GREEN SUPPLY CHAIN NETWORK DESIGN TO STUDY THE EFFECTS OF WASTE MANAGEMENT ON ENVIRONMENT

By

Rabia Maalik

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Supervisor

Dr. Waqas Ahmed

Department of Operations and Supply Chain

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Signature of Supervisor with stamp: ______________ DR. WAQAS AHMED, Associate Professor, HoD (Operations & Supply Chain), NUST Business School, H-12, Islamabad

Date: ______________

Programme Head Signature with stamp: ______________ DR. FARAN AHMED, Assistant Professor, NUST Business School (NBS), H-12, Sector Islamabad

Date: ______________

Signature of HoD with stamp: ______________ DR. WAQAS AHMED, Associate Professor, HoD (Operations & Supply Chain), NUST Business School, H-12, Islamabad

Date: ______________

Countersign by

Signature (Dean/Principal): ______________

Date: ______________

Principal & Dean
Dr. Naukhez Sarwar
NUST Business School

Declaration

I, Rabia Maalik declare that this Masters degree's thesis entitled "Green Supply Chain Network Design to study the effects of Waste Management on Environment" submitted to NUST Business School for the degree of Masters in Logistics and Supply Chain Management is the result of my own hard work and dedication. I have acknowledged all the material sources utilized in this research.

Student's Name: Rabia Maalik

Registration Number: 326838

Degree & Batch: MS L&SCM 2020

Signature: Rabia

Date: 12-09-2023

I hereby state that no portion of the work referred to in this dissertation has been submitted in support of an application for another degree or qualification of this or any other University or other institutes of learning.

Student's Name: Rabia Maalik

Signature: Rabia

Date: 12-09-2023

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Abstract

Waste management has become a crucial topic in modern civilization due to its negative environmental implications. This research focuses on the development of a green supply chain network for waste management, with an emphasis on incorporating environmental sustainability into decision-making. Waste management is necessary for environmental sustainability and it has impact on health of citizens and GDP of a country. The goal is to reduce the environmental impact of waste disposal while increasing resource recovery and recycling. The proposed green supply chain network design has three objectives of minimizing cost of transportation, minimizing GHG emissions due to transportation and maximizing saving of emissions due to waste management activities. The proposed model is multi-objective that take multi period into consideration. Interactive multi-objective fuzzy programming is used to optimize the model and study the results. The methodology is compared with goal programming to study its results and comparing the results of both methodologies. Various scenarios are discussed to study the effect of waste segregation as well. Higher the segregation of waste, emissions saved also increases. This study also mentions the importance of segregation of waste at consumer level. For future practice study on wet waste and food waste is also suggested with the dry waste.

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Chapter 1. Introduction

In this chapter, introduction of waste management, supply chain of waste management, green supply chain management and problem statement is elaborated. Aims and objective of the study are also mentioned in this chapter.

1.1 Introduction

The operations of Supply chain and Logistics are the most crucial for economic activities of a business and to stay competitive. These operations focus on profit maximization and customer satisfaction. Supply Chain Management evolved and started to take environment in consideration. Green Supply Chain Management introduces two types of "greenness" (Wang et al., 2011), Green product design and green operations. Green Supply Chain Network design falls into second category along with green manufacturing, waste management and reverse logistics. The purpose of Green Supply Chain is to reduce the impact of supply chain activities on environment. Transportation is the most significant factor which contributes highly towards the growth of economy due to increase in freight transportation but it also has most negative impact on environment as Green House Gas emissions causes global warming.

Waste management is the prominent activity all around the globe for clean environment. Waste can be categorized as Municipal solid waste, Industrial Waste, hazardous waste and e-waste. Usually waste has been considered as a cost due to only landfilling being a normal approach. This approach has caused numerous impacts on environment and economy. Studies has moved toward sustainable waste management for better economic and environmental solutions. Sustainable waste management includes waste segregation, recycling of waste (value capturing from waste), incineration and minimum landfilling of waste. Transportation is the most significant activity in waste management. The supply network of waste management starts from waste generation and ends at dumping of waste in landfills. This research focuses on the sustainable waste management process by focusing on the GHG emissions due to transportation of the waste, saving GHG emissions by segregation of waste and by introducing percentages criteria for waste activities.

