et al. (2022) experimented the pyrolysis of PP plastics used in face masks to convert PP into energy.

### 3.1.4. Forecasting Applications by Nonlinear Grey Bernoulli Modelling

Currently, Nonlinear Grey Bernoulli Model (NGBM) finds applications in various forecasting scenarios. A comprehensive review of articles utilizing the NGBM(1,1) was conducted to identify diverse forecasting areas and analyses. Table 3.2 offers a summary of the pertinent articles that employ the NGBM approach for forecasting.

Table 3.2: Summary of NGBM applications in the literature

| Reference | Data Source | Performance Measures |
|---|---|---|
| Chen, 2008 | Official Data | RPE and ARPE |
| Hsu, 2010 | Official Data | MAPE and RMSE |
| Wu et al., 2019 | Real-world data sets | MAPE |
| Şahin and Şahin, 2020 | Official Data | RMSE, MAPE, R2 |
| Wang, 2013 | Official Data | RPE |
| Duman et al., 2019 | Official Data | R2 |
| Xiao et Wang, 2022 | Official Data | MAE, MAPE, RMSE |
| Liu et al. , 2022 | Official Data | MAPE, APE |
| Xie et al., 2021 | Official Data | MAPE, RMSE |
| Şahin, 2021 | Official Data | MAPE |
| Wu et al., 2021 | Official Data | MAPE |
| Jiang et al.,2021. | Official Data | R2 and MAPE |
| Yang and Xie,2021 | Official Data | MAPE, RMSE |
| Duan et al., 2021 | Official Data | APE |
| Zheng et al., 2021 | Official Data | MAE, RMSE, MAPE |
| Wang and Jv, 2021 | Official Data | MAE, RMSE, MAPE |
| Wang et al. 2011 | Official Data | R2, MAPE |
| Wu et al., 2023 | Official Data | MAPE, RMSE, NRMSE |

The table compiles various studies retrieved from the literature, sourced through the Google Scholar and Web of Science databases. Within this literature, Chen (2008) utilized official unemployment rate data from ten countries to assist governments in policy development. Hsu (2010) integrated GM(1,1) and the Grey Verhulst model to compare NGBM(1,1) results, forecasting the performance of the circuit industry in Taiwan. This study demonstrated that NGBM(1,1) is more accurate than GM(1,1) and the Grey Verhulst model. Wang (2013) employed NGBM(1,1) modeling in the finance field to estimate the main economic indices of high-tech enterprises in China. The conclusion was that NGBM(1,1) remains accurate even with a small sample size. Wu et al. (2019) introduced a novel model, FANGBM(1,1), incorporating fractional order accumulation to forecast various energy consumptions, including hydroelectricity, wind, and solar.

In the healthcare domain, Şahin and Şahin (2020) highlighted a different application of NGBM(1,1) to forecast total COVID-19 cases in Italy and the USA. They also compared the results with GM(1,1) and FANGBM(1,1). Xie et al. (2021) estimated fuel combustion-related CO2 emissions using an integrated method, while Liu et al. (2022) optimized parameters using five different algorithms to apply NGBM(1,1) for estimating natural gas production in China.

In the energy consumption field, Şahin (2021) concluded that the nonlinear grey Bernoulli model yields accurate results with low errors when applied to renewable energy consumption in Spain, Germany, Turkey, Italy, and the UK. Similarly, NGBM(1,1) was employed to forecast solar energy production in China by Wu et al. (2021), and Jiang et al. (2021) attempted to estimate hydropower energy generation using NGBM(1,1) with a PSO algorithm-based parameter optimization. Yang and Xie (2021) presented a study to estimate coal consumption in China, emphasizing NGBM(1,1)'s high accuracy. Duan et al. (2021) integrated NGBM(1,1) with particle swarm optimization to predict global renewable energy consumption. Zheng et al. (2021) forecasted hydroelectricity consumption in the energy industry using an unbiased NGBM(1,1).

In the waste management field, NGBM(1,1) modelling has proven effective in forecasting waste. For instance, Wang et al. (2011) utilized NGBM(1,1) to estimate discharged wastewater in China. Duman et al. (2019) integrated NGBM(1,1) and particle swarm optimization to forecast electronic waste in Washington, comparing the results with multivariate grey models. Wang and Jv (2021) estimated solid waste and industry components by using NGBM(1,1) which yields high accuracy. Xiao and Wang (2022) used an improved NGBM(1,1) with particle swarm optimization of parameters to predict WEEE amount in China, concluding that the WEEE recycling industry's development trend aligns accurately with the results and actual values. As one of the latest studies in 2023, Wu et al. (2023) applied NGBM(1,1) combined with an MPA-based optimization to predict petroleum consumption in China.

It is also noteworthy that several authors have articulated the advantages of grey forecasting models over alternative methods in the literature (Tseng et al., 2001; Wang and Jiang, 2019; Zeng et al., 2020). The advantages inherent in the grey forecasting model are robust compared to other machine learning and statistical methods including ARIMA, SARIMA, ANN, time series methods and SVM (Wang and Jiang, 2019; Wang et al., 2018; Wu et al., 2021). Firstly, its adaptability shines in situations where data are scant; remarkable results have been attained with as few as four observations to predict outcomes in unknown systems (Xie and Wang, 2017). Secondly, its utilization of a first-order differential equation for system characterization is noteworthy. This feature enables the model to thrive even when confronted with sparse data, demonstrating that a minimal amount of discrete data points is ample for system characterization. As a consequence, the grey forecasting model emerges as a formidable tool, particularly adept for forecasting in competitive environments where decision-makers must rely on limited historical data (Chen and Wang, 2012; Es, 2021).

Despite numerous studies employing SVM, regression-based methods, ARIMA, and basic grey models to estimate medical waste in Turkey across various years (Altin et al., 2023; Erdebilli and Devrim-İçtenbaş, 2022; Çetinkaya et al., 2020; Hanedar et al., 2022; Ceylan et al., 2020; Korkut, 2018), the utilization of non-linear grey Bernoulli models, particularly optimized by metaheuristics, remains absent in the literature for estimating medical waste amounts in Turkey's largest city. Furthermore, there is a lack of comparison with traditional statistical and basic grey models, indicating a gap that necessitates a more comprehensive approach. To date, no studies have investigated the quantity of medical waste generated in Istanbul during the COVID-19 period and the subsequent impact of the pandemic on medical waste volumes using the Non-linear Grey Bernoulli Model (NGBM(1,1)) optimized by metaheuristics in comparison to classical grey models. Moreover, to the best of our knowledge, the existing literature lacks any study forecasting medical waste in

Istanbul within the time span of 2004-2023. This underscores the novelty and robustness of our method, providing a new contribution to the waste literature. In this regard, we contend that existing methods have not been optimized to forecast medical waste in Istanbul through the utilization of metaheuristics, such as the firefly algorithm, the effectiveness and accuracy of which have been demonstrated in the literature (Ma et al., 2020; Ma et al., 2017; Khodabaccus and Saib, 2023). Hence, our novelty and originality possess dual dimensions: firstly, our methodology involving the NGBM(1,1) optimized by the firefly algorithm to forecast medical waste generation in Istanbul; and secondly, our exploration of a new policy timeframe, contributing to the discourse in a novel manner.

### 3.1.5. MCDM Applications in the context of Medical Waste in Turkey

In the development of a healthcare waste management system within a specific country, decision-makers must consider a comprehensive range of parameters, encompassing technical, economic, social, and political factors. Addressing this multifaceted challenge, the Multi-Criteria Decision Making (MCDM) methodology proves indispensable in facilitating informed and holistic solutions, particularly within the Turkish context (Özkan, 2013; Çelik et al., 2022; Çakir et al., 2021). However, existing scholarly work indicates a paucity of analytical studies that integrate Healthcare Waste Management (HWM) with MCDM practices, thereby corroborating the primary findings of antecedent research (Görçün et al., 2023; Dursun et al., 2011).

The selection of an optimal location for a new recycling center in a major urban area and the analysis of influential factors affecting medical waste strategies, especially in complex metropolitan environments such as Istanbul, constitute a challenging and intricate decision-making task. This process involves the consideration of numerous criteria and potential site alternatives. In this context, MCDM methodologies emerge as robust and multidimensional tools that empower managers and streamline the decision-making process (Torkayesh & Simic, 2022; Dang et al., 2021; Singh et al., 2022; Mishra et al., 2021).

Table 2.3 provides an overview of healthcare waste management applications integrated with MCDM techniques in Turkey. Notably, spherical fuzzy sets have not been employed in medical waste management practices, particularly concerning the management policies for face mask and glove waste in Turkey. Consequently, this thesis posits that its methodology introduces a novel application of fuzzy sets within the medical waste management domain in Turkey focusing on Istanbul, addressing the prioritization of factors related to face mask and glove waste management—an aspect that remains unexamined in the current literature.

Table 3.3: Summary of MCDM applications in the literature

| Authors | Methods | The Sets used in MCDM applications | Data Source |
|---|---|---|---|
| Eren and Tuzkaya (2019) | AHP | Ordinary Fuzzy Sets | Survey |
| Özkan (2013) | ANP and ELECTRE | Ordinary Fuzzy Sets | Survey |
| Dursun et al. (2011) | Hierarchical distance-based fuzzy method | Ordinary Fuzzy Sets | Survey |
| Adar and Delice (2019) | MAIRCA and MABAC | Hesitant Fuzzy Sets | Survey |
| Torkayesh and Simic (2022) | CoCoSo and WASPAS | Interval-Valued İntuitionistic Fuzzy Set | Survey |
| Çakir et al. (2021) | AHP | Circular Intuitionistic Fuzzy Sets | Interview |
| Çelik et al. (2022) | AHP | Intuitionistic Fuzzy Sets | Survey |
| Görçün et al. (2023) | COPRAS | Interval-Valued Fermatean Fuzzy Sets | Survey |

### 3.2. Bibliometric Literature Review

This chapter presents a bibliometric analysis spanning the years 2005 to 2024. To conduct a comprehensive bibliometric examination, an Excel spreadsheet was utilized, enabling both quantitative and qualitative analysis of the existing literature. The chapter systematically delineates the evolution of medical waste studies over the specified timeframe, followed by an analysis of the contributing countries, the methodological approaches employed in the literature, the solution methodologies proposed by these studies, as well as the key journals and types of publications pertinent to the reviewed research.

The primary objective of this section is to highlight the originality of this thesis by critically analysing existing studies in terms of their employed methodologies and thematic focus. Through this detailed bibliometric analysis, the chapter seeks to identify gaps in the current literature and demonstrate how the present research contributes uniquely to the field of medical waste management. The detailed table regarding the inclusion of these studies is given in the Appendix 1.

### 3.2.1. Evolution of the studies in years

The literature on medical waste management encompasses various domains, including healthcare waste supply chain management, pharmaceutical and drug supply chain management, and medical waste forecasting. As illustrated in Figure 3.2, there is a discernible increasing trend in the coverage of these topics within the literature, as evidenced by the analysis of 168 articles.

However, despite the comprehensive inclusion of 168 studies sourced from multiple databases, as detailed in Table 2.1, there remains the potential for certain studies to have been inadvertently overlooked. This possibility underscores the inherent limitations of bibliometric analyses and highlights the need for continuous and exhaustive literature searches to ensure the most accurate and comprehensive understanding of the field.

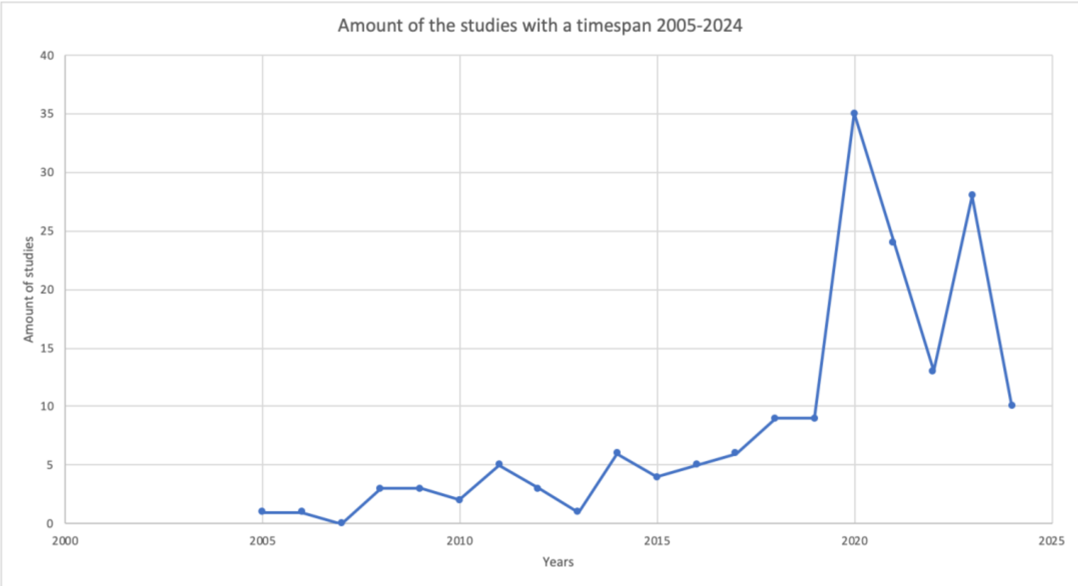


Figure 3.2: Amount of the studies versus years in the literature

### 3.2.2. The studies based on countries

The literature pertinent to this thesis encompasses studies from various countries, as illustrated in Figure 3.3. Notably, Iran, India, China, Turkey, and the United States are the most frequently represented nations in the published studies, particularly during the period from 2020 to 2024. This increase and leading position in the scholarly output can be attributed to the significant impact of the COVID-19 pandemic in these countries.

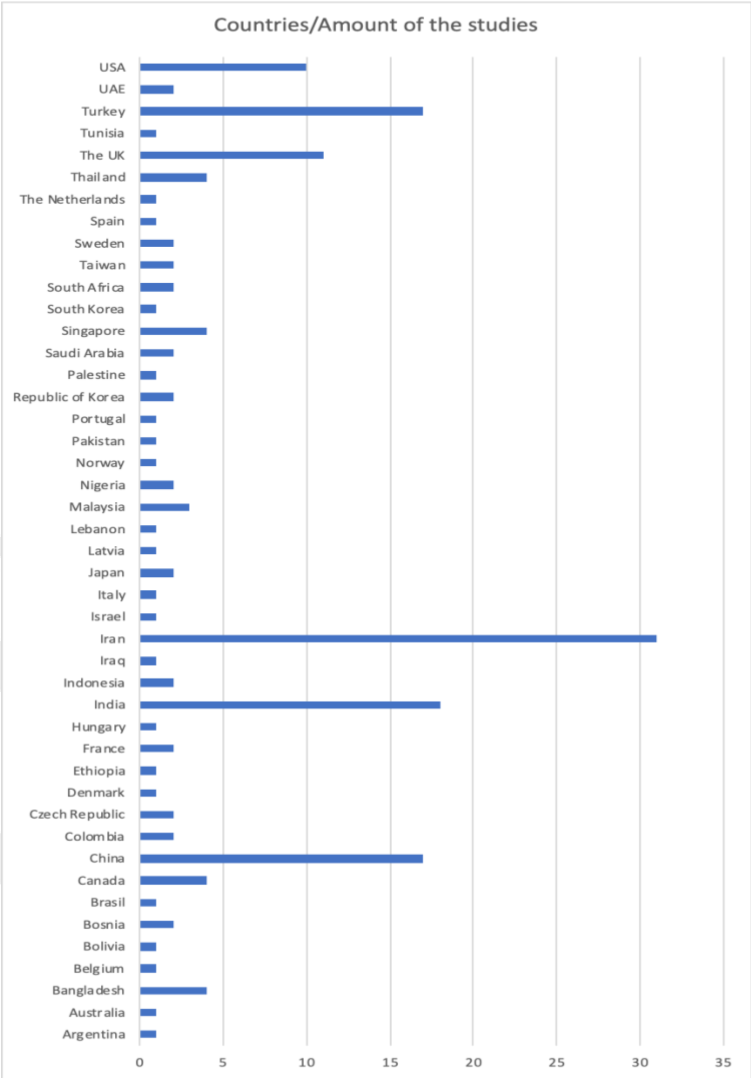


Figure 3.3: Amount of the studies versus countries in the literature

### 3.2.3. Methodological approaches in the literature

Within the corpus of 168 reviewed articles, diverse methodological approaches have been identified to underscore and analyse the originality of this thesis.

The predominant methodological approaches utilized in the literature include literature reviews, fuzzy approaches, statistical analyses, Mixed Integer Linear Programming (MILP), and quantitative analyses related to healthcare waste supply chain management, pharmaceutical and drug supply chain management, and medical waste forecasting. The authors generally emphasized tools such as literature reviews, fuzzy logic, and statistical analysis. However, there is a growing trend towards the integration of optimization and simulation tools within the literature, as evidenced in Table 3.4. Table 3.4 primarily delineates the 15 key methodologies employed in the literature to analyse healthcare supply chains, healthcare waste supply chains, and pharmaceutical supply chains.

Table 3.4: Methodologies (Top 15) in the literature

| Method | Shares in(%) | Example Studies |
|---|---|---|
| Literature Review | 19% | Atcha et al. (2024), Lyu et al. (2024), De Vries and Huijsman (2011), Abukhousa et al. (2014), Kammoun et al. (2014), Settanni et al. (2017), Clauson et al. (2018), Alotaibi and Mehmood(2017), Mathur (2018), Ageron et al. (2018), Beldek et al. (2019), Moons et al. (2019), Viegas et al. (2019), Khorasani et al. (2020), Leite et al. (2020), Alshemari et al. (2020), Argiyantari et al. (2020), Das et al. (2021), Ilyas et al. (2020), Torkashvand et al. (2021), Ranjbari et al. (2022) |
| Fuzzy Approach | 16% | Ala et al. (2024), Mishra et al. (2023),Beheshtinia et al. (2023),Dursun et al. (2011) , Ho (2011), Pishvaee et al. (2014), Priyan and Uthayakumar (2014), Mehralian et al. (2015), Chauhan and Singh (2016), Vishwakarma et al.(2016), Imran et al. (2018), Kees et al. (2019), Singh and Goh (2019), Govindan et al. (2020), Kargar et al. (2020a), Zandkarimkhani et al. (2020), Gómez and España (2020), Govindan et al. (2020), Zandkarimkhani et al. (2020), Manupati et al. (2021), Tirkolaee et al. (2021) |
| Statistical Analysis | 13% | Shinee et al. (2008), Ananth et al. (2010), Chong et al. (2015), Azadeh et al. (2016), Abbasi et al. (2020), Benson et al. (2021), Nzediegwu and Chang(2020), Van Fan et al. (2021), Klemeš et al. (2020), Yang et al. (2021), Sangkham (2020), Kulkarni and Anantharama(2020), Ma et al. (2020), Maalouf and Maalouf(2021) |
| Mixed Integer Linear Programming (MILP) | 5% | Cao et al. (2022),Sousa et al. (2011), Savadkoohi et al. (2018), Forghani et al. (2018), Alizadeh et al. (2020), Kargar et al. (2020b) |
| Quantitative Analysis | 5% | Woosley and Wiley-Patton (2009), Yap and Tan (2012), Scavarda et al. (2019), Chen et al. (2020), Yogiswari et al. (2022) |
| Simulation | 4% | Chaerul et al. (2008), Worby and Chang (2020), Samuel et al. (2010), Nikolopoulos et al. (2020) |
| Interview | 3% | Zheng et al. (2006), Kritchanchai (2014), Lenin (2014) |

Table 3.4 (cont.): Methodologies (Top 15) in the literature

| Method | Shares in(%) | Example Studies |
|---|---|---|
| Decentralized Model | 2% | Baboli et al. (2011), Nematollahi 2017) |
| Experimental Design | 2% | Aragaw(2020) and Harussani et al. (2022) |
| Hybrid Optimization-Simulation | 2% | Martins et al. (2017), Lucchese et al. (2020) |
| Mixed Integer Programming | 2% | Hovav and Tsadikovich(2015), Franco and Alfonso-Lizarazo (2020) |
| Vendor-Managed Inventory Approach | 2% | Kim (2005), Turhan and Vayvay (2009) |
| Bi-objective Model | 1% | Akbarpour et al. (2020) |
| Centralized Model Approach | 1% | Weraikat et al. (2016) |
| Mixed Integer Nonlinear Programming | 3% | Wang et al. (2019), Roshan et al. (2019), Zhao et al. (2022) |
| Pointview | 3% | Leite et al. (2020), Sharma et al. (2020), Hantoko et al. (2021) |

### 3.2.4. Solution methodologies in the literature

Building upon the methodologies utilized in the existing literature, various solution methods have been identified to address the primary issues highlighted in the studies. These techniques provide critical insights into the challenges within the domains of healthcare waste supply chain management, pharmaceutical and drug supply chain management, and medical waste forecasting. Table 3.5 delineates the fifteen solution methodologies documented in the literature, which correspond to the problems identified in the reviewed papers and discussed in this thesis.

By examining these solution approaches, this chapter elucidates how current research addresses and mitigates the complexities inherent in managing healthcare and pharmaceutical waste, thereby offering a comprehensive understanding of effective strategies within these fields.