Due to increase in population and consumerism waste generation has been rapidly increasing (Sharif et al., 2018). 1.2 kg per capita per day waste has been generated today that will increase to 1.42 kg per capita per day. In other words 1.3 Billion tons per year waste has been generated which will increase to 2.2 Billion Tons per year (Hoornweg and Bhada-Tata, 2012). Recycling of waste has been in discussion from quite a time but a few countries are actually working on it. Waste processing worth $410 billion per year (Edalatpour et al., 2018). Even though waste management has numerous benefits, the collection, transportation, and disposing of waste has very adverse environmental effects. These effects include Green House Gas emissions and other effects which are visible on daily basis i.e., land pollution, pungent smell and air pollution such as dust. Sustainable waste management includes economic, environmental and social impacts for betterment of humans and making sure that such activities do not have any effect on future generation's needs.

Waste management activities include source reduction, collection of waste, recycling, incineration, composting and landfilling. Most of the time these activities are overlooked and waste is dumped directly into landfills. To reduce the environmental impact of waste segregation of waste is encouraged. Moving to circular economy from linear economy is necessary for sustainable futures. Incineration and composting reduce the waste percentage that would otherwise go to landfilling (Zhang et al., 2014). This study focuses on municipal waste and its management. Municipal waste is composed of Food waste (perishable wet waste) and recyclable materials (dry waste) such as paper, cardboard, plastic, metals and glass (Buenrostro et al., 2001).

In this research, for designing a supply chain network, economic objective in terms of minimizing the cost of transportation is considered. In previous research works required number of vehicles are usually considered as a constant but we have taken required number of vehicles as a decision variable. Capacity of vehicles are taken into consideration with volume by weight criteria because vehicles doesn't carry full capacity load. For calculating the effects of waste activities, we have considered recycling, incineration and landfilling. GHG emissions vary depending on the type of waste, but for generalizing purpose of this research we have taken a constant value for GHG emissions. This will help in understanding the effect of waste management activities.

A supply chain network is designed for waste management based on multi-objective mathematical model. The proposed model has three objectives for minimization of cost of transportation of waste, minimization of GHG emissions of transportation and minimizing the effect of waste activities on environment. The first objective minimizing the cost of transportation takes into consideration of travelling between every point in supply chain network. The second objective function, minimizing GHG emissions of transportation process takes into consideration the fuel consumption rate of vehicles and the distance traveled. Fuel consumption rate of vehicles is calculated through linear regression. The third objective function gives the novelty to this research by taking recycling, incineration and landfill as waste management activities and defining percentage of waste to each activity and finding the saved emissions. The multi objective model is solved using genetic algorithm.

1.2 Problem Statement

The waste management supply chain is not sustainable and segregation of waste is not taken into consideration for environmental and economic aspects. The sustainable waste management is the dire need of this era to control global warming and reducing the cost of waste dumping. Waste segregation should be prioritized everywhere. For sustainable waste management, Condition of vehicles, vehicle routing to collect the waste, fuel consumption rate of vehicles, segregation of waste into different type of waste management activities needs taken into consideration. A proper supply chain network will reduce the cost of waste dumping, increase the job opportunities at segregation points also at other recyclable activities and reduce the effect of waste on environment. The waste management supply chain requires changes in waste segregation at homes and then at sortation centers. It also needs to maximize the recycling activities more so that GHG emissions are saved. The minimization of cost eventually results in more profit and job creations. The minimization of GHG through transportation and waste activities will result better in environmental sustainability. Hence, this research focuses on minimizing the cost of transportation of waste, minimizing GHG emissions of transportation and minimizing GHG emissions from waste activities by taking waste segregation ratios into consideration. This research emphasis on the basic concept of segregation of waste and avoided emission due to it. Following figure 1 shows a graphical representation of waste management's supply chain.