Table 3.5: Solution Methodologies (Top 15) in the literature

| Solution Method | Shares in (%) | Topic |
|---|---|---|
| AHP | 4% | Healthcare Supply Chain Management |
| Data Analysis | 4% | Healthcare Waste Supply Chain Management, Healthcare Waste Supply Chain Management |
| TOPSIS | 3% | Pharmaceutical/Drug Supply Chain Management, Healthcare Waste Supply Chain Management |
| Linear Approximation Method | 2% | Pharmaceutical/Drug Supply Chain Management |
| Neural Network | 2% | Healthcare Supply Chain Management |
| Scenario Analysis | 2% | Pharmaceutical/Drug Supply Chain Management, Healthcare Waste Supply Chain Management |
| Fuzzy Goal Programming Approach | 3% | Healthcare Waste Supply Chain Management, Pharmaceutical/Drug Supply Chain Management |
| Lagrangian Multiplier Algorithmic Approach | 2% | Healthcare Supply Chain Management, Pharmaceutical/Drug Supply Chain Management |
| Bi-objective Mixed Integer Linear Programming | 1% | Pharmaceutical/Drug Supply Chain Management |
| Credibility-based Fuzzy Chance Constrained Programming | 1% | Healthcare Supply Chain Management |
| Decomposition and Aggregation Methods | 1% | Pharmaceutical/Drug Supply Chain Management |
| Dempster-Shafer theory | 1% | Healthcare Waste Supply Chain Management |
| Differential Stochastic Modelling | 1% | Healthcare Waste Supply Chain Management |

Table 3.5 (cont.): Solution Methodologies (Top 15) in the literature

| Solution Method | Shares in (%) | Topic |
|---|---|---|
| Epsilon-Constraint Method. | 1% | Healthcare Supply Chain Management |
| Fuzzy Interactive Programming Approach | 1% | Pharmaceutical/Drug Supply Chain Management |
| Fuzzy VIKOR | 1% | Healthcare Waste Supply Chain Management |
| Fuzzy-MICMAC | 1% | Healthcare Waste Supply Chain Management |
| Nearest Neighbor Approach | 1% | Healthcare Supply Chain Management |
| Nonlinear Modelling and Solution Methods | 1% | Healthcare Waste Supply Chain Management |
| Quadratic Approximation Method | 1% | Pharmaceutical/Drug Supply Chain Management |

### 3.2.5. Key Journals in the literature

Based on the literature review, the key journals have been identified and are summarized in Table 3.6. The topics of healthcare waste supply chain management, pharmaceutical and drug supply chain management, and medical waste forecasting are predominantly published in journals that focus on environmental challenges and recycling. Furthermore, as illustrated in Appendix 1, journals specializing in fuzzy logic methodologies have also been selected to align with the subjects covered in this thesis. This selection underscores the interdisciplinary nature of the research, integrating environmental sustainability with advanced analytical techniques to address the complexities of medical waste management.

Table 3.6: Key Journals in the literature

| Key journals in the Literature | Shares in % | Examples of Studies |
|---|---|---|
| Science of The Total Environment | 7% | Abed-Elmdoust and Kerachian (2012), Harussani et al. (2022), Tirkolaee et al. (2021), Ilyas et al. (2020) |
| Journal of Cleaner Production | 6% | Nematollahi (2017), Chauhan and Singh (2016), Nematollahi et al. (2018), Viegas et al. (2019) |
| Waste Management | 5% | Zhao et al. (2021), Shinee et al. (2008) |
| Resources, Conservation and Recycling | 5% | Sharma et al. (2020), Dursun et al. (2011) |
| Transportation Research Part E: Logistics and Transportation Review | 4% | Pishvaee et al. (2014), Govindan et al. (2020), |
| Operations Research for Health Care | 4% | Kelle et al. (2012), Priyan and Uthayakumar(2014) |
| Computers & Industrial Engineering | 3% | Weraikat et al. (2016), Martins et al. (2017) |

### 3.3. Overview of the Literature review and the Contribution of the Thesis

The literature significantly underscores the growing importance of topics such as healthcare waste supply chain management and medical waste forecasting, particularly in the post-COVID-19 era. In Turkey, as in other countries, these subjects have garnered substantial scholarly attention. However, investigations into medical waste management by researchers remain fragmented and limited in scope, especially concerning methodological approaches and the specific focus on face masks and gloves waste management within the context of Turkey. For instance, recent studies by Demir and Moslem (2024), Soyler et al. (2025), Altin et al. (2023), and Coban et al. (2023) have made significant contributions to the fields of medical waste management, supply chain logistics for such waste, and recycling policies in Turkey. Nonetheless, none of these studies specifically address the management of face masks and gloves waste, highlighting a critical gap that this thesis aims to fill. This focus on face masks and gloves waste management constitutes the first original contribution of this thesis to the existing literature.

As outlined in the introduction, the originality of this thesis is twofold. Firstly, through an extensive and comprehensive literature review, it has been identified that the integration of a system dynamics approach to evaluate the current situation and provide insights for proposed policies and models has not been previously utilized in this context. Secondly, the application of nonlinear grey Bernoulli modelling to forecast medical waste, including face masks and gloves, in Turkey, alongside the implementation of a spherical fuzzy Multi-Criteria Decision Making (MCDM) approach, represents a novel methodological advancement. These combined methodologies offer a unique analytical framework that has not been employed in prior studies, thereby providing the second original contribution of this thesis.

In summary, this thesis makes two significant original contributions to the literature:

1. *Novel Research Focus*: It addresses critical research questions related to the management of face masks and gloves waste, an area that has not been adequately explored in existing studies.

2. *Methodological Innovation*: It introduces a methodological novelty by integrating three distinct approaches—system dynamics, nonlinear grey Bernoulli modelling optimized by the Firefly Algorithm, and spherical fuzzy MCDM—thereby enhancing the analytical rigor and comprehensiveness of waste management strategies.

These advancements not only address previously unfilled gaps in the literature, but also establish a solid foundation for subsequent scholarly inquiries and real-world implementations in medical waste management, both within Turkey and in comparable environments elsewhere.

# 4. METHODOLOGY

This chapter presents the evaluation methodologies proposed for this thesis, including a simulation-based system dynamics approach, nonlinear grey Bernoulli modelling optimized by the firefly algorithm, and a multi-criteria decision-making approach utilizing spherical fuzzy sets. Additionally, the chapter provides detailed descriptions of these methodologies and outlines the computational procedures involved in implementing the proposed evaluation approaches within this study. The figure 4.1 illustrates how these methodologies are used in this thesis.

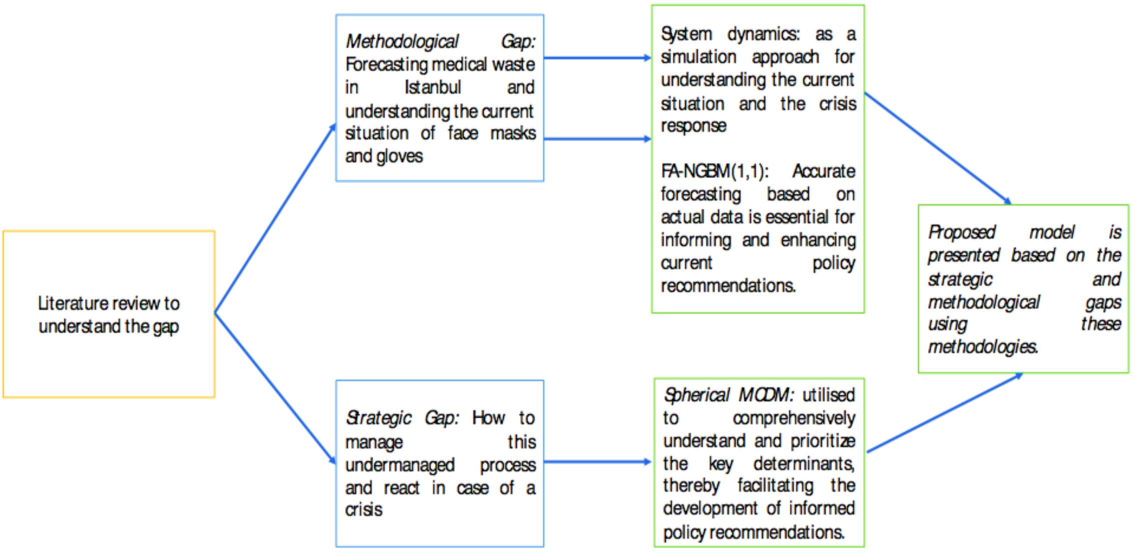


Figure 4.1: The flowchart of the methodologies used in the thesis

## 4.1. System Dynamics and Causal Loop Diagrams

This section employs the system dynamics methodology to improve the recycling rates of nitrile and latex gloves, as well as face masks.

Building upon the methodology discussed earlier, this part offers a brief introduction to system dynamics. Defined as a simulation-based approach, system dynamics serves as a systematic method for comprehending the behavior of complex systems over time (Forrester, 1993). The system consists of various components—such as stocks, feedback mechanisms, both negative and positive relationships, and dynamic variables—to elucidate the interactions among interconnected variables and how changes in one variable affect others within the system. Before initiating the analysis, it is crucial to determine whether the current system is suitable for modeling, given that system dynamics relies on cause-and-effect relationships between variables (Bala et al., 2017). According to Forrester (1993), system dynamics encompasses several conceptual elements. Figure 4.2 presents the system dynamics methodology in a sequential manner.

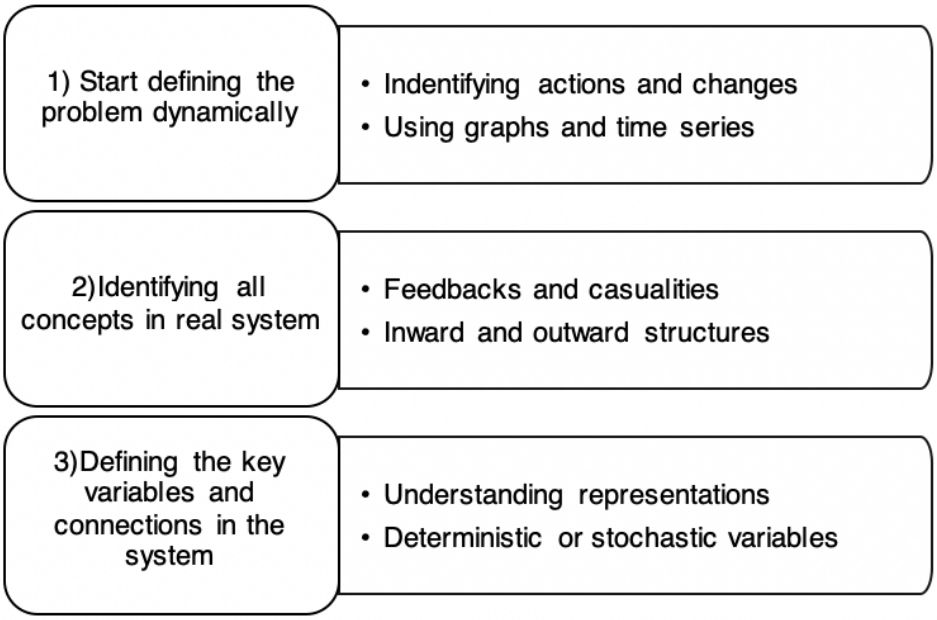


Figure 4.2: System Dynamics methodology (Adapted from (Forrester, 1993))

As presented by Richardson (2020), the essential framework of system dynamics, often referred to as a state-determined system, can be represented mathematically as follows (4.1):

$$\frac{d}{dt}X(t) = f(x,p) \quad (4.1)$$

In this formulation, X is a vector of state variables (or stocks), f is a non-linear vector-valued function, and pp denotes the set of parameters defining the system.

Within the system dynamics methodology, primary variables are generally grouped into four categories: stocks, dynamic variables, links, and flows. Stocks function as the relatively static elements of the system, capturing accumulations of materials or other entities. Dynamic variables depend on these stocks and are shaped by their underlying values, the flows into or out of them, and the interconnections among variables. Links indicate the directional influences (positive or negative) that variables exert on one another. Finally, flows describe the rates at which stocks change over time (Forrester, 1993).

A complementary tool, the causal loop diagram, is used to identify the feedback loops that drive system behavior. These diagrams visually represent the central causal mechanisms hypothesized to produce the characteristic patterns observed in a system's dynamics (Sterman, 2010). Feedback loops involve two or more variables linked in a cycle, either reinforcing each other to amplify certain behaviors or balancing one another to stabilize system outcomes (Maani, 2016; Bala et al., 2017). In these diagrams, arrows denote the direction of causal influence. A plus (+) sign indicates that a change in the originating variable leads to a change in the same direction for the affected variable, whereas a minus (−) sign signifies that an increase in one variable yields a decrease in the other (Spector et al., 2001; Maani, 2016, Bala et al., 2017).

To enhance the traditional interpretation of positive and negative influences—particularly in the context of curvature—one can define a positive influence as follows: Variable A has a positive influence on Variable B if an increase (or decrease) in A results in B reaching a higher (or lower) value than it would have if A had remained unchanged. The same principle applies inversely for negative influences. For instance, consider a beer glass scenario. An increase in flow rate raises the beer level above what it would have been if the flow remained constant; similarly, decreasing the flow results in a lower beer level than would be the case without that change (Sterman, 2010).

## 4.2. Nonlinear Grey Bernoulli Modelling

The following sections detail the steps and procedures of the NGBM(1,1) model, which will be employed within this thesis (Ding et al., 2021; Konyalıoğlu et al., 2024b).

Step 1: Taking the original data by assuming that the collected observations with $n$ entries are given as $\mathbf{X}^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \cdots, x^{(0)}(n)\}, n \geq 4$, in which the datasets are all positives and equally spaced over time. Subsequently, the corresponding taken sequence is given by $\mathbf{Y}^{(0)} = \{y^{(0)}(1), y^{(0)}(2), \cdots, y^{(0)}(n)\}, n \geq 4$, obtained by using accumulated generating operation (AGO) technique.

Step 2: Obtaining the intermediate series by the aid of applying one-time accumulated generating operation in order to obtain the intermediate series: $\mathbf{Y}^{(1)} = \{y^{(1)}(1), y^{(1)}(2), \cdots, y^{(1)}(n)\}$, for which the kth entry is defined as given in (4.2) (Ding et al., 2021).

$$y^{(1)}(k) = \sum_{i=1}^{k} y^{(1)}(i), k = 1,2, \cdots, n. \quad (4.2)$$

Step 3: Constructing the grey differential equations and estimating the parameters to create the first-order grey differential equation of NGBM (1,1) and it can be defined as given in (4.3):

$$y^{(0)}(k) + \beta_1 z^{(1)}(k) = \beta_2 \left(z^{(1)}(k)\right)^{\gamma}, \gamma \neq 1, k = 2,3, \cdots, n. \quad (4.3)$$

Here, it should be noted that $y^{(0)}(k)$ is defined as the grey derivative, and $z^{(1)}(k) = 0.5 * \left(y^{(1)}(k) + y^{(1)}(k-1)\right)$ is identified as the background value of the grey derivative, while $\beta_1, \beta_2$ are the generating parameters.

Furthermore, $\gamma$ is to be referred to the power exponent serving as a nonlinear adjustable parameter endowing NGBM (1,1) model which provides an accurate flexibility and adaptability to estimate nonlinear sequences (Ding et al., 2021).

Now, let us assume that the power exponent is known and let us substitute the values of $k$ into Eq. (4.3). Thus, one may see in Eq. (4.4).

$$\begin{gathered}
y^{(0)}(2)+\beta_1 z^{(1)}(2)=\beta_2\left(z^{(1)}(2)\right)^{\gamma} \\
y^{(0)}(3)+\beta_1 z^{(1)}(3)=\beta_2\left(z^{(1)}(3)\right)^{\gamma} \\
\vdots \\
y^{(0)}(n)+\beta_1 z^{(1)}(n)=\beta_2\left(z^{(1)}(n)\right)^{\gamma}
\end{gathered} \qquad (4.4)$$

The same equation can be given in the matrix form, $\mathbf{Y}=\mathbf{Z}\beta$, as given in Eq. (4.5).

$$\mathbf{Y}=\begin{bmatrix} y^{(0)}(2) \\ y^{(0)}(3) \\ \vdots \\ y^{(0)}(n) \end{bmatrix} \mathbf{Z}=\begin{bmatrix} -z^{(1)}(2) & \left(z^{(1)}(2)\right)^{\gamma} \\ -z^{(1)}(3) & \left(z^{(1)}(3)\right)^{\gamma} \\ \vdots & \vdots \\ -z^{(1)}(n) & \left(z^{(1)}(n)\right)^{\gamma} \end{bmatrix} \boldsymbol{\beta}=\begin{bmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \end{bmatrix} \qquad (4.5)$$

The matrix form given in (4.5) can be solved by using the least-squares estimation for $\beta_1$ and $\beta_2$ and $\boldsymbol{\beta}=\left[\hat{\beta}_1, \hat{\beta}_2\right]^{T}=(\mathbf{Z}^{\mathbf{T}}\mathbf{Z})^{-1}\mathbf{B}^{\mathbf{T}}\mathbf{Y}$. Furthermore, one may see that $\hat{\beta}_1$ and $\hat{\beta}_2$ can also be calculated as given in Eq. (4.6)

$$\begin{aligned}
\hat{\beta}_1 &= \frac{\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{\gamma+1}\sum_{k=2}^{n} y^{(0)}(k)\left(z^{(1)}(k)\right)^{\gamma}-\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{2\gamma}\sum_{k=2}^{n} y^{(0)}(k)z^{(1)}(k)}{\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{2\gamma}\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{2}-\left(\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{\gamma+1}\right)^{2}} \\
\hat{\beta}_2 &= \frac{\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{2}\sum_{k=2}^{n} y^{(0)}(k)\left(z^{(1)}(k)\right)^{\gamma}-\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{\gamma+1}\sum_{k=2}^{n} y^{(0)}(k)z^{(1)}(k)}{\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{2\gamma}\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{2}-\left(\sum_{k=2}^{n}\left(z^{(1)}(k)\right)^{\gamma+1}\right)^{2}}
\end{aligned} \qquad (4.6)$$

Step 4: Whitening differential equation can be built and solved based on the grey theory, the whitening differential function of NGBM (1,1) is illustrated as given in Eq. (4.7)

$$\frac{dy^{(1)}(t)}{dt} + \beta_1 y^{(1)}(t) = \beta_2 y^{(1)}(t)^{\gamma}, \gamma \neq 1 \quad (4.7)$$

The parameters $\boldsymbol{\beta} = \left[\hat{\beta}_1, \hat{\beta}_2\right]^T$ can be substituted into Eq. (4.7) and the differential function in Eq. (4.7) can be solved to obtain the generalized solution in Eq. (4.8):

$$y^{(1)}(t) = \left[Ce^{-(1-\gamma)\hat{\beta}_1 t} + \frac{\hat{\beta}_2}{\hat{\beta}_1}\right]^{\frac{1}{1-\gamma}} \quad (4.8)$$

Here it can be noted that $C$ is a constant and by taking $y^{(1)}(t)\big|_{t=1} = y^{(1)}(1)$ as the initial condition and by substituting it into Eq. (4.8), we now obtain the Eq. (4.9)

$$\mathrm{C} = \left[\left(y^{(0)}(1)\right)^{1-\gamma} - \hat{\beta}_2/\hat{\beta}_1\right] e^{(1-\gamma)\hat{\beta}_1} \quad (4.9)$$

Subsequently, the time response function of NGBM $(1{,}1)$ model can be obtained as given in Eq. (4.10).

$$\hat{y}^{(1)}(k) = \left\{\left[\left(y^{(0)}(1)\right)^{1-\gamma} - \frac{\hat{\beta}_2}{\hat{\beta}_1}\right] e^{-(1-\gamma)\hat{\beta}_1(k-1)} + \frac{\hat{\beta}_2}{\hat{\beta}_1}\right\}^{\frac{1}{1-\gamma}} \quad (4.10)$$

### 4.3. Firefly Algorithm

In the firefly optimization algorithm, two critical considerations must be addressed: the variation in light intensity and the formulation of attractiveness (Gandomi et al., 2013). The attractiveness of a firefly is typically determined by its brightness, also referred to as light intensity, which is associated with the objective function (Gazi and Passino, 2004). Moreover, attractiveness is commonly assessed by the firefly's visual perception, where light intensity decreases with distance from the source due to absorption in the medium

(Gandomi et al., 2013). Let's define the light intensity, denoted as $I(r)$, according to the law of inverse square and absorption given in Eq. 4.11:

$$I(r) = I_0 \cdot e^{-\gamma \cdot r^2} \quad (4.11)$$

where $I_0$ and $\gamma$ are subsequently explained as the original light intensity and light absorption coefficient (Gandomi et al., 2013). And the definition of attractiveness $\beta(r)$ is given by the Eq. 4.12:

$$\beta(r) = \beta_0 \cdot e^{-\gamma \cdot r^2} \quad (4.12)$$

Here, it should be noted $\beta_0$ is expressed as the attractiveness when $\gamma$ is equal to 0. To calculate the distance between any two fireflies $i$ and $j$ at $\mathbf{x_i}$ and $\mathbf{x_j}$ , one may use the Cartesian distance as given in Eq. 4.13:

$$r_{ij} = \sqrt{\sum_{p=1}^{d} \left(x_{i,p} - x_{j,p}\right)^2}, \quad (4.13)$$

where $x_{i,p}$ is donated as the $p$-th component of the spatial coordinate $\mathbf{x_i}$ of $i$-th firefly (Gandomi et al., 2013).

Another issue is explained the concept of rand denoted as a d-dimensional uniform random vector given in $[0, 1]^d$, and $\alpha$ defined as a parameter in the interval of $[0,1]$. Then, one may see that the new position $\mathbf{x_i}$ of a firefly attracted by the brighter firefly $j$ at time $t + 1$, can be followed as given in Eq. (4.14)

$$\mathbf{x_{i,t+1}} = \mathbf{x_{i,t}} + \beta_0 \cdot e^{-\gamma \cdot r_{ij}^2} \cdot \left(\mathbf{x_{j,t}} - \mathbf{x_{i,t}}\right) + \alpha \cdot (\text{rand} - 0.5) \quad (4.14)$$

Given that while the distance $r$ is small value, the random term may avoid blockages in the local minima optimally. Contrary to this fact, if $r$ is large, the firefly goes like a random walk.

Firefly algorithm is seen as being a powerful method for non-linear design optimization problems (Koziel & Yang, 2011). The use of firefly algorithm in this study can be stated as the fact that existing PSO and evolutionary algorithms do not show a performance as much as FA to search for the global optimum (Yang, 2010).

### 4.4. Proposed Approach: FA-NGBM(1,1) Hybrid Model

Nonlinear grey Bernoulli model has two parameters such as production coefficient of the background value (α) and power index (γ). Correct adjustment of these parameters significantly affects the prediction quality. This problem can be formulated using the optimization model expressed by Equations 4.15-4.17. In this model, production coefficient of the background value (α) and power index (γ) are decision variables and the objective function is to minimize mean absolute percentage error (MAPE).

$$\min Z = \frac{1}{n} \sum_{k=1}^{n} \left| \frac{\hat{x}_0(k) - x_0(k)}{x_0(k)} \right| \times 100\% \qquad (4.15)$$

s.t.

$$0 \leq \alpha \leq 1 \qquad (4.16)$$

$$\gamma \neq 1 \qquad (4.17)$$

In Eq. (4.15), $x_0(k)$ indicates the actual value, $\hat{x}_0(k)$ indicates the predicted value and n is the number of test data.

In the existing literature, data partitioning methods frequently rely on specifying a particular ratio. A commonly utilized split is 80:20, in which 80% of the data is reserved for training and 20% for testing. Alternatives such as 90:10, 70:30, 60:40, or even a balanced 50:50 division are also found in practice. Nonetheless, there are no definitive guidelines for choosing the most appropriate ratio for a given dataset. The predominance of the 80:20 ratio is often linked to the Pareto principle, though it essentially remains a heuristic favored by practitioners (Joseph, 2022; Medar et al., 2017; Baglaeva et al., 2020).

In the present thesis, the firefly algorithm serves as the optimization tool to solve the parameter tuning problem described above. The pseudocode for the integrated FA-NGBM(1,1) model is provided in Table 4.1.

Table 4.1: The pseudo-code of the proposed FA-NGBM(1,1) hybrid method

1: **Load** the dataset

2: **Divide** data into training and testing datasets<br>
3: **Initialize** firefly parameters (light absorption coefficient=1, step factor=0.01, $\beta_0$=1 and $\beta_{min}$=0.2)<br>
4: **Define** α and γ parameters of NGBM(1,1) *randomly*<br>
5: **Set** t=1<br>
6: While (t < max number of iterations)<br>
7: **Calculate** MAPE of NGBM(1,1) by using training data<br>
8: **Set** fitness function=$MAPE_i$<br>
9: Calculate $MAPE_i$<br>
10: **if** (MAPE(i+1) <MAPE(i)) **then**<br>
11:         **Update** α and γ<br>
12:**end if**<br>
13: t=t+1<br>
14:**end while**<br>
15: Create a NGBM(1,1) model with finalized α and γ parameters<br>
16: Calculate MAPE value of the test data

## 4.5. Fuzzy Set Theory and Multi-Criteria Decision Making

Before delving into the concept of SFS, it is important to recognize that the groundwork for managing uncertainty and imprecise information in decision-making contexts was laid by Zadeh’s introduction of Fuzzy Set Theory (Zadeh, 1978; Çelik et al., 2022). Figure 4.3 provides a chronological overview of the various extensions of fuzzy sets that have since emerged within the realm of MCDM.

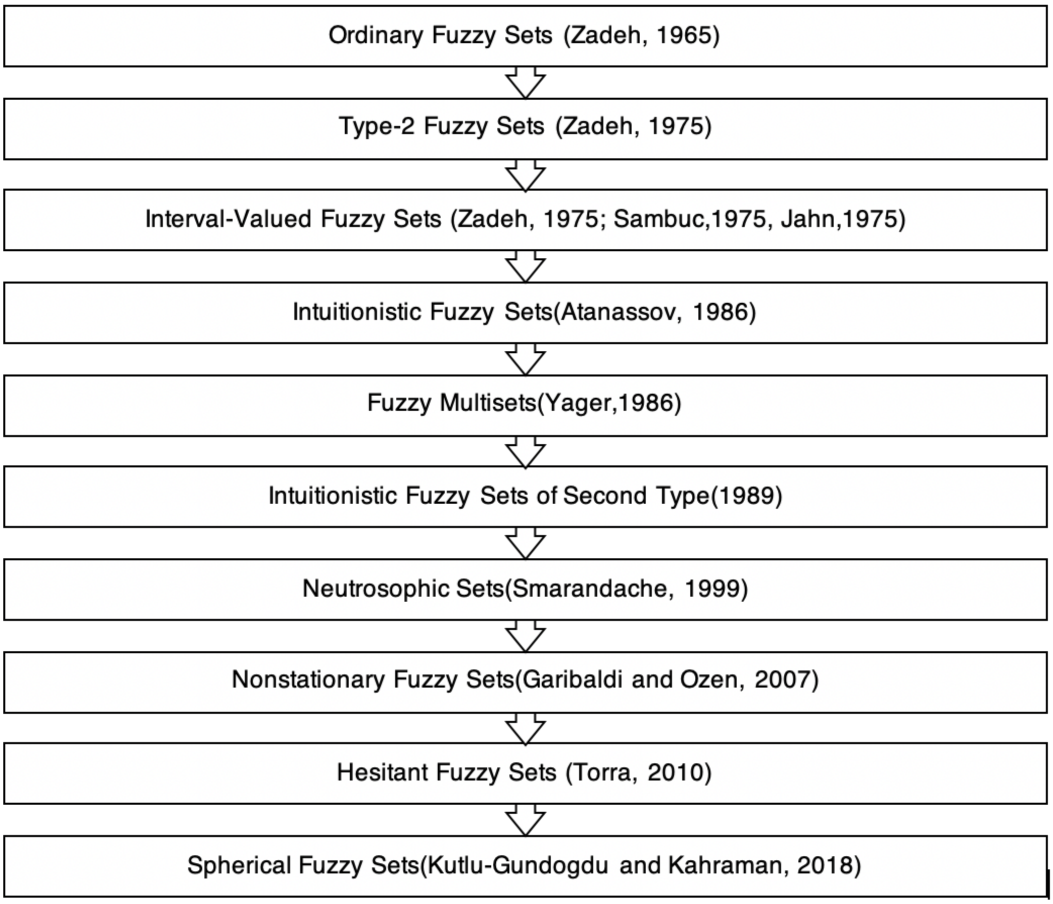


Figure 4.3: Extensions of Fuzzy Sets (Adapted from Kutlu-Gundogdu and Kahraman, 2018)

Decision-making becomes particularly complex in situations characterized by high uncertainty and limited information. Nevertheless, the adoption of multi-criteria decision-making (MCDM) approaches under fuzzy logic can greatly simplify this task (Kutlu-Gundogdu & Kahraman, 2020a). In this vein, Spherical Fuzzy Sets (SFS), originally proposed by Kutlu-Gundogdu and Kahraman (2018), offer a robust means of efficiently handling uncertainty.

SFS can be regarded as an extension of Neutrosophic and Pythagorean fuzzy sets, with their defining feature being the treatment of hesitancy degrees, which are restricted to values at or below 1 (Dogan, 2021). In addition, SFS include three distinct membership functions: membership, non-membership, and an indeterminacy (or hesitancy) degree

(Mathew et al., 2020). This explicit acknowledgment of hesitancy enhances the ability to address the ambiguity that is often inherent in decision-making processes (Liao et al., 2020).

Within the existing literature, SFS have been utilized as an advanced alternative to other fuzzy set models, offering a more nuanced approach to managing uncertainty. Figure 4.4 provides a visual comparison, highlighting how SFS differ from other fuzzy set constructs.

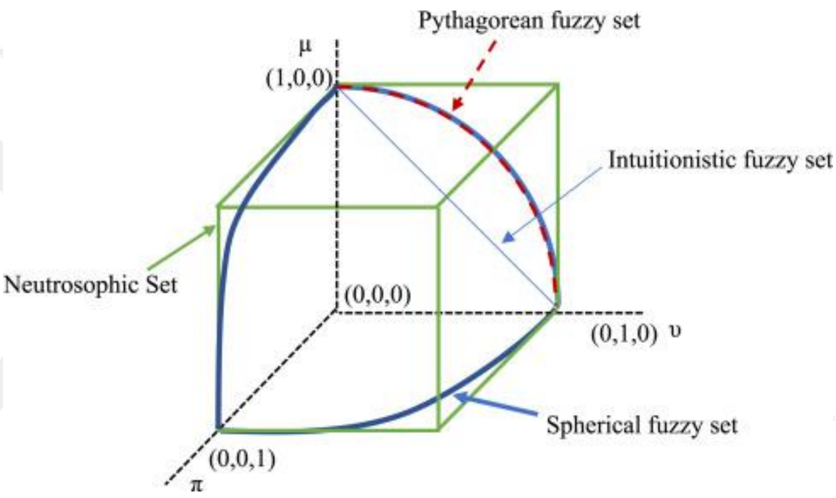


Figure 4.4: SFS and other fuzzy sets' geometric representations (Kutlu-Gündoğdu and Kahraman, 2020a)

This section of the thesis is guided by two primary motivations: (1) the absence of any existing studies in the literature that integrate spherical fuzzy sets with the management of face mask and glove waste, and (2) the capacity of spherical fuzzy sets to facilitate mitigation strategies and consensus-building based on expert and decision-maker evaluations concerning such waste management challenges in Istanbul.

Recent research highlights that the three-dimensional spherical fuzzy set extends traditional fuzzy set theory, enhancing its capability to address uncertainty and quantify expert opinions effectively for prioritization and decision-making across diverse fields (Mathew et al., 2020; Akram et al., 2021). Traditional fuzzy sets (FS) and interval-valued fuzzy sets (IFS) have limitations in resolving complex decision-making scenarios due to their constrained structures. To overcome these challenges and align more closely with human reasoning, spherical fuzzy sets were developed (Mahmood et al., 2019). Consequently, this thesis proposes spherical fuzzy AHP as a robust and precise method for prioritizing factors influencing face mask and glove waste management. This approach reflects the alignment of fuzzy sets with human reasoning and demonstrates a high degree of accuracy, as noted by Farrokhizadeh et al. (2021), Dogan (2021), and Yüksel et al. (2022). Furthermore, factors associated with managing face mask and glove waste as part of medical waste management have not yet been explored using spherical fuzzy sets, offering a novel and rigorous perspective.

Several studies employing spherical fuzzy sets in waste management further substantiate this method's applicability. For instance, research has been conducted to evaluate food waste (Buyuk and Temur, 2020; Buyuk and Temur, 2022), select landfill sites for medical waste in Iran (Ghoushchi et al., 2021), determine locations for waste disposal in Iran (Haseli and Ghoushchi, 2022), and plan medical waste disposal from healthcare facilities (Menekşe and Akdağ, 2023).

In this context, Figure 4.5 depicts the methodology proposed in this thesis for utilizing spherical fuzzy AHP to rank the factors affecting the management of face mask and glove waste in Istanbul. This approach considers that the importance attributed to decision-makers varies based on their expertise and experience in waste management within the Istanbul setting. Consequently, the linguistic terms established by Kutlu-Gundogdu and Kahraman (2018) are employed, with the assumption that all decision-makers hold equal significance.

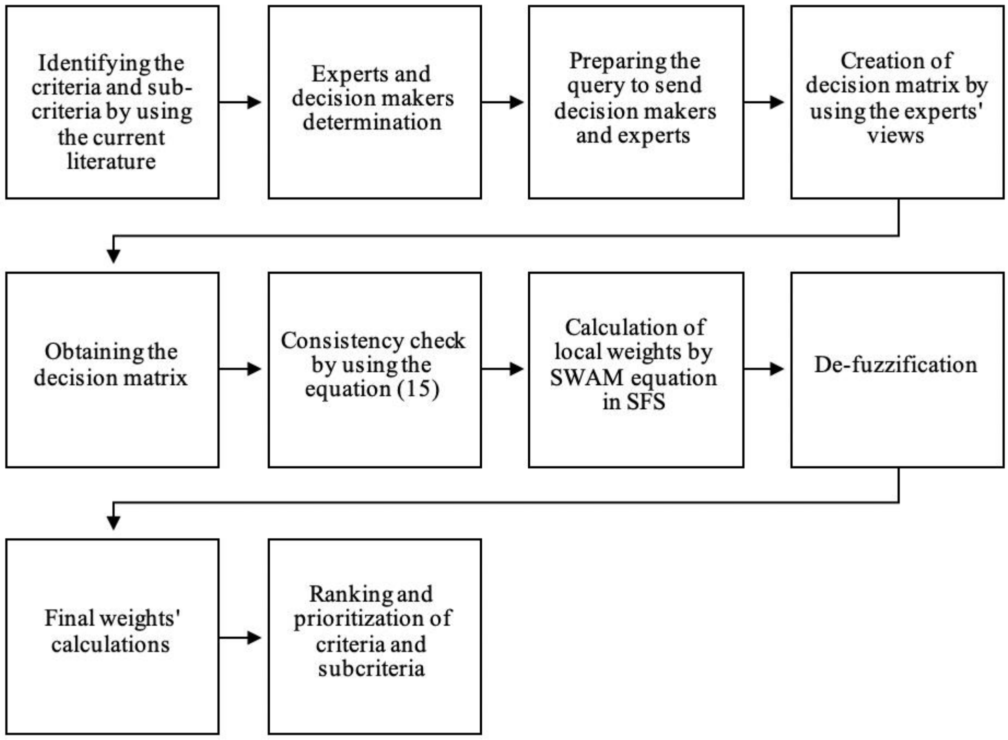


Figure 4.5: The proposed methodology of SF-AHP

### 4.5.1. Spherical Fuzzy Analytic Hierarchy Process (SF-AHP)

Spherical Fuzzy Sets (SFS) proposed by Kutlu-Gündoğdu and Kahraman (2020a) and Spherical Analytic Hierarchy Process (SF-AHP) are now aimed to use for waste management factors prioritization of face masks and gloves. In this part of methodology section, SFS and SF-AHP methodologies are defined by the study of Gündoğdu and Kahraman (2020a), who proposed SF-AHP methodology.

In order to explain the methodology of SF-AHP, let $U_1$ and $U_2$ be defined as two different universes and related spherical fuzzy sets for $U_1$ and $U_2$ as $\tilde{A}_S$ and $\tilde{B}_S$ respectively. In this case, let $\tilde{A}_S$ be defined as given in the equations (4.18) (Gündoğdu and Kahraman, 2020a).

$$\tilde{A}_S = \left\{x, \left(\mu_{\tilde{A}_S}(x), \nu_{\tilde{A}_S}(x), \pi_{\tilde{A}_S}(x)\right) | x \epsilon U_1\right\} \quad (4.18)$$

$$\text{Where}\quad \begin{gathered} \mu_{\tilde{A}_S}(x): U_1 \to [0,1], v_{\tilde{A}_S}(x): U_1 \to [0,1] \\ \pi_{\tilde{A}_S}(x): U_1 \to [0,1] \\ \text{and} \\ 0 \leq \mu^2_{\tilde{A}_S}(x) + v^2_{\tilde{A}_S}(x) + \pi^2_{\tilde{A}_S}(x) \leq 1 \forall x \in U_1 \end{gathered} \qquad (4.19)$$

In this context, each of $\mu_{\tilde{A}_S}(x), \nu_{\tilde{A}_S}(x), \pi_{\tilde{A}_S}(x)$ belongs to $U_1$ set and their ranges are of [0,1] given in (4.20) that

$$0 \leq \mu^2_{\tilde{A}_S}(x) + \nu^2_{\tilde{A}_S}(x) + \pi^2_{\tilde{A}_S}(x) \leq 1. \quad \forall u \epsilon U_1 \quad (4.20)$$

It is noted that $\mu_{\tilde{A}_S}(x), \nu_{\tilde{A}_S}(x), \pi_{\tilde{A}_S}(x)$ defines respectively membership, non-membership, and hesitancy belonging to $U_1$ which are on the surface of the sphere. It can be written as given above in (4.20) if the equality holds.

$$\mu^2_{\tilde{A}_S}(x) + \nu^2_{\tilde{A}_S}(x) + \pi^2_{\tilde{A}_S}(x) = 1. \quad \forall u \epsilon U$$

Another definition in SFS as a basic operation of Cartesian product is defined as given in (4.21).

$$\tilde{A}_S \times \tilde{B}_S = \left\{ \left( (x,y), \min\left(\mu_{\tilde{A}_S}(x), \mu_{\tilde{B}_S}(y)\right), \begin{array}{c} \max\left(v_{\tilde{A}_S}(x), v_{\tilde{B}_S}(y)\right), \\ \min\left(\pi_{\tilde{A}_S}(x), \pi_{\tilde{B}_S}(y)\right) \end{array} \right) \right\} \quad (4.21)$$

In multiplication symbol, let us define $\left\{ \left\langle x, \left( \mu_{\tilde{A}_i}(x), v_{\tilde{A}_i}(x), \pi_{\tilde{A}_i}(x) \right) \middle| \, x \in U_i \right\}$ in SFS. Thus, Cartesian product of $SFS$ is given in (4.22).

$$\tilde{B}_S^n = \prod_{i=1}^{n} \tilde{A}_{si} = \left\{ \left( (x_1, x_2, \dots x_n), \min_{i=1}^{n} \mu_{\tilde{A}_{si}}(x_i), \max_{i=1}^{n} v_{\tilde{A}_{si}}(x_i), \min_{i=1}^{n} \pi_{\tilde{A}_{si}}(x_i) \right) \mid \forall x_i \in U_i, i = 1, \dots, n \right\} \quad (4.22)$$

$$\text{is a SFS on } \prod_{i=1}^{n} U_i$$

For the addition and multiplication operators, the following equations (3.23) and (3.24) are defined to obtain.

$$\tilde{A}_S \oplus \tilde{B}_S = \left\{ z, \left( \max_{z=x+y} \min \left\{ \mu_{\tilde{A}_S}(x), \mu_{\tilde{B}_S}(y) \right\} \right), \begin{matrix} \left( \min_{z=x+y} \max \left\{ v_{\tilde{A}_S}(x), v_{\tilde{B}_S}(y) \right\} \right), \\ \left( \min_{z=x+y} \min \left\{ \pi_{\tilde{A}_S}(x), \pi_{\tilde{B}_S}(y) \right\} \right) \end{matrix} \right\} \quad (4.23)$$

$$\tilde{A}_S \otimes \tilde{B}_S = \left\{ z, \left( \max_{z=x*y} \min \left\{ \mu_{\tilde{A}_S}(x), \mu_{\tilde{B}_S}(y) \right\} \right), \begin{matrix} \left( \min_{z=x*y} \max \left\{ v_{\tilde{A}_S}(x), v_{\tilde{B}_S}(y) \right\} \right), \\ \left( \min_{z=x*y} \min \left\{ \pi_{\tilde{A}_S}(x), \pi_{\tilde{B}_S}(y) \right\} \right) \end{matrix} \right\} \quad (4.24)$$

Furthermore, Kutlu Gündoğdu and Kahraman (2020a) have introduced some operations including union, intersection, addition, multiplication and power for spherical fuzzy sets as given in (4.25), (4.26), (4.27), (4.28)

Union can be seen in the equation (4.25) while intersection, addition multiplication, multiplication by a scalar and power of the value are followed in (4.26), (4.27), (4.28), (4.29) and (4.30) respectively.

$$\tilde{A}_S \cup \tilde{B}_S = \left\{ \max\left\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\right\}, \min\left\{v_{\tilde{A}_S}, v_{\tilde{B}_S}\right\}, \min\left\{ \left( 1 - \left( \left( \max\left\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\right\} \right)^2 + \left( \min\left\{v_{\tilde{A}_S}, v_{\tilde{B}_S}\right\} \right)^2 \right) \right)^{1/2}, \max\left\{\pi_{\tilde{A}_S}, \pi_{\tilde{B}_S}\right\} \right\} \right\}$$

(4.25)

$$\tilde{A}_S \cap \tilde{B}_S = \left\{ \min\left\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\right\}, \max\left\{v_{\tilde{A}_S}, v_{\tilde{B}_S}\right\}, \max\left\{ \left( 1 - \left( \left( \min\left\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\right\} \right)^2 + \left( \max\left\{v_{\tilde{A}_S}, v_{\tilde{B}_S}\right\} \right)^2 \right) \right)^{\frac{1}{2}}, \min\left\{\pi_{\tilde{A}_S}, \pi_{\tilde{B}_S}\right\} \right\} \right\}$$

(4.26)

$$\tilde{A}_S \oplus \tilde{B}_S = \left\{ \left( \mu_{\tilde{A}_S}^2 + \mu_{\tilde{B}_S}^2 - \mu_{\tilde{A}_S}^2 \mu_{\tilde{B}_S}^2 \right)^{1/2}, v_{\tilde{A}_S} v_{\tilde{B}_S}, \left( \left( 1 - \mu_{\tilde{B}_S}^2 \right) \pi_{\tilde{A}_S}^2 + \left( 1 - \mu_{\tilde{A}_S}^2 \right) \pi_{\tilde{B}_S}^2 - \pi_{\tilde{A}_S}^2 \pi_{\tilde{B}_S}^2 \right)^{1/2} \right\}$$

(4.27)

$$\tilde{A}_S \otimes \tilde{B}_S = \left\{ \mu_{\tilde{A}_S}\mu_{\tilde{B}_S}, \left(v^2_{\tilde{A}_S} + v^2_{\tilde{B}_S} - v^2_{\tilde{A}_S} v^2_{\tilde{B}_S}\right)^{1/2} \left( \left(1 - v^2_{\tilde{B}_S}\right)\pi^2_{\tilde{A}_S} + \left(1 - v^2_{\tilde{A}_S}\right)\pi^2_{\tilde{B}_S} - \pi^2_{\tilde{A}_S}\pi^2_{\tilde{B}_S}\right)^{1/2} \right\} \quad (4.28)$$

Multiplication by a scalar; $\lambda > 0$ is given in (4.29).

$$\lambda \cdot \tilde{A}_S = \left\{ \left(1 - \left(1 - \mu^2_{\tilde{A}_S}\right)^{\lambda}\right)^{1/2}, v^{\lambda}_{\tilde{A}_S}, \left( \left(1 - \mu^2_{\tilde{A}_S}\right)^{\lambda} - \left(1 - \mu^2_{\tilde{A}_S} - \pi^2_{\tilde{A}_S}\right)^{\lambda}\right)^{1/2} \right. \quad (4.29)$$

And Power of $\tilde{A}_S; \lambda > 0$ in (4.30)

$$\tilde{A}_S^{\lambda} = \left\{ \mu^{\lambda}_{\tilde{A}_S}, \left(1 - \left(1 - v^2_{\tilde{A}_S}\right)^{\lambda}\right)^{1/2}, \left( \left(1 - v^2_{\tilde{A}_S}\right)^{\lambda} - \left(1 - v^2_{\tilde{A}_S} - \pi^2_{\tilde{A}_S}\right)^{\lambda}\right)^{\frac{1}{2}} \right\} \quad (4.30)$$

The steps for Spherical Fuzzy AHP is explained as follows (Gündoğdu and Kahraman, 2020a).

Step 1. A hierarchical structure for the main selection problem is constructed. Spherical fuzzy pairwise comparison matrices are formed by the questionnaire sent to the experts.

Step 2. Consistency Ratio (CR) and Consistency Index (CI) given in the equation (3.31) for each pairwise comparison matrices of AHP, denoted also as CR, are checked and all has been found as consistent (Saaty, 1980). In the realm of decision-making using Saaty's Analytic Hierarchy Process (AHP), the notation $\lambda_{max}$ denotes the largest eigenvalue of pairwise comparison matrices, while n represents the order (dimension) of these matrices.

The term R.I. refers to the random index, a value contingent on the matrices' size, indicative of the average Consistency Index (C.I.) derived from a substantial number of randomly generated multiplicative preference relations (Saaty, 1980)

$$CI = \frac{\lambda_{max} - n}{n - 1}, CR = \frac{CI}{RI} \quad (4.31)$$

Step 3. In order to obtain spherical fuzzy global weights, hierarchical layer sequencings have been constructed and calculated

Step 4. For each alternative, the score values and local values are calculated and the alternatives are ranked based on calculations. These steps can be seen in Fig. 4.5. in detail.

For the calculations of decision matrices, Table 4.2 has been used to convert linguistic measures into numerical values in SF-AHP (Gündoğdu and Kahraman, 2020a).

Table 4.2: Linguistic measures of importance used for pairwise comparisons (Gündoğdu and Kahraman, 2020a).

| | **(μ, v, π)** | **Score Index (SI)** |
|---|---|---|
| Absolutely more importance (AMI) | (0.9, 0.1, 0.0) | 9 |
| Very high importance (VH1) | (0.8, 0.2, 0.1) | 7 |
| High importance (HI) | (0.7, 0.3, 0.2) | 5 |
| Slightly more importance (SMI) | (0.6, 0.4, 0.3) | 3 |
| Equally importance (El) | (0.5, 0.4, 0.4) | 1 |
| Slightly low importance (SU) | (0.4, 0.6, 0.3) | 1/3 |
| Low importance (LI) | (0.3, 0.7, 0.2) | 1/5 |
| Very low importance (VU) | (0.2, 0.8, 0.1) | 1/7 |
| Absolutely low importance (ALI) | (0.1, 0.9, 0.0) | 1/9 |

In this context, based on experts' views given in (4.32), pairwise comparisons have been realized and SWAM operator was applied by weighted arithmetic mean for calculating fuzzy local weights.

$$\text{SWAM}_w\ (A_{S1}, \dots, A_{Sn}) = w_1 A_{S1} + w_2 A_{S2} + \cdots + w_n A_{Sn} \quad (4.32)$$

$$= \left\langle \left[1 - \prod_{i=1}^{n} \left(1 - \mu_{A_{Si}}^2\right)^{w_i}\right]^{1/2}, \prod_{i=1}^{n} v_{A_{Si}}^{w_i}, \left[\prod_{i=1}^{n} \left(1 - \mu_{A_{Si}}^2\right)^{w_i} - \prod_{i=1}^{n} \left(1 - \mu_{A_{Si}}^2 - \pi_{A_{Si}}^2\right)^{w_i}\right]^{1/2} \right\rangle$$

where $w = 1/n$.

Then, the score function given in (4.33) has been used to de-fuzzify the criteria and sub-criteria.

$$S\left(\tilde{w}_j^s\right) = \sqrt{\left|100 * \left[\left(3\mu_{\tilde{A}_s} - \frac{\pi_{\tilde{A}_s}}{2}\right)^2 - \left(\frac{v_{\tilde{A}_s}}{2} - \pi_{\tilde{A}_s}\right)^2\right]\right|} \quad (4.33)$$

In order to then normalize the criteria and sub-criteria weights, the Eq. (4.34) has been taken into consideration.

$$\bar{w}_j^s = \frac{S\left(\tilde{w}_j^s\right)}{\sum_{j=1}^{n} S\left(\tilde{w}_j^s\right)} \quad (4.34)$$

Finally, under spherical fuzzy multiplication given in (4.24), the equation (4.35) was applied for final defuzzification.

$$\tilde{A}_{S_{ij}} = \bar{w}_j^s \cdot \tilde{A}_{S_i} = \left\langle \left(1 - \left(1 - \mu_{\tilde{A}_S}^2\right)^{\bar{w}_j^s}\right)^{1/2}, v_{\tilde{A}_S}^{\bar{w}_j^s}, \left(\left(1 - \mu_{\tilde{A}_S}^2\right)^{\bar{w}_j^s} - \left(1 - \mu_{\tilde{A}_S}^2 - \pi_{\tilde{A}_S}^2\right)^{\bar{w}_j^s}\right)^{1/2} \right\rangle \quad (4.35)$$

Finally, in order to rank the criteria and sub-criteria for prioritization, final spherical fuzzy AHP score has been found by Eq. (4.36).

$$\tilde{F} = \sum_{j=1}^{n} \tilde{A}_{S_{ij}} = \tilde{A}_{S_{i1}} \oplus \tilde{A}_{S_{i2}} \cdots \oplus \tilde{A}_{S_{in}} \forall i$$

i.e. $$\tilde{A}_{S_{11}} \oplus \tilde{A}_{S_{12}} = \left\langle \left(\mu_{\tilde{A}_{S_{11}}}^2 + \mu_{\tilde{A}_{S_{12}}}^2 - \mu_{\tilde{A}_{S_{11}}}^2 \mu_{\tilde{A}_{S_{12}}}^2\right)^{1/2}, v_{\tilde{A}_{S_{11}}} v_{\tilde{A}_{S_{12}}}, \left(\left(1 - \mu_{\tilde{A}_{S_{12}}}^2\right)\pi_{\tilde{A}_{S_{11}}}^2 + \left(1 - \mu_{\tilde{A}_{S_{11}}}^2\right)\pi_{\tilde{A}_{S_{12}}}^2 - \pi_{\tilde{A}_{S_{11}}}^2 \pi_{\tilde{A}_{S_{12}}}^2\right)^{1/2} \right\rangle \quad (4.36)$$

# 5. APPLICATION ON THE MEDICAL WASTE MANAGEMENT IN ISTANBUL

This chapter presents an integrated approach for managing gloves and face masks waste in Istanbul. Prior to detailing the application section, it’s worth noting that the study exclusively examines the municipal household waste collection system, deliberately excluding hospital-generated waste from the scope of analysis. The investigation encompasses the collection of face masks and gloves from both the Asian and European sides of Istanbul. The selection of Istanbul as the focal point of this research is underpinned by two primary factors: it is the most populous city in Turkey, and it generates the highest volume of glove and face mask waste within the country. Consequently, the model proposed in this thesis is intended to serve as a benchmark for application in other urban centres.

This chapter also delineates the application of the methodologies introduced in the preceding section to the management of medical waste, with a specific focus on face masks and gloves waste in Istanbul, thereby facilitating the development of the proposed model. The primary objective of this section is to apply a system dynamic modelling to assess the existing state of face mask and glove waste management in Istanbul. Then a nonlinear grey Bernoulli modelling optimized by the Firefly Algorithm for accurate forecasting, utilizing data from the Turkish Statistical Institute (TUIK, 2024) is assessed. Additionally, a Spherical Fuzzy Multi-Criteria Decision Making (MCDM) approach is employed to evaluate the current situation and identify the factors influencing face mask and glove waste management. By integrating these methodologies, this chapter aims to provide a comprehensive evaluation of the face masks and gloves waste management system in Istanbul, thereby supporting the formulation of an effective and sustainable proposed model.

### 5.1. System Dynamics Application Focusing on Face Masks and Gloves

#### 5.1.1. Gloves waste management in Istanbul

In this part of the thesis, it is aimed to use system dynamics methodology in order to increase recycling ratio of nitrile gloves used during COVID-19 pandemic and post-pandemic period. It is known that gloves, especially nitrile, latex, vinyl and rubber gloves, can be recycled if they are not contaminated (UniGloves, 2022). Thus, a system dynamics model will be constructed based on these types of gloves.

Furthermore, in order to use in the system dynamics model, the total medical waste generation in Turkey has been accepted based on Shangham's equations as a start of simulation (Sangkham, 2020). In order to suggest new policies, the simulation of system dynamics, causal loop diagrams and the results of the proposed FA-NGBM(1,1) are used. Thus, in this part, an overview of the quantitative variables used in the simulation is presented. Along with this, the equation 5.1 shows the total medical waste amount including gloves, face masks and aprons generated in Turkey (Sangkham, 2020; Konyalıoğlu and Bereketli, 2022).

$$M_W = \frac{N_{CC} x M_{WGR}}{1{,}000} \quad (5.1)$$

Where, $M_W$ , $N_{CC}$, $M_{WGR}$ denote respectively medical waste amount, number of COVID-19 cases or number of ill people after COVID-19 pandemic and medical waste generation rate which is equal to 3.95 kg/bed/day. Considering these variables, in Turkey, 908.07 tons/day generated medical waste has been taken into consideration while constructing the model (Konyalıoğlu and Bereketli, 2022).

Furthermore, it's accepted that the use of gloves decreases since the COVID-19 is about to finish in Istanbul, which indicates that COVID-19 preventions are being stopped in Istanbul, affecting the use of gloves. *In this thesis, it's accepted that the use of gloves depends on the surgical operations in hospitals.*

Furthermore, as there is not certain or exact amount of using gloves during pandemic in Turkey to start the simulation, the rate of 24.1 of medical waste has been accepted as plastic gloves based on the study of Jędruchniewicz et al. (2021).

Figure 5.1 shows the system dynamics modelling for a waste collection system for single use plastic gloves, that are largely used in Turkey during COVID-19 pandemic and post-COVID-19 period. In this model, a governmental support has been added as a rate of 2% in order to increase awareness (Shaw and Maynard, 2008; Konyalıoğlu and Bereketli, 2022). Moreover, firstly gloves raw material has been launched and conventional supply chain parts, such as distributors, sub-distributors have been included. It is known that a big rate of gloves is contaminated, thus approximately 81% of gloves are put as contaminated gloves in the model while the rest is accepted as uncontaminated gloves (Alhmidi et al., 2019). Considering that contaminated gloves cannot be effectively recycled currently in 2024, uncontaminated gloves go through the recycling process in order to be included in the remanufacturing process. However, as the literature starts to indicate that the gloves can be recycled after UV or other disinfection methods process as discussed in the previous sections of the thesis, during COVID-19 pandemic or post-COVID-19, there is not any recycling or reusing process for uncontaminated gloves. That is why, as a start, the gloves recycling rate has been accepted as 4% like another medical recyclable waste in the current situation (Konyalıoğlu and Bereketli, 2022).

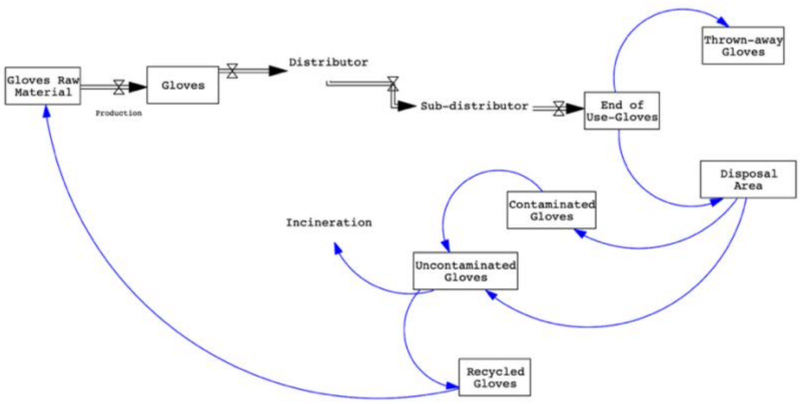


Figure 5.1: System dynamics modelling for a waste collection system for single use gloves

After that simulation has been run 5 years, Figure 5.2 shows that it can be achieved that nearly 290 tons of uncontaminated gloves can be gone through remanufacturing process while 410 tons go through incineration process. As there is not any recycling process for uncontaminated gloves currently in Istanbul, with incentives and effective collection, 290 tons have participated to manufacturing process(Konyalıoğlu and Bereketli, 2022).

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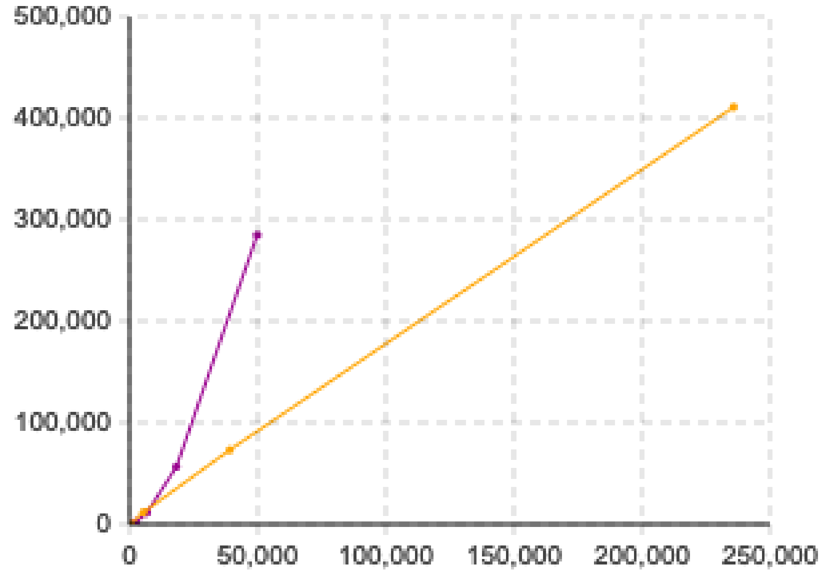


Figure 5.2: Production amount (tons) obtained by recycling process of uncontaminated gloves and disposal amounts vs recycled amount (x axis) (Konyalıoğlu and Bereketli, 2022).

Furthermore, the exact values of recycled gloves (red) and incinerated amount (yellow) in 5 years can be seen in Figure 5.3.

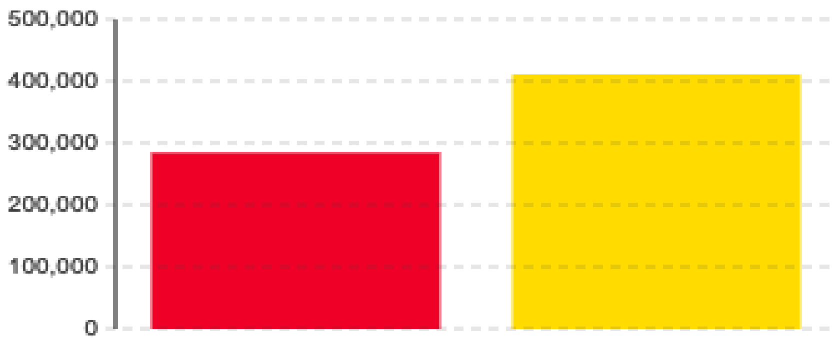


Figure 5.3: Recycling and Incineration Amount of uncontaminated gloves

As seen in Figure 5.3, considering that there is no recycling or reusing policy for single use gloves in Turkey, by system dynamics modelling and an effective policy, nearly 285 tons of single use gloves will be recycled. Also 410 tons of gloves will be incinerated and this amount has important effects on environmental sustainability (Konyalıoğlu and Bereketli, 2022).

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### 5.1.2. Face masks waste management in Istanbul

Face mask production and consumption continues to rise up in Turkey (URL2). However, it is not always clear to estimate face mask waste during COVID-19 pandemic in Turkey or post-COVID-19 period. According to Sangkham (2020) and Nzediegwu and Chang (2020), estimation of daily mask use of urban population is given in equation (5.2).

$$D_{FM} = PxU_P xF_{MAR} x\left(\frac{F_{MGP}}{10{,}000}\right) \quad (5.2)$$

Here, it is noted that $D_{FM}$ indicates daily face mask use (pieces) while $PxU_P$ respectively indicate population (people) and urban population as percentage. Also, face masks acceptance rate, which is taken as 80% according to Sangkham (2020), and assumption of the fact that the general population daily use one face mask, are respectively denoted as $F_{MAR}$ and $F_{MGP}$.

According to TÜİK (Turkish Statistic Institute), Turkey's population in 2021 is 83.614.362 while urban population as percentage is 75,3% (URL4). After calculating, the estimated daily mask use of Turkey is found as 50.569.966 as a start of the simulation.

Furthermore, Sangkham (2020) states that medical waste generation during COVID-19 pandemic or post-COVID period can be found as given in equation as a starting point (5.3)

$$M_W = \frac{N_{CC} xM_{WGR}}{1{,}000} \quad (5.3)$$

where, $M_W$ is the medical waste (tons/day) and $N_{CC}$ is the number of COVID-19 cases or number of sick people using face masks during post-Covid period . $M_{WGR}$ is donated as medical waste generation rate which is equal to 3,95 kg/bed.

### 5.1.3. Causal Loop Diagram for Face Mask Collection and Recycling

Casual Loop Diagram (CLD) can be defined as a very crucial tool in order to observe and understand system behavior, especially in closed loops, considering negative or positive feedbacks forming a basis for a system dynamics mentality. Also, CLD includes and explains the mapping of cause-effect relationships between variables. (Sterman, 2010). A loop of feedback includes two or more causality between related variables. In the relationship between two or more variables, negative or positive relationship may be possible. Figure 5.4 illustrates the causal loop diagram for face mask collection and recycling system in Turkey focusing on Istanbul.

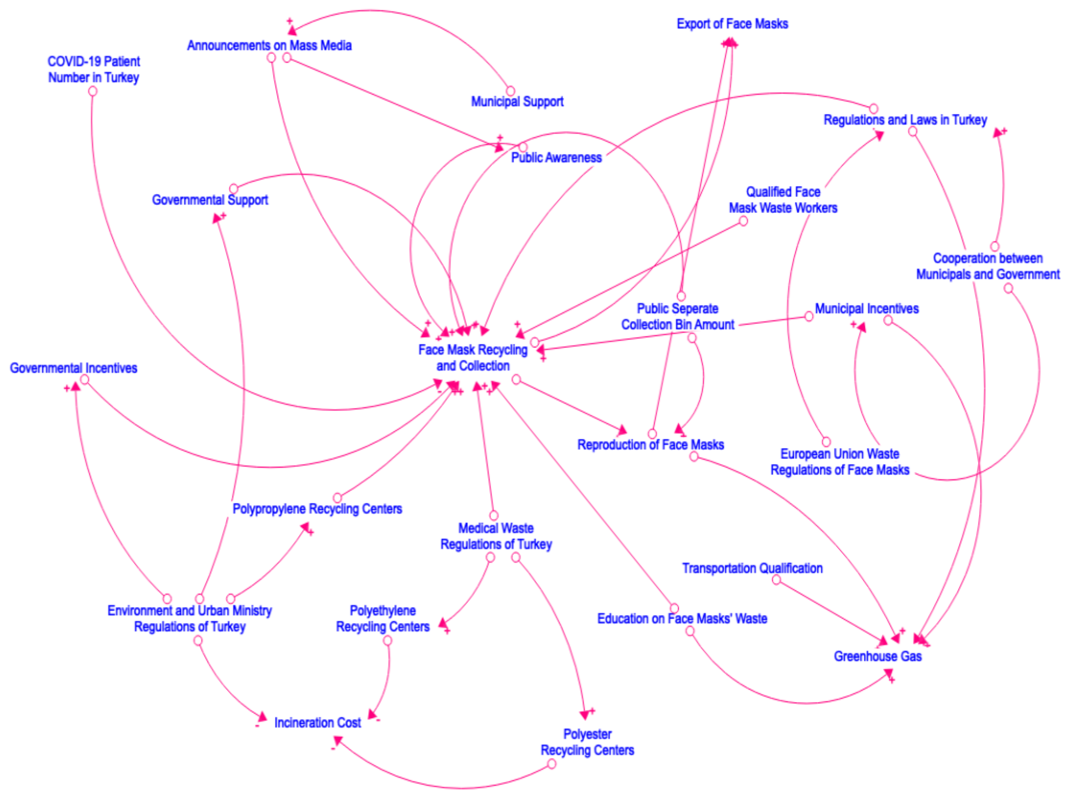


Figure 5.4: Causal Loop Diagram (CLD) of face mask collection system in Istanbul

The positive relationship between two variables indicates that they are proportionally affected which means one related variable increases when the other one increases. As an example, if there exists an arrow positively (+) signed at the end, starting from A and coming to B, it indicates that if A increases, B also increases. Inversely, if there is a negative relationship between two variables having cause-effect relationship, an increase in A causes a decrease in B assigned as a negative (-) sign at the end (Bala et al., 2016).

In the system dynamics modelling part, supply chain management of face masks collection and recycling for Turkey is simulated and the results are shared. To begin with, system dynamics can be defined as the methodology to understand the complex system's behaviour by the time. (Forrester, 1993). The system, as a whole, includes stocks, feedback mechanisms, negative or positive relationships, dynamics variables in order to understand the relation between interrelated variables and how a change of a variable in the complex system effects on the other variable in the system. In order to start analysing the system, firstly it is essential to understand if the existing system is suitable for being a system or not as the system dynamics methodology is based on cause-effect relationship between variables (Forrester, 1993). For face mask recycling and collecting supply chain management, the daily average face mask is taken as 50.569.966 based on the formula given in equation (5.3). Furthermore, according to the Chamber of Turkish Textile Engineers Report, a face mask includes three polypropylene layers, which have an average of 1,5 gr (URL4). As there is no face mask recycling policy in Turkey because of infection risk (URL5), a governmental and municipal recycling system do not exist. Face masks are collected at different point and they are sent to incineration area. In official gazette published in 2019 (URL6), the governmental incentive has been indicated as 5%, which is used in simulation to increase recycling ratio of face masks. By stating that face masks are not categorized under medical waste coming from hospitals, this incentive is not applied actually. In the model, the incentive for medical waste is used. The medical face mask waste is calculated based on the equation given in (5.3). Figure 5.5 shows the system dynamics modelling for supply chain management of face masks collection and recycling.

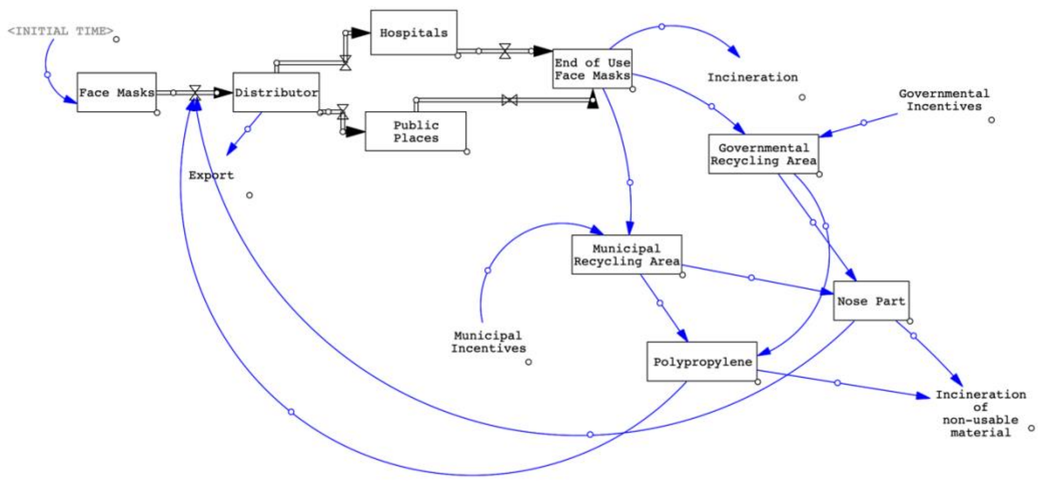


Figure 5.5: System dynamics modelling for supply chain management of face masks collection and recycling

The simulation has been run for 5 years with the incentive of 5%, which nearly increases 4,72 of recycling ratios in governmental and municipal recycling areas. Considering that there is no recycling policy of face masks, including polypropylene and nose part including metals, Figure 5.6 shows production (red) and polypropylene (yellow) in gram amount after recycling with the proposed model.

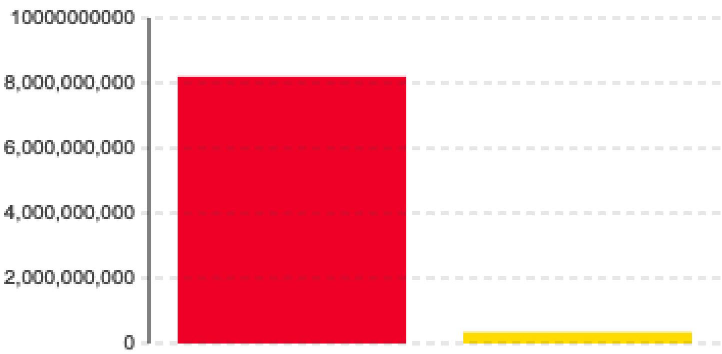


Figure 5.6: Face Mask production and recycled polypropylene amount

Furthermore, municipal and governmental recycling areas are separately put in the model with the equal capacities. After 5 years of simulation, Figure 5.7 shows recycled masks amount (gram) in municipal and governmental recycling areas in Turkey.

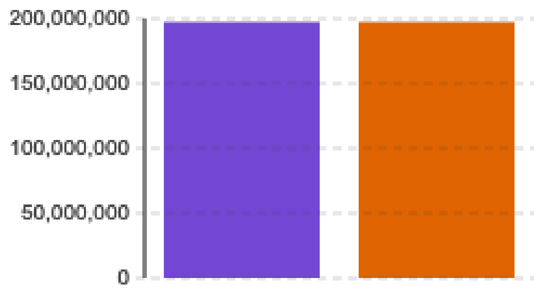


Figure 5.7: Recycled masks amount (kg) in municipal and governmental recycling areas in Turkey.

## 5.2. NGBM(1,1) based NGBM(1,1)-FA Application on medical waste

As discussed in earlier sections of this thesis, the study centers on Istanbul, Turkey's largest metropolis. Within Turkey, municipalities are tasked with managing the entire lifecycle of medical waste—encompassing collection, handling, transport, incineration, and disposal—in accordance with the Medical Waste Control Legislation (MWCR, 2017). For this research, medical waste data spanning two decades were obtained from the Turkish Statistical Institute (https://www.tuik.gov.tr/Home/Index, accessed March 4, 2024) and the Istanbul Metropolitan Municipality database (https://data.ibb.gov.tr/dataset?q=data, accessed March 4, 2024). Both institutions play pivotal roles in gathering relevant data. Figure 1 depicts medical waste generation in Istanbul between 2004 and 2023, including the COVID-19 era, during which medical waste volumes significantly increased (Konyalıoğlu et al., 2024b)

It is important to emphasize that the underlying rationale for employing the forecasting approach and the proposed model in this thesis is the absence of reliable, specific data pertaining to face mask and glove waste in Istanbul. This data gap necessitates effective forecasting methods for medical waste and, subsequently, the utilization of the Shangkam equation (presented in the equations 5.1 and 5.2). By relying on these equations, it is possible to approximate the quantity of face masks and gloves based on the total amount of medical waste. Integrating these estimated values into the proposed model is therefore essential to address the existing data limitations.

The dataset comprises annual medical waste figures for Istanbul from 2004 to 2023 (n=20). Over this period, the volume of medical waste in Istanbul expanded approximately 4.5-fold. In contrast, the number of hospital beds grew by about 1.5 times and the number of doctors increased by roughly 1.7 times. Figure 5.8 further illustrates the progression of medical waste amounts in Istanbul from 2004 through 2023.

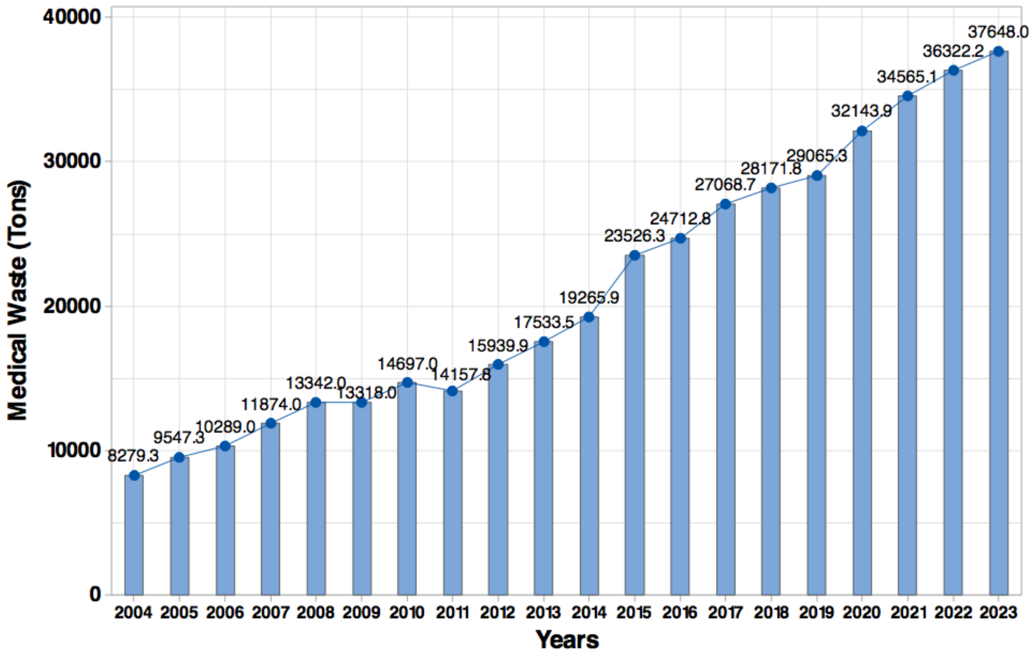


Figure 5.8: Medical waste amounts in Istanbul from 2004 to 2023

In this section of the thesis, a nonlinear grey Bernoulli model enhanced with the firefly algorithm (FA-NGBM(1,1)) is employed to forecast Istanbul's future medical waste output (in tons). The accuracy and robustness of this model are then evaluated by comparing it against GM(1,1), FA-GM(1,1), FA-FGM(1,1), and a linear regression model. The data is partitioned into three sets: 60% for training (2004–2015), 25% for testing (2016–2020), and 15% for validation (2021–2023). Figure 5.9 provides a visual representation of the rolling mechanism used to develop these predictive models. (Konyalıoğlu et al., 2024b)

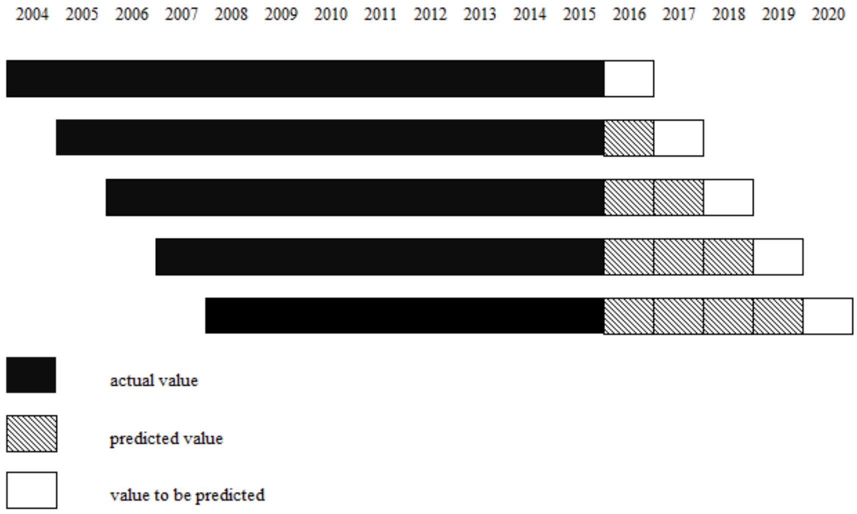


Figure 5.9: The diagram of the rolling mechanism in this thesis (Konyalıoğlu et al., 2024b)

In the parameter optimization model, mean absolute percentage error (MAPE) is used as the fitness function. The parameters of firefly algorithm for the optimization model are as follows: the maximum iteration number is 1000, the population size is 50, the light absorption coefficient ($\gamma$) is 1, the step factor ($\alpha$) is 0.01, $\beta_0$ is 1 and the minimum attractiveness ($\beta min$) is 0.2. In the firefly algorithm, MAPE converges very fast to a stationary point. The prediction models and parameter optimization problem are programmed on MATLAB 2022a. The prediction results and MAPE values obtained by the proposed models for testing data are given in Table 5.1.

In the proposed FA-NGBM(1,1) model, the minimum MAPE (3.47%), $\alpha$=0.88 and $\gamma$=-0.42 are obtained by using firefly algorithm. Similarly, the minimum MAPE (3.62%) and $\alpha$=0.53 are found with the parameter optimization in the FA-GM(1,1) model. Also, in the fractional grey model with firefly algorithm (FA-FGM(1,1)), minimum MAPE (3.60%), α=0.21 and r=0.98 are calculated (Konyalıoğlu et al., 2024b).

Table 5.1: MAPE and predicted values of the proposed models for testing data

| Year | Actual Value | Linear Regression | | GM(1,1) | | FA-GM(1,1) | | FA-FGM(1,1) | | FA-NGBM(1,1) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fitted Value | Error (%) | Fitted Value | Error (%) | Fitted Value | Error (%) | Fitted Value | Error (%) | Fitted Value | Error (%) |
| 2016 | 24712.81 | 21815.35 | 11.72% | 23395.68 | 5.33% | 23286 | 5.77% | 23290.57 | 5.76% | 23319.75 | 5.64% |
| 2017 | 27068.74 | 22969.38 | 15.14% | 25361.12 | 6.31% | 25185.57 | 6.96% | 25160.74 | 7.05% | 25230.63 | 6.79% |
| 2018 | 28171.81 | 24123.4 | 14.37% | 27468.77 | 2.50% | 27206.26 | 3.43% | 27134.44 | 3.68% | 27328.94 | 2.99% |
| 2019 | 29065.25 | 25277.43 | 13.03% | 29920.41 | 2.94% | 29539.15 | 1.63% | 29450.88 | 1.33% | 29625.44 | 1.93% |
| 2020 | 32143.85 | 26431.46 | 17.77% | 32791.42 | 2.01% | 32249.84 | 0.33% | 32196.32 | 0.16% | 32148.85 | 0.02% |
| MAPE(%) 2016-2020 | | | **14.41%** | | **3.82%** | | **3.62%** | | **3.60%** | | **3.47%** |

Table 5.2: MAPE and predicted values of the proposed models for validation data

| Year | Actual Value | Linear Regression | | GM(1,1) | | FA-GM(1,1) | | FA-FGM(1,1) | | FA-NGBM(1,1) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fitted Value | Error (%) | Fitted Value | Error (%) | Fitted Value | Error (%) | Fitted Value | Error (%) | Fitted Value | Error (%) |
| 2021 | 34565.10 | 27585.49 | 20.19% | 35454.39 | 2.57% | 35252.98 | 1.99% | 35535.79 | 2.81% | 34396.90 | 0.49% |
| 2022 | 36322.21 | 28739.52 | 20.88% | 38426.32 | 5.79% | 38130.16 | 4.98% | 38559.71 | 6.16% | 36945.43 | 1.72% |
| 2023 | 37648.01 | 29893.55 | 20.60% | 41622.98 | 10.56% | 41207.30 | 9.45% | 41812.43 | 11.06% | 39725.36 | 5.52% |
| MAPE(%) 2021-2023 | | | **20.56%** | | **6.31%** | | **5.47%** | | **6.68%** | | **2.57%** |

As indicated by the findings in Table 5.1, the hybrid FA-NGBM(1,1) model achieves the lowest MAPE value at 3.47%, while the LR model yields the highest MAPE value at 14.41%. These results also suggest that the implementation of parameter optimization and the adoption of a rolling strategy enhance the forecasting accuracy for GM(1,1), FGM(1,1), and NGBM(1,1) models (Konyalıoğlu et al., 2024b).

To validate the proposed models, the final three years of data are used. By applying the optimized parameters and the rolling mechanism derived from the training data, each prediction model is evaluated on the validation set. Table 5.2 presents the performance analysis of the prediction models using this validation data.

As indicated in Table 5.2, the proposed FA-NGBM(1,1) model achieves a prediction error of 2.57% for the validation dataset. This model outperforms other predictive approaches, including linear regression, GM(1,1), FA-GM(1,1), and FA-FGM(1,1). The comparative performance analysis of these prediction models for both testing and validation data is illustrated in Performance analysis of the prediction models for the testing and validation data (Konyalıoğlu et al., 2024b).

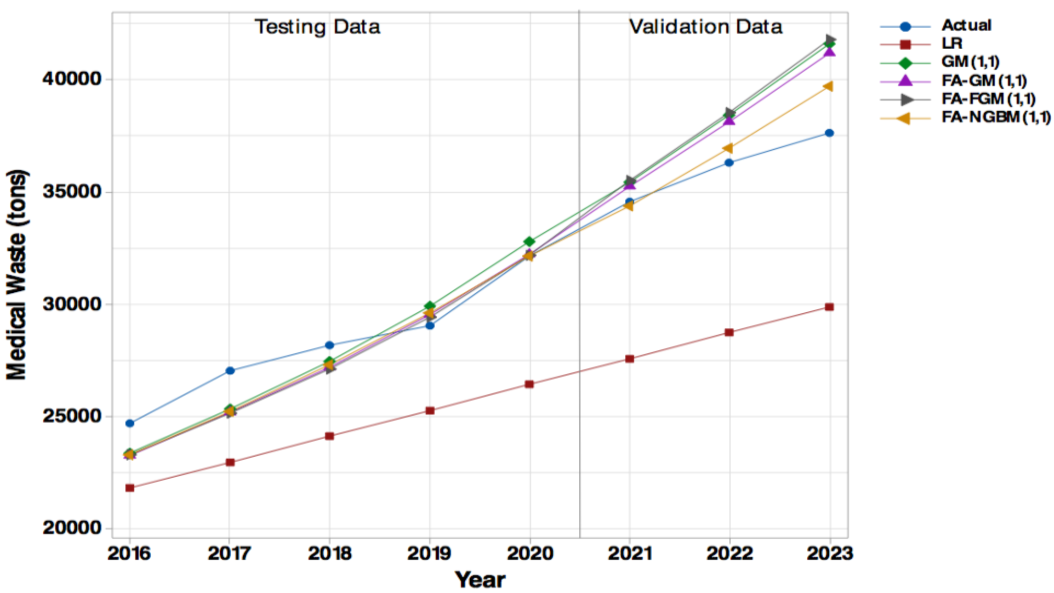


Figure 5.10: Performance analysis of the prediction models for the testing and validation data

Finally, the amount of waste is estimated for 2024, 2025 and 2026 using the FA-NGBM(1,1) model, which has the lowest prediction error in the validation and test data. Prediction results for future 3 years are presented in Table 5. These prediction results provide guidance for policy makers in terms of resource planning and management.

Table 5.3: Waste amount predictions for future years with FA-NGBM(1,1) model

| Year | 2024 | 2025 | 2026 |
|---|---|---|---|
| Medical Waste (tons) | 41096.34 | 43825.85 | 46779.47 |

After forecasting total medical waste in Istanbul, it’s important to estimate total face masks and gloves waste using Shangham’s equation (2020) to initiate the suggested model. According to Shangham (2020), as stated in Equation 5.1 and 5.2, approximately 9–10% of medical waste consists of contaminated face masks and gloves. This indicates that over the next three years, an estimated 4,000–5,000 tons of face masks and gloves will be generated in Istanbul, as illustrated in Table 5.4 based on the forecasting results.

Table 5.4: Face Masks and Gloves Waste amount predictions for future years with the FA-NGBM(1,1) model and Shangham equation

| Year | 2024 | 2025 | 2026 |
|---|---|---|---|
| Face Masks and Gloves in total as an estimated interval (tons) | 3.698,64-4109,63 | 3.944,32-4.382,58 | 4.210,14-4.677,94 |

### 5.3. SF-AHP Application on face masks and gloves’ waste in Istanbul

Istanbul is the most-populated city in Turkey, which generates 23,7% of total medical waste of Turkey (TUIK, 2021). As hospitals in Istanbul already used substantial quantities of face masks and gloves for standard procedures, the volume of such medical waste rose significantly during the COVID-19 pandemic, the post-pandemic period, and following the 6 December 2023 earthquake that affected other regions of Turkey, even though Istanbul was not directly impacted. In the event of a future earthquake in Istanbul—given its high seismic risk—the use of these protective materials would likely surge further, intensifying the city’s medical waste burden in Istanbul. Thus, it is important to take into consideration that ineffective medical waste management of face masks and gloves, like all medical waste, will result in health downturn, increasing cost and environmental pollution that directly affect on all human beings living in Istanbul (Hanedar et al., 2022).

In the context of managing the disposal of face masks and gloves in Istanbul- categorized as “ineffective” -it is not sufficient to merely highlight the importance of incorporating waste management considerations focusing on face masks and gloves waste. It is equally vital to establish a well-defined management framework supported by systematically determined criteria (Lyu et al., 2024). These criteria, once identified, must be rigorously weighted to ensure a structured, transparent, and justifiable decision-making process (Özdemir et al., 2024; Demir and Moslem, 2024) to be used in the proposed model of the thesis. Without such a foundational structure, the rationale behind each methodological step remains obscure, potentially weakening the integrity and applicability of the proposed face masks and gloves waste management strategy.

To address this need, the methodology employed in this thesis—specifically the SF-AHP—serves as more than a mere analytical tool. It provides a means to elucidate the underlying motivations behind each sub-chapter and sub-application to consider in the proposed model focusing on Istanbul’s face masks and gloves waste management strategy and policy. By systematically prioritizing the factors that influence the management of face masks and gloves waste, the chosen approach assists in uncovering the fundamental motivations that guide each evaluative phase (Kahraman et al., 2024). For instance, beyond selecting which criteria (e.g., environmental impact, health and safety concerns, logistical feasibility, and economic costs) to incorporate, it is essential to explain why these particular criteria were chosen and how they align with broader waste management objectives. Similarly, the weighting of these criteria should reflect their relative importance, drawing from stakeholder inputs, regulatory standards, and sustainability goals.

This explanatory depth is indispensable. Each application sub-section of the study, from identifying relevant criteria to applying spherical fuzzy AHP, must be grounded in a clear set of motivations. By thoroughly articulating why a given factor deserves priority, the thesis not only justifies its methodological choices but also provides actionable insights to policymakers, waste management professionals, and other stakeholders including Istanbul municipality, waste regulatory and Turkish government. Such explicit clarification ensures that the management system is robust, replicable, and scalable, ultimately enhancing the reliability of any resulting recommendations as indicated in the proposed model section.

### 5.3.1. Determining the decision makers and experts

In this thesis, decision makers have been selected based on their theoretical or practical knowledge in the field associated with face masks and gloves waste management. In order to gather and unify the responses, a comprehensive and technical study has been conducted. As all the respondents were experts, the importance weights have been equally taken for decision making matrix. Table 5.5 shows the information of decision makers responding the questionnaire.

Table 5.5: Decision makers’ information about face masks and gloves waste management in Istanbul

| Profession | Number | Quality of Decision Makers |
|---|---|---|
| Academicians | 3 | Academicians who have knowledge about the related area and published scientific papers in medical waste management topic are involved in this study. |
| Environmental Engineers | 2 | Environmental Engineers are responsible for inspecting and developing waste management processes in the facility in Istanbul. |
| Medical Doctors | 2 | Medical Doctors use a high amount of face masks and gloves during surgery and routine controls. Thus, they have knowledge about criteria and sub-criteria of this research. |
| Industrial Engineers | 2 | Industrial Engineers are assumed to inspect and build the waste management facilities in an effective and efficient way. |

### 5.3.2. Determining the criteria and sub-criteria

The criteria and sub-criteria to be prioritized are defined thanks to the current literature and the experts’ views.

The initial step of the decision-making is to identify the main purpose of the model, and to identify criteria, sub-criteria and alternatives. In this context, it is very essential to identify and know the model's accuracy (Çelik et al., 2022). Fuzzy systems endowed with a specified approximation accuracy can be derived, and their respective approximation accuracies can be scrutinized and compared through the application of sensitivity analysis (Zeng and Singh, 1996). Thus, in the fifth section, we provide a sensitivity analysis to measure the accuracy of our SF-AHP application in the field of face masks and glove waste management criteria and sub-criteria.

Table 5.6. presents criteria and sub-criteria followingly based on the literature and experts' views.

Table 5.6: Criteria and sub-criteria for face masks and gloves waste management in Istanbul

| Criteria | Sub-criteria | Attributes and Explanations | References |
|---|---|---|---|
| **Financial and Cost Related Criteria (C1)** | Recycling Cost (C11) | Encompasses the total expense for recycling one mask or glove (unit cost), including disinfection, labor, and energy. Understanding this cost is crucial for appraising the feasibility and sustainability of recycling for face masks and gloves in Istanbul. | Ray et al., 2022; Teymourian et al., 2021; Aung et al., 2019 |
| | Collection and Transportation Cost (C12) | Covers the cost of collecting and moving waste (fuel, vehicle operation, labor) to processing facilities. Istanbul's traffic density and geographic scale can greatly impact these expenditures. | Tirkolaee et al., 2020; Li et al., 2019; Arifoğulları et al., 2022; Dursun et al., 2011 |
| | Incineration Cost (C13) | Involves the expenses for thermally treating contaminated masks and gloves, including specialized equipment and regulatory compliance. Evaluating this cost informs decisions on incineration viability. | dos Santos et al., 2020; Cherubini et al., 2009; Xin-Gang et al., 2016 |
| | Landfill Cost (C14) | Encompasses site selection, operation, and oversight expenses for disposing of masks and gloves in landfills. Proper assessment ensures that landfill use aligns with public health and environmental goals. | Bartolacci et al., 2019; Kamaruddin et al., 2017; Wang et al., 2009 |
| | Economic Benefits (C15) | Addresses potential revenue or savings from managing mask and glove waste, such as material recovery. Highlighting these benefits stresses the financial incentives of improved waste practices. | Huysveld et al., 2019; Liu et al., 2022; Skrzyniarz et al., 2022 |

Table 5.5 (cont.): Criteria and sub-criteria for face masks and gloves waste management in Istanbul

| Criteria | Sub-criteria | Attributes and Explanations | References |
|---|---|---|---|
| **Organization Related Criteria (C2)** | Personnel Qualifications (C21) | Reflects the need for appropriately trained staff to handle infectious waste safely and in accordance with Turkish policies, ensuring compliance and minimizing public health risks. | Aung et al., 2019; MWCR, 2017 |
| | Regulations and Laws (C22) | Focuses on the legal frameworks for medical waste disposal. Strict enforcement is central to uniform, safe handling of infectious waste in Istanbul’s urban environment. | Agamuthu & Barasarathi, 2021; Balci et al., 2022; Berkun et al., 2011 |
| | Infrastructure of Health Institution (C23) | Refers to onsite equipment, protocols, and staff readiness for managing infectious waste. Robust infrastructure proved vital during post-COVID-19 or any possible health crisis for mitigating waste-related health risks. | Jayasinghe et al., 2023; Manzoor & Sharma, 2019 |
| | Organizational Structure (C24) | Covers the distribution of leadership roles and responsibilities, facilitating consistent decision-making and accountability in waste management processes. | Abduli, 1995 |
| | Organizational Awareness (C25) | Highlights the collective mindset of an organization regarding environmental responsibility. Greater awareness fosters proactive resource use and policy adherence for face masks and gloves waste management in Istanbul. | Vazquez et al., 2011; Ramli et al., 2023 |

Table 5.5 (cont.): Criteria and sub-criteria for face masks and gloves waste management in Istanbul

| Criteria | Sub-criteria | Attributes and Explanations | References |
|---|---|---|---|
| **Technique Related Criteria (C3)** | Supply Chain Management Policy (C31) | Examines how medical waste including face masks and gloves moves from generation to final disposal. Effective policies reduce operational costs while enhancing environmental performance. | Alberti et al., 2000; Vachon et al., 2007 |
| | Quality of Material (C32) | Considers the composition and condition of masks and gloves, affecting recyclability and treatment suitability. Higher-quality materials generally enable more efficient waste management. | Zorpas, 2016 |
| | Recycling, Landfilling, and Incineration Capabilities (C33) | Assesses the availability and capacity of facilities to handle different waste types. Adequate infrastructure underpins a cohesive, reliable treatment strategy for medical waste including face masks and gloves in Istanbul. | Yin et al., 2021; Luttenberger, 2020 |
| | Existence of Facilities (C34) | Addresses the presence (or absence) of specialized recycling or disposal centers. Limited facilities may escalate transportation costs and potential health hazards. | Coker et al., 2009; Akarsu et al., 2021 |
| | Incentives for People and Companies (C35) | Refers to governmental or municipal measures (e.g., subsidies, free collection) encouraging waste segregation and recycling. Such incentives often raise participation and recycling/reusing rates. | Massoud et al., 2010; Onan et al., 2016; Sezer et al., 2003 |
| | Citizens’ Awareness (C36) | Reflects the public’s knowledge of correct disposal practices and the environmental impacts of mismanaged waste, influencing overall recycling and reuse rates for face masks and gloves. | Almulhim, 2022; Hasan, 2004 |
| | Regular Technical Controls (C37) | Involves systematic inspections to ensure facilities meet operational standards and compliance in Istanbul. Such controls reduce risks and uphold effective handling across the waste cycle. | Kumar & Samadder, 2017; Gentil et al., 2010 |

As explained in Table 5.6., the hierarchical illustration of the prioritization can be seen in Extensions of Fuzzy Sets. This hierarchical illustration provides a broader understanding about how to construct our decision-making model to prioritize face masks and glove waste management affecting factors in Istanbul.

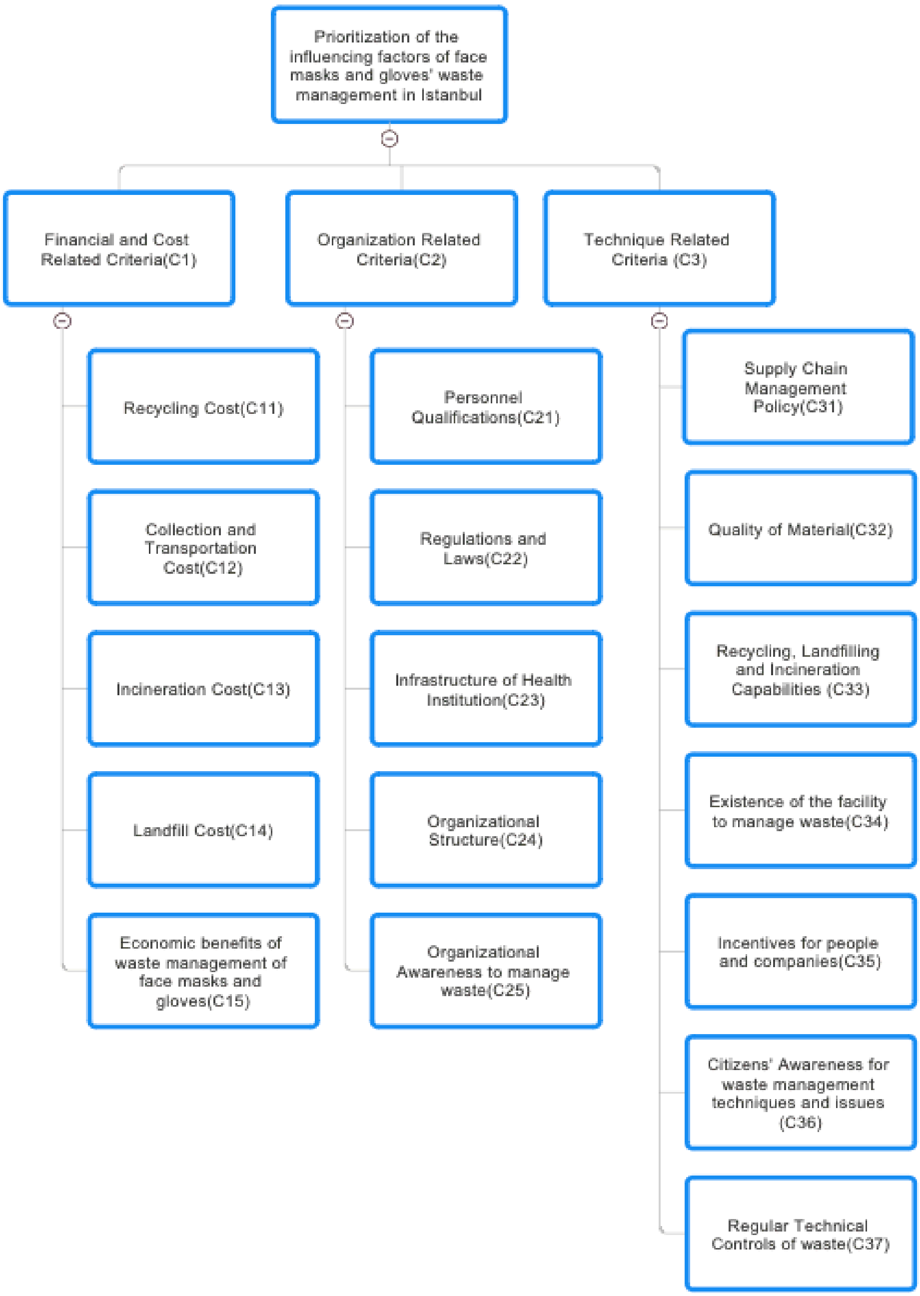


Figure 5.11: The hierarchical illustration of the prioritization problem

### 5.3.3. Sensitivity Analysis of the Results

After applying SF-AHP, one dimensional sensitivity analysis has been conducted in order to analyze the variations of criteria and sub-criteria. Sensitivity analysis is used to identify the variations and deviations in the existence of uncertainty (Karande et al., 2016), because methods such as ANP and AHP may have subjectivity, as they are based on personal opinions (Chang et al., 2007). Another reason of conducting a sensitivity analysis in decision making models is stated as the fact that sensitivity analysis in AHP and ANP provide robustness of the results showing which criteria and sub-criteria are the most important factors affecting the main purpose (Butler et al., 1997). In this context, the equation 5.4 shows the weight contribution constraint for understanding how to conduct one-dimensional sensitivity analysis.

$$\sum_{l=1}^{n} w_j = 1. w_j w_j' \quad (5.4)$$

where, $w_j$ is the most important criterion or sub-criterion weight and it can be fluctuated between 0 and its value obtained by SF-AHP process. $w_j'$ is defined as given in the equation (5.5).

$$w_j' = \left[w_{jmax} + (n-1)w_{jmin}\right] \quad (5.5)$$

where, $w_{jmax}$ and $w_{jmin}$ are respectively the highest and lowest level of the related criterion and sub-criterion (Butler et al., 1997).

### 5.3.4. Application of SF-AHP to face masks and gloves waste

In the context of weighted criteria, the data from the experts must be jointly considered. Hence, the perspectives of experts are accorded equal importance in the criteria ranking. The decision matrix for criteria weighting is presented in Table 5.7 in terms of linguistic variables. The consistency ratio has been found as 0,01 as calculated in the equation given in (4.31).

Table 5.7: Criteria evaluation results by experts (decision matrix)

| Main Criteria | Financial and Cost Related Criteria(C1) | Organization-Related Criteria(C2) | Technique-Related Criteria(C3) |
|---|---|---|---|
| **Financial and Cost Related Criteria(C1)** | EI | SLI | ALI |
| **Organization-Related Criteria(C2)** | SMI | EI | ALI |
| **Technique-Related Criteria(C3)** | AMI | VHI | EI |

The initial segment of the questionnaire, as outlined in Table 5.6, was primarily administered to experts. It is crucial to note that comprehensive information regarding the criteria was provided to ensure informed responses, thus facilitating an accurate ranking. The questionnaire comprised multiple inquiries designed to elicit importance weights for each criterion through pairwise comparisons.

Additionally, it is noteworthy that the Consistency Ratio (CR) for the pairwise comparison matrices of both main and sub-criteria were determined to be less than 0.10 (Saaty, 1980). Specifically, for the decision matrix related to technique sub-criteria, the CR was calculated as 0.0809. Similarly, the CRs for the decision matrices associated with Organization-Related sub-Criteria and Financial and Cost-Related sub-Criteria were found to be 0.070633 and 0.0807, respectively. This suggests a satisfactory level of consistency in the obtained results as stated by Saaty (1980). Table 5.8 reveals the decision matrix evaluation for each sub-criterion.

Table 5.8: Sub-criteria evaluation results by experts (decision matrix) for each criterion

| Financial and Cost-Related Criteria | **C11** | **C12** | **C13** | **C14** | **C15** |
|---|---|---|---|---|---|
| **C11** | **EI** | **SLI** | **LI** | **HI** | **SMI** |
| **C12** | **SLI** | **EI** | **EI** | **HI** | **AMI** |
| **C13** | **HI** | **EI** | **EI** | **HI** | **AMI** |
| **C14** | **LI** | **LI** | **LI** | **EI** | **SMI** |
| **C15** | **SLI** | **ALI** | **ALI** | **HI** | **SLI** |
| Organization-Related Criteria | **C21** | **C22** | **C23** | **C24** | **C25** |
| **C21** | **EI** | **SLI** | **SLI** | **SMI** | **HI** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **C22** | **SMI** | **EI** | **SMI** | **VHI** | **AMI** | | |
| **C23** | **SMI** | **SLI** | **SLI** | **EI** | **VHI** | | |
| **C24** | **SLI** | **VLI** | **EI** | **EI** | **SMI** | | |
| **C25** | **LI** | **ALI** | **VLI** | **SLI** | **SLI** | | |
| Technique Related Criteria | **C31** | **C32** | **C33** | **C34** | **C35** | **C36** | **C37** |
| **C31** | **EI** | **SLI** | **VLI** | **HI** | **SLI** | **HI** | **HI** |
| **C32** | **SMI** | **VLI** | **LI** | **VHI** | **HI** | **SMI** | **SMI** |
| **C33** | **VHI** | **HI** | **EI** | **VHI** | **VHI** | **HI** | **VHI** |
| **C34** | **EI** | **VLI** | **VLI** | **SLI** | **EI** | **EI** | **EI** |
| **C35** | **SMI** | **LI** | **VLI** | **EI** | **EI** | **SLI** | **EI** |
| **C36** | **EI** | **SLI** | **LI** | **EI** | **SMI** | **EI** | **EI** |
| **C37** | **VLI** | **SLI** | **VLI** | **EI** | **EI** | **EI** | **LI** |

Considering the importance of criteria and sub-criteria for face masks and glove waste management in Istanbul, which has been obtained by using SF-AHP, Technique-Related Criteria (C3) has the highest weight, which is the first priority amidst criteria while Recycling, Landfilling and Incineration Capabilities (C33), Supply Chain Management Policy (C31) and Quality of Material (C32) are followed as the most important sub-criteria respectively. Technique-Related criteria are about technical issues for the process of waste management including recycling, incineration or landfill. Thus, it is assumed that any complication arising from technical issues may result in the deterioration of the process of face masks and glove waste management in Istanbul. Integrated solid waste management, including medical waste, policies in developing countries contribute to minimizing the burden on landfills, thereby advancing the achievement of UN Sustainable Development Goals (Pujara et al., 2019). As an example, inexistence or incapability of waste treatment techniques can cause the increase of costs and deterioration of human health (Yu and Ma, 2022). This result is aligned with the previous findings that implementing effective safety measures, strategic capacity planning for recycling and reusing, and the adoption of well-defined working strategies can facilitate proper healthcare waste management, mitigating the risk of virus transmission. Disinfecting waste, coupled with meticulous segregation and on-site treatment, further enhances the overall quality and effectiveness of healthcare waste management practices based on UN Development Goals for waste management (Das et al., 2021).

As the second most important criteria, organizational-related criteria affect the management of the waste as well. Turkey has regulations and laws of waste management that supports the organizations, and increases the public awareness. It is stated by the calculations of SF-AHP that Regulations and Laws(C22) is the most significant sub-criteria under organizational-related criteria, which forces each citizen, hospitals and companies to treat the infectious and medical waste. Regarding the results of SF-AHP, it is seen that Infrastructure of Health Institution(C23) and Personnel Qualifications(C21) have significant importance since the infrastructure of the health institutions should be aligned with the collection, separation and storage policies of the government and municipalities. Face masks and gloves should be separated from other type of waste since they can be infectious, which results in spreading infections. This can be only achieved by the fact that elevating the level of education, infrastructure of healthcare institutions and comprehension in healthcare waste management significantly contributes to improving the overall situation of healthcare waste management. It is imperative to develop continuous training and educational programs for staff members, as this approach serves to mitigate the likelihood of inappropriate healthcare waste management in developing countries, especially in Turkey (Qaiser, 2012; Khan et al., 2019).

Among the criteria prioritized by the calculations given in methodology section, Financial and Cost-Related Criteria has the lowest weight. However, this result does not mean that the criteria could not be developed. Each institution including municipalities and governmental ones should aim to seek ways to reduce their waste management costs, and to provide not only environmentally but also economically and socially sustainable city to the citizens. Considering the sub-criteria, Incineration Cost(C13) is the most significant sub-criterion among the others. This can be explained by the fact that there is no policy to recycle and reuse face masks and gloves after disinfection process in Istanbul (Akarsu et al., 2021). The second most significant one is followed by the Collection and Transportation Cost(C12) implying that the consumption of fuel are seriously taken into consideration to collect the waste from places who generate face masks and gloves and transfer them to the facilities. In high-index level countries, the collection costs of healthcare waste typically constitute less than 10% of the waste management budget. These countries, employing mechanized, efficient, and frequent collection methods, can achieve remarkably high collection rates, ranging from 76% to 100%. OECD countries exemplify this trend, boasting the highest collection rates at 98%. However, in uppermiddle-income countries like Turkey, the collection rate may vary, falling within the range of 50% to 95%, which is relatively lower compared to developed countries in OECD (Margallo et al., 2019; Ranjbari et al., 2022).

When all sub-criteria are taken into consideration together, the most significant and effective ones for the face masks and gloves waste management process in Istanbul are Recycling, Landfilling and Incineration Capabilities (C33), Regulations and Laws(C22), Incineration Cost(C13) and Incineration Cost(C13) subsequently. On the contrary, Organizational Awareness to manage waste(C25), Regular Technical Controls of waste(C37), Existence of the facility to manage waste(C34) and Landfill Cost(C14) have the least importance sub-criteria, respectively. Table 5.9 and 5.10 show Final Results of Criteria and Sub-Criteria respectively.

Table 5.9: Final Results of Criteria

| **Main Criteria** | **Local Weights (μ,v,π)** | | | **Score Value** | **Ranking** |
|---|---|---|---|---|---|
| **Financial and Cost Related Criteria(C1)** | 0,3814 | 0,6003 | 0,3080 | 9,902 | 3 |
| **Organization-Related Criteria(C2)** | 0,4685 | 0,5245 | 0,3089 | 12,501 | 2 |
| **Technique-Related Criteria(C3)** | 0,8363 | 0,1590 | 0,1519 | 24,318 | 1 |

Table 5.10: Final Results of Sub-criteria

| | Local Weights (μ,v,π) | | | Score Value | Ranking |
|---|---|---|---|---|---|
| **Financial and Cost-Related Criteria** | μ | v | π | | |
| Recycling Cost(C11) | 0,5337 | 0,6093 | 0,2913 | 14,5530 | 3 |
| Collection and Transportation Cost(C12) | 0,6474 | 0,4743 | 0,2829 | 18,0031 | 2 |
| Incineration Cost(C13) | 0,7152 | 0,4129 | 0,2428 | 20,2398 | 1 |
| Landfill Cost(C14) | 0,4290 | 0,6454 | 0,2855 | 11,4360 | 5 |
| Economic benefits of waste management of face masks and gloves(C15) | 0,4338 | 0,6949 | 0,2203 | 11,8429 | 4 |
| **Organization-Related Criteria** | μ | v | π | | |
| Personnel Qualifications(C21) | 0,5442 | 0,5908 | 0,3032 | 14,8100 | 3 |
| Regulations and Laws(C22) | 0,7336 | 0,3807 | 0,2233 | 20,8887 | 1 |
| Infrastructure of Health Institution(C23) | 0,5861 | 0,5448 | 0,2821 | 16,1722 | 2 |
| Organizational Structure(C24) | 0,4681 | 0,5771 | 0,3309 | 12,3823 | 4 |

| | | | | | |
|---|---|---|---|---|---|
| Organizational Awareness to manage waste(C25) | 0,3067 | 0,7796 | 0,2229 | 7,9119 | 5 |
| **Technique-Related Criteria** | μ | v | π | | |
| Supply Chain Management Policy(C31) | 0,5940 | 0,4137 | 0,2428 | 16,6008 | 2 |
| Quality of Material(C32) | 0,5822 | 0,4406 | 0,2296 | 16,3165 | 3 |
| Recycling, Landfilling and Incineration Capabilities (C33) | 0,7639 | 0,2340 | 0,1786 | 22,0169 | 1 |
| Existence of the facility to manage waste(C34) | 0,4267 | 0,5167 | 0,3440 | 11,0471 | 6 |
| Incentives for people and companies(C35) | 0,4505 | 0,5155 | 0,3302 | 11,8426 | 5 |
| Citizens' Awareness for waste management techniques and issues (C36) | 0,4837 | 0,4591 | 0,3565 | 12,6652 | 4 |
| Regular Technical Controls of waste(C37) | 0,3989 | 0,5597 | 0,3184 | 10,3690 | 7 |

In order to obtain the robustness of the study, sensitivity analysis has been conducted in one-dimensional way showing the variability of the results. Underneath all, considering the findings of this study, the most important sub-criterion has been obtained as Recycling, Landfilling and Incineration Capabilities (C33) having a maximum priority local weight of 22,0169. In the sensitivity analysis, this weight has been aligned with a proper range as given in the equation 5.4, and all sub-criterion weights have been equally adapted. Thus, during sensitivity analysis process, the weight of the most important criterion has firstly been decreased to the minimum level and increased up to the top limit by using Eq. 5.5 and Eq. 5.6 based on the local weights. Along the sensitivity analysis process, it has been seen that the sensitivity analysis is conducted and analysed within the range of $13.00 \leq C14 \leq 22{,}0169$. Consequently, new values of criteria and sub-criteria ranking have been obtained as given in Figure 5.12. The weights of C25, C11 and C34 are not assumed to decrease lower than 0,1258 since the weight of C25-Organizational Awareness to manage waste(C25) criterion turns into negative and not have not been able to be enhanced. Considering the sensitivity analysis results, one may argue that the variation in criterion and sub-criterion weights do not seem to have a significant effect on the prioritization which can state that the results of the proposed method obtained by decision makers’ responses are consistent and robust.

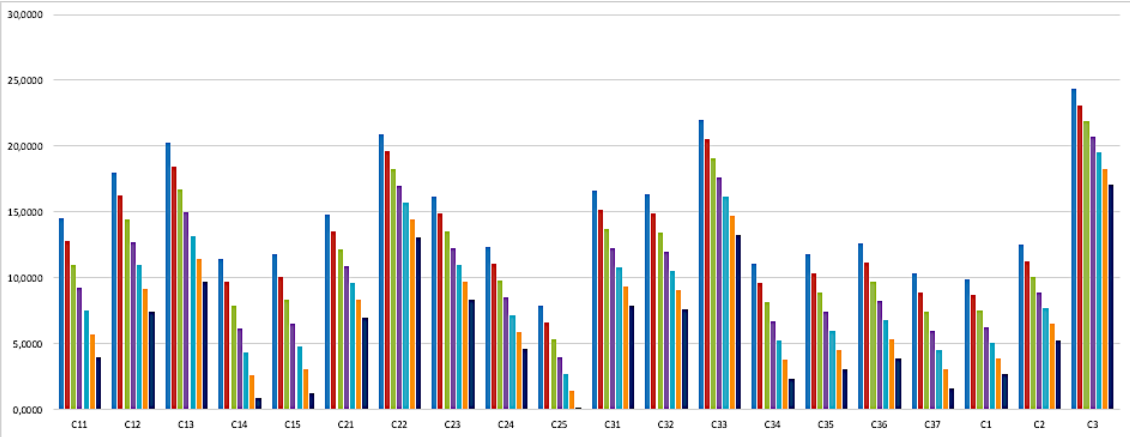


Figure 5.12: The visualisation of sensitivity analysis

# 6. PROPOSED MODEL USING INTEGRATED METHODOLOGIES

This chapter introduces a proposed model that integrates three distinct methodologies: a simulation-based system dynamics approach, nonlinear grey Bernoulli modelling optimized through the firefly algorithm, and a multi-criteria decision-making method utilizing spherical fuzzy sets. The model illustrates a stock-flow diagram that employs the results from the methodology and application sections presented earlier, specifically addressing the waste management of face masks and gloves in Istanbul. Detailed information regarding the proposed model is provided in the subsequent sections.

## 6.1. Suggested Model via Stock-Flow Diagram

The proposed model presented in this thesis is developed based on a system thinking approach and is illustrated as a stock-flow diagram in Figure 6.1. As depicted in this figure, the integrated model encompasses the waste management dynamics of face masks and gloves, as well as the factors influencing this inherently unstable process. Given that such a system does not currently exist in Istanbul, the proposed model offers a novel contribution to the literature by employing a stock-flow diagram that utilizes the outcomes of the distinct methodologies discussed in the preceding sections.

Furthermore, to gain a comprehensive understanding of this system, the subsequent sections elucidate how to develop the proposed model within the context of systematically managing face mask and glove waste using systems thinking methodologies. Recognizing that the proposed model can also be applied during high-risk periods, and that such types of waste can be efficiently managed if an action plan and the proposed model are implemented in Istanbul, the economic aspects are also incorporated into the system dynamics model. Figure 6.1 illustrates the stock-flow diagram representing the proposed model.

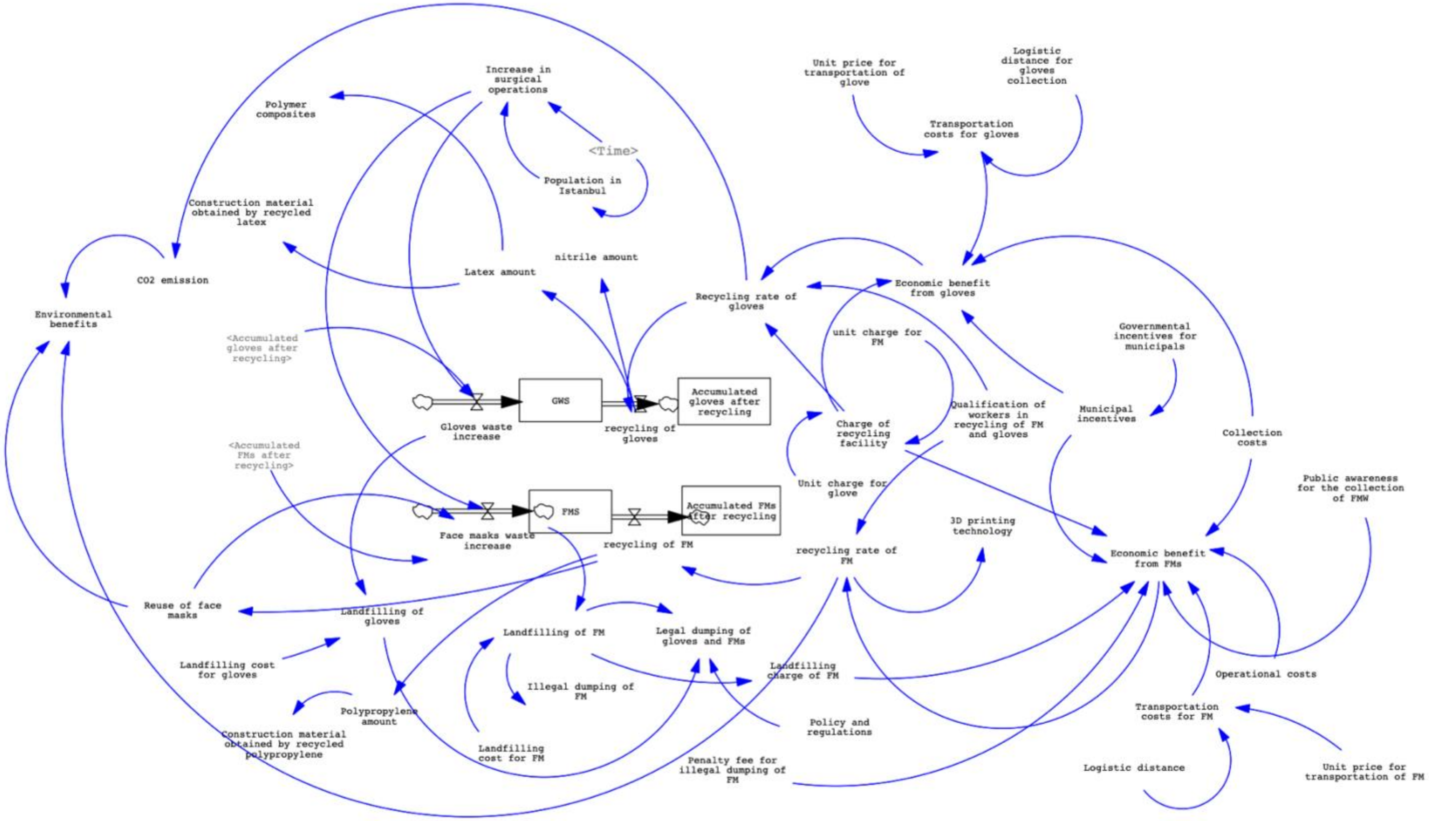


Figure 6.1: The visualisation of stock-flow diagram for the proposed model

Furthermore, it should be emphasized that the input variables required for initiating simulations of the proposed model are derived from the methodologies and findings discussed in the preceding sections. Figure 6.2 provides a detailed illustration of how these inputs are incorporated into the model's simulation process, as well as the specific variables considered in generating the model's outcomes.

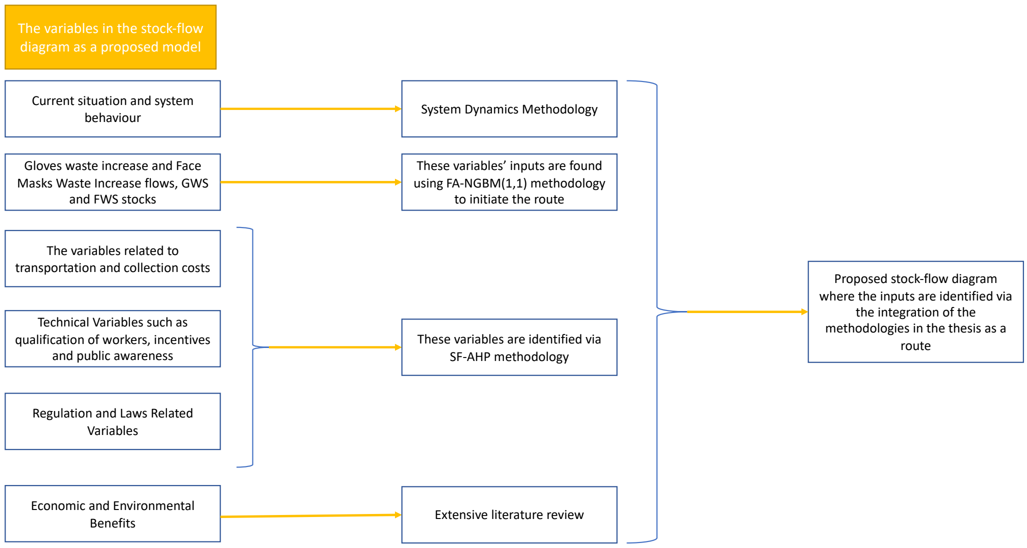


Figure 6.2: The process of proposed model simulation and the integration of thesis outputs

### 6.1.1. Collection of face masks and gloves

In the proposed model, the initial step involves collecting contaminated waste masks and gloves from various locations, addressing the lack of an accurate collection system for recycling and reusing this type of waste. As highlighted in the literature, gathering waste from diverse sources is a crucial component of waste management and disposal strategies for materials of this nature. Specifically, in the context of disposable face masks, potential recycling methods encompass mechanical, thermochemical, and chemical processes that transform waste materials into new products with enhanced quality or increased environmental value (Lyu et al., 2024; Ray et al., 2022).

In Istanbul, the prevailing waste collection strategy relies predominantly on incineration, resulting in face masks not undergoing any recycling processes for potential reuse. Furthermore, as the municipality and the Ministry of Environment, Urbanization, and Climate Change are responsible for the collection of this waste—including gloves and face masks—a recycling and reusing strategy could commence with the implementation of an effective collection system. This would involve introducing separate recycling bins specifically designated for face masks and gloves.

As illustrated in Figure 6.1, the collected waste is promptly directed into separate stocks for face masks and gloves. These stocks represent specialized facilities, collection centres, or depots designated specifically for handling this type of waste. To facilitate this collection process, the results obtained from the forecasting methodologies presented in Sections 3 and 4 can be employed for the collection of gloves and face masks in Istanbul. The capacities for collection—including trucks, vans, and other vehicles—should be adapted to accommodate the anticipated increase in these types of waste. According to Shangham (2020), as stated in Equations 5.1 and 5.2 , approximately 9–10% of medical waste consists of contaminated face masks and gloves. This indicates that over the next three years, an estimated 4,000–5,000 tons of face masks and gloves will be generated in Istanbul, as illustrated in Table 5.4 based on the forecasting results.

Furthermore, given that the second most important sub-criterion identified is the Collection and Transportation Cost, the proposed system incorporates transportation charges for face masks and gloves, considering unit costs and logistical distances for collection and transportation. In the proposed model, governmental incentives should be provided to municipalities to enhance recycling and reuse rates for this type of waste. This approach aims to alleviate the economic burden on municipalities, which are also responsible for the collection of medical waste.

### 6.1.2. Recycling Pathways for face masks and gloves

In the second part of the proposed model, the recycling pathways for face masks and gloves is presented. Considering that there is no recycling facility for face masks and gloves in Istanbul, the assumptions are only made upon the recycling process of this type of waste.

In the literature, there are several ways to recycle face masks and gloves with different methods including mechanical, thermochemical, and chemical processes. For example, Germany is recognized as the foremost leader in waste recycling within Europe, distinguished by its distinctive waste sorting system. During the COVID-19 pandemic, Germany mandated the segregation and collection of all medical waste—excluding sharps and glass—in designated containers as non-recyclable raw materials for disposal in advanced incineration facilities. Furthermore, the country enforces regulations that assign the responsibility of proper waste disposal to hospitals and other healthcare institutions (Attrah et al., 2022). In Turkey, the medical waste collection and recycling options are very limited compared to EU regulations (Altin et al., 2023; Özgüven and Okur, 2022; Sürme and Maraş, 2022).

Before initiating the recycling and upcycling processes, it is essential to disinfect face masks and gloves (Hassan et al., 2022). The literature identifies five methods for disinfecting medical waste: Autoclave Disinfection, Dry Heat Technique, Microwave/Radio-Wave Disinfection, Chemical Disinfection, and Ultraviolet (UV) Disinfection. Economically, all these methods are cost-effective; however, to reduce labor costs and eliminate handling procedures, the literature suggests that Autoclave Disinfection, Microwave/Radio-Wave Disinfection, and Ultraviolet (UV) Disinfection are more efficient technologies (Lyu et al., 2024; Ray et al., 2022).

For face masks specifically, four different recycling or upcycling methods are presented in the literature: Mechanical Reprocessing (Crespo et al., 2021; Cruz Sanchez et al., 2020), Thermochemical Recycling (Zhang et al., 2021), Pyrolysis Upcycling—including vacuum pyrolysis, catalytic pyrolysis, co-pyrolysis, and microwave pyrolysis (Yuwen et al., 2023; Zander et al., 2019; Parku et al., 2020; Cao et al., 2022; Park et al., 2021)—and Chemical Repurposing (Guselnikova et al., 2022). These processes enable the reuse of face masks or their conversion into valuable byproducts such as fuels, gases, and carbonaceous materials, as well as alternative and value-added products. Notably, the thermochemical recycling method is capable of processing various types of face masks and converting them into useful products while simultaneously eliminating bacteria and viruses without the need for pretreatment (Lyu et al., 2024; Ray et al., 2022).

In the context of contaminated gloves, these items can be recycled and transformed into materials such as expansive clay soil for pavement subgrade (Zhu et al., 2022), concrete composites (Albiajawi et al., 2024), or asphalt pavement (Gedik et al., 2023) through thermochemical or chemical processes facilitated by 3D printing technology (Mousavi and Deheshani, 2023). Given the significance of recycling gloves after the disinfection process, it is pertinent to note that in Istanbul, these gloves can be recycled, especially considering that this type of waste is currently not subjected to any recycling procedures (Konyalıoğlu et al., 2024a).

However, it is well-recognized that not all face masks and gloves can undergo recycling and reuse processes, implying that some will inevitably be directed to landfill operations in Istanbul. Moreover, in many countries—including those within the European Union—legal dumping is permitted (Gokdemir et al., 2024; Cook et al., 2023). In the context of the proposed model for Istanbul, illegal dumping outside authorized landfill sites should be discouraged and penalized with fines. This strategy aims to enhance the recycling rates of face masks and gloves, thereby providing economic benefits derived from recycling regulations for these materials. Given that regulations and laws were identified as significantly important in the SF-AHP application, it is imperative that municipalities and governments actively promote and enforce legislation related to the recycling of face masks and gloves.

### 6.1.3. Policy and Regulations in Istanbul

In the stock-flow diagram seen in Figure 6.1, "Policy and Regulations in Istanbul" play a crucial role in shaping the management of face masks (FM) and gloves waste (GW). These policies act as the backbone of the system aligned with the results obtained by SF-AHP methodology, guiding proper collection, recycling, and disposal processes while mitigating the environmental and health impacts of unmanaged face masks and gloves.

Policies influence key areas such as landfilling practices, recycling rates, public awareness, and economic incentives, thereby creating a structured framework for sustainable waste management.

One significant aspect of these policies is their role in regulating landfilling and preventing illegal dumping. By imposing landfilling costs on the municipality of Istanbul or waste management organizations including the ministry, the policies encourage alternative waste management solutions such as possible recycling and reuse as discussed in the section of 5.1.2. Furthermore, penalties for illegal dumping act as a deterrent to improper disposal, reducing environmental harm. Policies also mandate public awareness campaigns to educate residents about the environmental consequences of improper disposal and the importance of proper waste collection and recycling. This increases participation in the waste management system, ensuring higher collection rates for FM and GW.

Furthermore, another key effect of policies is their impact on the collection of FM and GW. Governmental incentives as illustrated in the proposed model, such as financial support or subsidies for municipalities, reduce collection costs and encourage local governments to prioritize waste collection efforts. This results in higher collection rates, as municipalities are better equipped to cover logistical costs. Policies also mandate public awareness campaigns to educate individuals and organizations on the importance of proper waste disposal. This increased awareness further boosts collection rates, ensuring that more FM and GW are directed to appropriate recycling or disposal facilities instead of being improperly discarded.

Policies also play a vital role in increasing the recycling rate of FM and GW. By setting mandatory recycling standards or targets, regulations incentivize recycling facilities to expand their capacity and improve efficiency. Municipal incentives and requirements for qualified workers in recycling facilities, as depicted in the proposed model, ensure that the workforce is adequately trained to handle waste safely and efficiently obtained as a qualification of recycling workers in the SF-AHP methodology whose weight is considerably high. Furthermore, policies promote the adoption of advanced technologies, such as 3D printing, to enhance material recovery from recycled waste from face masks and gloves. These measures create a positive feedback loop where increased recycling leads to reduced landfill dependency and greater resource recovery.

Another critical objective of policies is to reduce illegal dumping of FM and GW. Punishments for illegal dumping, as shown in the diagram, act as a deterrent and encourage individuals and businesses to adhere to proper disposal practices. As a result, less waste ends up in unauthorized sites, reducing environmental harm and redirecting waste to legal collection and recycling pathways. This creates a reinforcing feedback loop: stricter regulations reduce illegal dumping, leading to improved environmental outcomes and increased waste recovery through formal channels.

Economic and operational factors directly affected by the forecasted amount obtained by FA-NGBM(1,1) and facility capacities are also significantly influenced by policies. Regulations that impose unit charges for landfill use discourage reliance on landfilling and make recycling a more attractive and cost-effective option. By promoting material reuse—such as transforming recycled polypropylene or latex into construction materials or polymer composites—policies generate economic benefits from recycling. These benefits make the system more financially sustainable and create opportunities for reinvestment in waste management infrastructure and public awareness programs.

Policies based on the regulations also influence environmental and sustainability outcomes through interconnected cause-effect relationships. By incentivizing recycling and discouraging illegal dumping, regulations help reduce waste accumulation in landfills, mitigating their associated environmental impacts. This aligns with the principles of a circular economy, where waste is repurposed into valuable materials and reintegrated into the production cycle. The result is a system that minimizes environmental harm while creating economic value from waste recovery efforts.

#### 6.1.4. Incentivization of Face Masks Waste and Gloves Waste Recycling in Istanbul

In the context of the incentivization of FMW and GW recycling in Istanbul, all the assumptions and suggestions are based on the forecasting value obtained by the methodology proposed in the third section. The results show that in 2024, 4,109 tons face masks and gloves will be generated while in 2026, this amount will be reaching to 4.677 tons as seen in the Table 5.4 considering Shangham equations given in 5.1 and 5.2 accepting that nearly 9-10% of total medical waste will be composed of face masks and gloves in Turkey, mainly in the city of Istanbul. The stock-flow diagram as a proposed model highlights the importance of feedback loops and system dynamics in the waste management system for face masks (FM) and gloves waste (GW) in Istanbul. These feedback loops illustrate the interconnected relationships between regulations, policies, infrastructure, and the operational components of waste management. *A critical challenge in Istanbul is the inexistence of dedicated FM and GW recycling and reuse facilities, which significantly disrupts positive feedback loops and amplifies negative ones, ultimately limiting the effectiveness of existing laws and regulations.*

Positive feedback loops as seen in Figure 6.1 are key drivers of sustainable waste management. For example, public awareness campaigns, mandated by policies, can increase awareness about proper FM and GW disposal. This heightened awareness leads to higher collection rates, ensuring more waste is funnelled into formal management systems mandated by official regulatory. When collection rates improve, recycling facilities can process larger volumes of waste, increasing recycling rates and generating economic benefits from recovered materials such as polypropylene and latex or nitrile. These materials can then be reused in the production of construction materials or polymer composites, aligning the system with the principles of a circular economy. The economic benefits from recycling—such as revenue from selling recycled materials—can be reinvested into expanding recycling infrastructure, funding further public awareness campaigns, and incentivizing municipalities. This creates a virtuous cycle where environmental impacts are reduced through greater recycling and less dependency on landfills.

However, the lack of FM and GW recycling and reuse facilities in Istanbul disrupts this positive feedback loop. Even if public awareness and collection rates increase, the absence of infrastructure to process the waste results in most of it being sent to landfills or illegally dumped. This undermines the economic benefits of recycling, as the opportunity to generate revenue from recovered materials is lost. Without recycling infrastructure, the policies and regulations intended to foster a circular economy cannot achieve their full potential, as the waste cannot be repurposed effectively. This breaks the reinforcing cycle of economic and environmental gains, leaving municipalities and stakeholders with limited options for managing FM and GW sustainably. Thus, it is suggested that by taking into consideration of the forecasted results and the important factors affecting this management process, a new facility should be urgently considered in Istanbul.

The inexistence of recycling facilities also intensifies negative feedback loops, creating significant environmental and economic challenges. As FM and GW waste generation increases due to population growth and rising medical demand such as surgical operations as illustrated in the Figure 6.1, the reliance on landfill sites grows. This leads to escalating landfilling costs, which strain municipal budgets and make the system less financially sustainable. Additionally, with limited recycling options and logistical barriers and costs, illegal dumping becomes a more attractive alternative for individuals and organizations. This results in widespread environmental degradation, including soil, water, and air pollution, while increasing the social and financial costs of enforcement and cleanup. Such outcomes hinder the effectiveness of penalties for illegal dumping, as the root issue—the lack of infrastructure—remains unresolved.

Regulations and policies in Istanbul, such as landfilling charges, penalties for illegal dumping, and governmental incentives, aim to improve the waste management system, which is not clearly and strictly implemented for face masks and gloves waste in Istanbul. However, their effectiveness is constrained by the absence of recycling infrastructure, which is a very important factor in Istanbul as seen in the Table 5.10. For example, landfilling charges are designed to discourage landfill dependency, but without recycling facilities as an alternative, they simply increase the financial burden on municipalities without reducing waste. Similarly, penalties for illegal dumping may deter improper disposal, but they do not address the underlying lack of accessible recycling options.

Governmental incentives and subsidies for municipalities can reduce collection costs and improve collection rates, but without facilities to process the collected waste, these efforts are unlikely to yield significant environmental or economic benefits.

The costs of lacking recycling and reuse facilities are extensive. Environmentally, the over-reliance on landfills leads to greenhouse gas emissions, leachate production, and land degradation. Illegal dumping further exacerbates these issues by polluting soil and water sources, posing health risks to local communities, which are not considered in the suggested model numerally. On the other hand, economically, the missed opportunity to recover and sell valuable materials such as polypropylene and latex, which can be converted into other materials as recycled or reused, reduces potential revenue streams for municipalities. Additionally, high transportation costs associated with hauling waste to distant landfill sites increase operational expenses, further straining municipal budgets. Socially, inefficient waste management undermines public trust in government policies and exposes communities to health hazards from unmanaged waste.

The addition of recycling facilities would transform the system dynamics in Istanbul. Positive feedback loops, such as those driven by public awareness, higher collection rates, and increased recycling, would be amplified. With more waste processed into valuable materials, economic benefits would grow, incentivizing further investments in the system. At the same time, negative feedback loops tied to illegal dumping and landfill overuse would diminish, as waste would be diverted into formal recycling channels. This would align Istanbul's waste management system with global sustainability goals and ensure long-term success in addressing FM and GW waste challenges.

#### 6.1.5. Capacity Planning for recycling

Effective capacity planning for the collection and recycling of face masks (FM) and gloves waste (GW) in Istanbul is crucial to address the forecasted increase in waste generation, which is expected to grow from 4,109 tons in 2024 to 4,677 tons in 2026. The stock-flow diagram highlights the interdependencies between collection systems, facility capacities, recycling technologies, and the associated economic, environmental, and social dynamics. Addressing these factors requires a comprehensive approach to infrastructure development, operational optimization, and the integration of innovative recycling methods.

The collection system forms the backbone of waste management and must scale to handle the anticipated waste volumes. In 2024, approximately 342.4 tons of waste per month will need to be collected, increasing to 389.8 tons per month by 2026 as forecasting. Expanding collection capacity will involve establishing additional collection points and optimizing transportation routes to minimize costs. However, logistic distances between collection points and processing facilities, as highlighted in the stock-flow diagram in Figure 6.1., contribute significantly to transportation costs. Investing in fuel-efficient vehicles and the collection capacities in Istanbul, decentralized collection hubs, and improved routing systems will be essential to maintain cost-efficiency. Additionally, public awareness campaigns, mandated by policies, can encourage proper disposal practices and increase collection rates, reinforcing positive feedback loops within the system.

Facility capacity planning is another critical component. Currently, Istanbul lacks dedicated FM and GW recycling and reuse facilities, creating a significant bottleneck in the system. To meet forecasted demands and provide a buffer for surges, new facilities capable of processing at least 5,500 tons per year by 2026 must be established. Advanced recycling technologies, such as Thermochemical Recycling, Mechanical Reprocessing, Pyrolysis Upcycling, and Chemical Repurposing, offer viable solutions for processing FM. These methods convert FM into high-value products, including fuels, gases, carbonaceous materials, and alternative products, while simultaneously eliminating pathogens without requiring pre-treatment. Similarly, contaminated GW can be recycled into expansive clay soil for pavement subgrades, concrete composites, or asphalt pavements using thermochemical and chemical processes. Technologies like 3D printing facilitate the creation of value-added products from recycled GW, enhancing the economic viability of the system.

The costs associated with these efforts include the initial capital investment for facility construction, operational expenses such as energy and labor, and ongoing transportation costs. Establishing recycling facilities equipped with advanced technologies is expensive, but the long-term benefits justify the investment. The ability to recover valuable materials like polypropylene and latex from FM, and repurpose GW into construction materials, generates significant economic returns. Additionally, reducing reliance on landfills lowers landfilling charges and mitigates environmental penalties associated with excessive landfill use or illegal dumping. These economic benefits create a positive feedback loop, where revenues from material recovery can be reinvested into further infrastructure development and operational improvements.

Policy integration is essential for the success of capacity planning. Regulations must mandate recycling targets for face masks and gloves, provide subsidies for facility development, and enforce penalties for non-compliance with proper waste disposal practices. Public-private partnerships can distribute the financial burden of infrastructure development, while incentives for industries to use recycled materials can stimulate demand for recovered products. Policies encouraging innovation, such as the adoption of 3D printing and other advanced recycling technologies as explained in the previous sections, will further enhance the system's sustainability for FM and Gloves waste management.

## 6.2. Environmental Impact of Face Masks and Gloves Incineration

As extensively documented in the current body of literature, incineration activities within waste management processes substantially contribute to CO2 emissions and overall carbon footprints, thereby exacerbating environmental concerns for face masks and gloves waste (Konyalıoğlu et al., 2024a; Konyalıoğlu et al., 2024b). To counteract this trend and prevent further ecological degradation, recycling initiatives assume a position of critical importance, as they can significantly reduce the volume of waste diverted to incineration.

In this thesis a greenhouse gas (GHG) emission calculation was performed using the GHG simulator (URL: https://www.iges.or.jp/en/pub/ghg-calculator-solid-waste-ver-ii-2013/en) to quantitatively assess the environmental implications of the proposed strategies. The equation 6.1 shows the formula to calculate GHG emission (Chen and Lin, 2008).

$$GHG_E = \sum (M \; x \; C_i) \quad (6.1)$$

Where $GHG_E$ = total volume of greenhouse gases emitted (MTCE);
$M$ = amount of organic waste composted (tonne);
$C_i$ = emission factor for greenhouse gas i for treating each tonne of waste (MTCE/tonne; i: GHG type such as CO2, CH4 and N2O).

The input parameters for this analysis were derived from the outcomes of the FA-NGBM(1,1) modelling results, thereby ensuring that the estimates are aligned with the methodological frameworks previously established in this thesis. Table 6.1 presents a detailed breakdown of the resulting emission values, encompassing operational activities, incineration processes, and transportation operations. This integrated assessment provides a more comprehensive perspective on the potential environmental benefits of optimized waste management practices and informed policy interventions for face masks and gloves waste management in Istanbul.

Table 6.1. The results of the GHG emission simulation

| | | |
|---|---|---|
| GHG emissions from operational activities | 34,78 | kg of $CO_2$-eq/tonne of combusted waste |
| GHG emissions from the incineration of waste | 1389,57 | kg of $CO_2$-eq/tonne of combusted waste |
| Direct fossil-based GHG emissions from incineration | 1424,36 | kg of $CO_2$-eq/tonne of combusted waste |

Table 6.1 shows that greenhouse gas (GHG) emissions from face mask and glove waste management exhibit stark differences across various stages of the disposal process. Operational activities—covering waste collection, transportation, and preliminary

handling—account for approximately 34.78 kg of $CO_2$-equivalent per tonne of combusted waste, reflecting a relatively minor contribution compared to the incineration phase. By contrast, incineration processes produce 1,389.57 kg of $CO_2$-equivalent per tonne of combusted waste, while direct fossil-based emissions associated with incineration amount to 1,424.36 kg of $CO_2$-equivalent per tonne. These significant figures underline how critical the combustion stage is to overall GHG generation and signal the need for targeted interventions to mitigate emissions.

As a result, the dominance of incineration in GHG emissions highlights a pressing challenge for municipal authorities, policymakers, and healthcare facilities in urban centers like Istanbul, where the volumes of face mask and glove waste continue to rise. Although optimizing operational activities—through more efficient collection routes, better facility layouts, or advanced waste-handling technology—can yield modest but meaningful reductions, the principal gains lie in addressing the incineration stage. In the broader context of sustainability objectives, such as the United Nations Sustainable Development Goals (SDGs), reducing incineration-related emissions aligns with Goals 3 (Good Health and Well-Being), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), and 13 (Climate Action). By pinpointing the most emission-intensive stages, this thesis related to face masks and gloves waste management offers strategic insights that can guide the development of cleaner incineration technologies, encourage investment in alternative waste treatments, and foster integrated policies to minimize carbon footprints—ultimately contributing to more sustainable waste management practices and better environmental approach.

# 7. CONCLUSION

The critical need to manage waste from face masks and gloves is increasingly recognized in both developed and developing nations, driven by rising pollution levels, insufficient waste management infrastructure, and the complexity of existing strategies and inadequate policies. This thesis thus develops a comprehensive framework for managing waste from face masks and gloves in Istanbul, addressing a notable gap in the existing literature. By integrating three distinct methodologies—system dynamics simulation, nonlinear grey Bernoulli modeling optimized by the Firefly Algorithm, and a multi-criteria decision-making technique using spherical fuzzy sets—this research offers two major contributions. First, it focuses on an underexplored area of waste management, bringing attention to the unique challenges posed by face masks and gloves. Second, it presents a methodological innovation by uniting these three approaches, thereby enhancing both the analytical rigor and the overall effectiveness of waste management strategies.

This thesis presents the development of a novel hybrid model, FA-NGBM(1,1), aimed at predicting waste quantities in Istanbul. The performance of the proposed hybrid model is evaluated against classical models such as GM(1,1), FA-GM(1,1), FA-FGM(1,1), and linear regression (LR). Numerical results indicate that the FA-NGBM(1,1) model, which incorporates a rolling mechanism, provides satisfactory predictions for medical waste amounts in Istanbul. Grey forecasting models demonstrate robust predictive capabilities, particularly in scenarios with limited data availability. Furthermore, the combination of parameter optimization and the rolling mechanism significantly enhances the performance of grey forecasting models like GM(1,1), FGM(1,1), and NGBM(1,1). The application of the firefly algorithm proves to be highly effective in terms of solution quality and computational efficiency for addressing the parameter optimization problem.

Another focus of this thesis is the examination of factors influencing waste management policies and strategies for the treatment of face masks and gloves focusing on especially post-COVID-19 period. Recognizing that experts may hold uncertain and subjective opinions; a sensitivity analysis was conducted to elucidate differences among decision-makers and to assess the robustness of the methodology employed. The results from this analysis demonstrate that the Spherical Fuzzy Analytic Hierarchy Process (SF-AHP) is a highly robust method for validating our findings.

As a result of this methodology, the thesis identifies Recycling, Landfilling, and Incineration Capabilities as the most critical sub-criteria affecting waste management strategies during the COVID-19 period and especially post-COVID period in Istanbul. These technical aspects are crucial because any inefficiencies can disrupt the waste management process for face masks and gloves, leading to increased costs and health risks. Organizational Factors and Infrastructure of Health Institutions also play pivotal roles, emphasizing the need for robust legal frameworks and well-equipped facilities that incorporate municipal and governmental policies for Istanbul. Although Financial and Cost-Related Criteria have the lowest weighting, they remain essential for sustainable waste management during crisis periods. High incineration costs highlight the necessity for policies that promote recycling and reusing medical waste to reduce overall expenses and logistics costs, as discussed in previous literature.

To enhance the adaptability and resilience of the methodology within the context of Istanbul and Turkey's medical waste management activities, it is recommended that the proposed model in this thesis incorporates a mechanism for waste management factors and adjustment of the criteria and their weightings. This approach is essential given the dynamic nature of pandemics and the continually evolving best practices in waste management. Istanbul, being Turkey's most populous city, presents unique challenges and opportunities due to its dense population, significant medical infrastructure, and diverse waste generation patterns. The proposed mechanism in this thesis should involve systematic data collection and analysis to monitor changes in waste generation, regulatory requirements, technological advancements, and public health directives. For instance, fluctuations in waste volumes during peak pandemic periods compared to regular times necessitate flexible and responsive waste management strategies, especially in anticipation of earthquakes or natural disasters. Regular updates to the criteria and weightings will ensure that waste management practices remain relevant and effective under varying conditions.

Overall, the suggested model of the thesis implies a significant contribution to addressing the management of face mask (FM) and glove waste (GW) in Istanbul. Grounded in systems thinking, forecasting and decision-making methodologies, this model systematically integrates key aspects of waste management, including collection, recycling, and disposal processes, while incorporating the economic, operational, and regulatory dimensions necessary for sustainable implementation. By offering a dynamic and interconnected framework, the suggested model of the thesis aims to mitigate the social, and economic challenges posed by the escalating accumulation of FM and GW in Istanbul. This thesis positions the model as a foundational step toward aligning Istanbul's face masks and gloves waste management system with the principles of a circular economy and global sustainability goals.

The lack of an effective and organized collection system for FM and GW in Istanbul has been identified as a significant bottleneck, leading to their predominant disposal through incineration or landfilling. These practices not only pose environmental hazards but also represent a missed opportunity for material recovery and economic gain. The proposed model addresses this gap by introducing targeted strategies for collection, including the deployment of designated recycling bins, optimization of logistical networks, and the provision of governmental incentives to municipalities. Public awareness campaigns are emphasized as critical drivers of behavioural change, enhancing the community's active participation in the proper disposal of FM and GW. These measures collectively ensure higher collection rates, reducing the environmental footprint of improper waste management.

*Central to the model is the establishment of recycling pathways for FM and GW, which currently lack dedicated facilities in Istanbul. Advanced recycling technologies such as thermochemical recycling, chemical repurposing, and 3D printing are identified as* *transformative solutions for converting FM and GW into value-added products, including construction materials, fuels, and polymer composites. These technologies not only reduce the environmental burden associated with waste accumulation but also generate significant economic returns from recovered materials. However, the absence of recycling infrastructure disrupts these positive feedback loops, as collected FM and GW cannot be processed into reusable materials.* Addressing this infrastructural deficit is imperative for realizing the full potential of the model and fostering a sustainable waste management ecosystem. The establishment of recycling facilities equipped with state-of-the-art technologies represents a critical investment to enable material recovery, reduce dependency on landfills, and close the loop within the waste management system.

Regulatory and policy measures are identified as pivotal to the successful implementation of the proposed model. Policies such as the imposition of landfilling charges, penalties for illegal dumping, and the provision of subsidies to municipalities create an enabling environment for the model's operationalization. These measures incentivize alternative waste management practices, such as recycling and reuse, while discouraging environmentally detrimental behaviours like illegal dumping. Public awareness campaigns mandated by policy further reinforce collection and recycling efforts, ensuring higher participation rates and compliance. However, the effectiveness of these policies is currently constrained by the lack of accessible recycling facilities. The thesis underscores the urgent need for policy enforcement and infrastructural investments to unlock the full potential of the regulatory framework and create a structured pathway toward sustainable waste management.

The economic and environmental implications of the proposed model highlight its transformative potential for Istanbul. Recycling FM and GW reduces landfill dependency, mitigates greenhouse gas emissions, and minimizes other environmental hazards, such as soil and water contamination. Economically, the recovery of valuable materials like polypropylene and latex generates new revenue streams that can be reinvested into expanding infrastructure and enhancing operational efficiency. The creation of a positive feedback loop, where increased recycling rates drive further economic and environmental benefits, underscores the model's alignment with the principles of a circular economy. Conversely, the current reliance on landfilling perpetuates negative feedback loops, increasing municipal costs and environmental degradation. The proposed model, therefore, offers a pathway to break this cycle by enabling the systematic recovery and reuse of FM and GW.

Capacity planning is presented as a cornerstone of the model, ensuring that Istanbul can meet the projected increase in FM and GW generation as forecasted in the thesis. Forecasting indicates that waste volumes will exceed 4,600 tons annually by 2026, necessitating the expansion of collection systems and the establishment of new recycling facilities. This thesis emphasizes the need for decentralized collection hubs, optimized transportation routes, and the adoption of advanced recycling technologies to manage these rising waste volumes effectively. Policy mandates, including recycling targets and subsidies for facility development, are critical to ensuring the scalability and sustainability of these capacity-building efforts.

In conclusion, this thesis presents a comprehensive and novel framework for the management of FM and GW in Istanbul, addressing critical gaps in collection, recycling, and policy enforcement. The proposed stock-flow diagram model not only highlights the interconnected dynamics of these processes but also offers actionable insights for policymakers, municipalities, and other stakeholders. While the model provides a robust foundation, its success depends on overcoming significant challenges, including the absence of recycling infrastructure, financial constraints, and logistical barriers. Investments in advanced technologies, public awareness initiatives, and regulatory enforcement are essential to realizing the model’s potential. By implementing these measures, Istanbul can transition toward a sustainable, economically viable, and environmentally responsible waste management system for FM and GW, setting a benchmark for similar urban contexts in other cities in Turkey.

# 8. LIMITATIONS AND FUTURE WORK

This thesis, which applies three distinct methodologies, naturally presents certain limitations that should be considered for future research.

Regarding the system dynamics methodology, although data were utilized to propose a strict and rigorous approach, data certainty may pose limitations, and some influencing factors might have been overlooked in the modelling. Additionally, certain elements such as environmental factors and the carbon emissions associated with recycling face masks and gloves were not included. Moreover, while a proposed model has been presented, its simulation has not yet been realized.

Concerning the second methodological component employing the FA-NGBM(1,1), this part of the thesis has several inherent limitations that warrant acknowledgment. Firstly, not all parameters relevant to estimating medical waste in Istanbul—such as waste generation and collection from private institutions—were included. This omission may result in overlooking some data, potentially impacting the model's accuracy. Furthermore, during the COVID-19 period, challenges in data management could have introduced deviations or missing inputs, influencing the outcomes of the hybrid model. Secondly, although the model appears effective, the thesis did not explore alternative error calculation techniques commonly used in the literature, such as MAD, MAE, MARE, MSE, NAR, PLS, RME, RMSE, or $R^2$. Future research could benefit from investigating the optimization of the NGBM(1,1) model using different metaheuristic algorithms, including ant colony optimization, artificial bee colony, or grey wolf optimization. Additionally, enhancing the study by developing multivariate grey models (GM(1,N)) that incorporate variables such as the number of hospital beds, medical centres, bed occupancy rates, pharmacy branch counts, and daily outpatient numbers could provide valuable insights, especially when considering other error calculations like $R^2$, RMSE, or RME.

While this thesis presents a comprehensive decision-making approach for evaluating and prioritizing factors affecting face mask and glove waste management in Istanbul, it is important to acknowledge several limitations in this part of the methodology. First, the decision-making framework, although robust, is based on specific assumptions that may not hold universally. For instance, the SF-AHP relies on expert judgments, which are inherently subjective and may introduce biases into the study. The experts' opinions, though carefully selected and validated through sensitivity analysis, might not fully capture the diversity of perspectives necessary for a holistic approach. Furthermore, the findings are specifically tailored to Istanbul's unique socio-economic and environmental conditions, potentially limiting the generalizability of the conclusions to other regions with different characteristics. Future research should consider applying this methodology to various geographical settings and incorporating a broader range of expert inputs to enhance the robustness and applicability of the results. Additionally, exploring alternative decision-making techniques and fuzzy sets, such as neutrosophic or intuitionistic sets, could provide further insights and validate the findings under different scenarios. Other MCDM techniques like VIKOR, TOPSIS, and ELECTRE could also be considered to enhance objectivity.

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## BIOGRAPHICAL SKETCH

Aziz Kemal Konyalıoğlu earned Bachelor's degrees in Mathematical Engineering and in Management Engineering from Istanbul Technical University, Turkey, in 2015 and 2016, respectively. In 2014, he participated in the Erasmus Programme at the Université de Nantes in France for one year. Before starting his MSc, he studied advanced and applied mathematics in France. He subsequently pursued his MSc in Industrial Engineering at Université Galatasaray under the supervision of Asst. Prof. Ilke Bereketli, completing the program in 2018. Concurrently, he has been serving as a research assistant in the Management Engineering Department at Istanbul Technical University since 2016. In 2022, he joined the University of Strathclyde in Glasgow as a researcher. He is currently nearing completion of his PhD in Industrial Engineering at Université Galatasaray. His research interests include system dynamics, optimization, and multi-criteria decision-making applications. He has authored numerous publications, including SCI-indexed journal articles, book chapters, and conference proceedings.

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