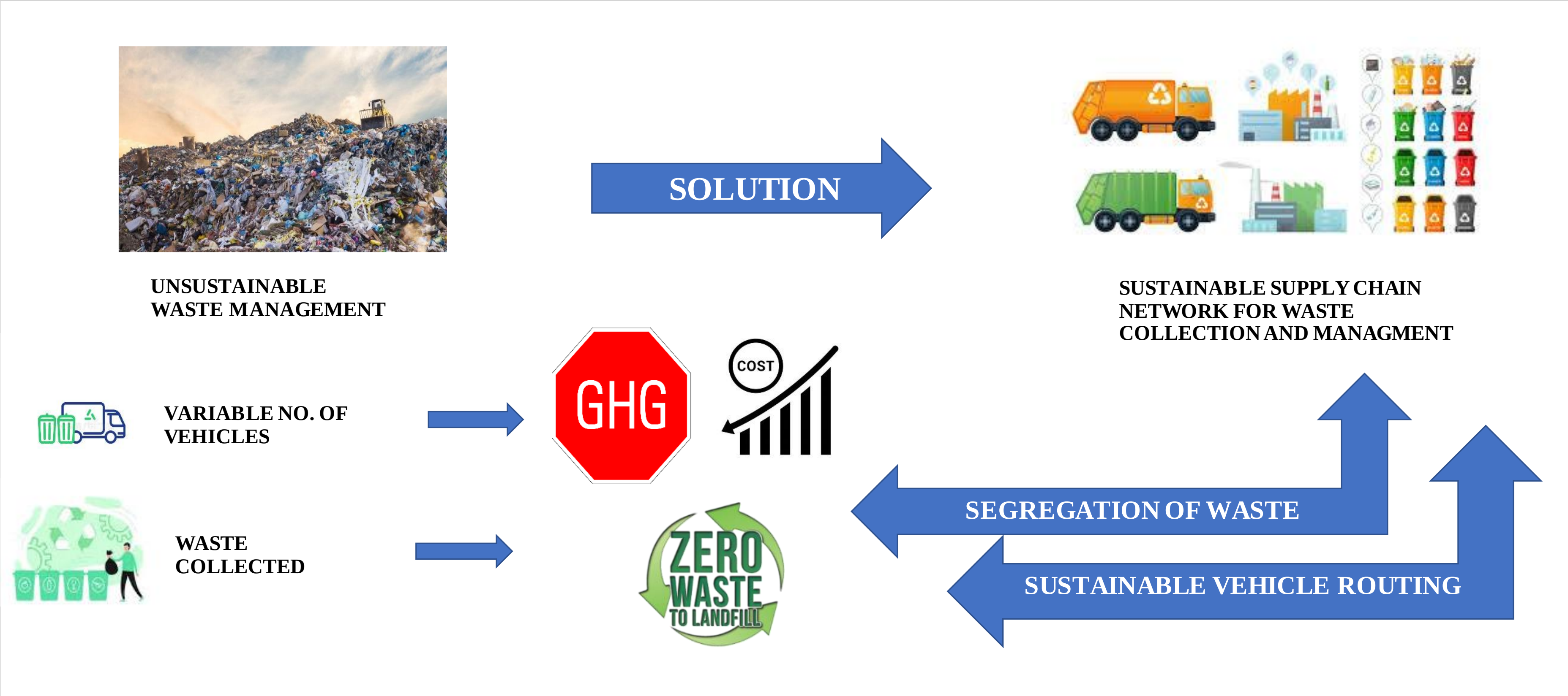

Figure 1-1:Problem Statement of Waste Management Supply Chain

1.3 Aims and Objectives

This research is based on the following aims and objectives:

- To formulate a multi objective mathematical model for designing a green supply chain network for waste management activities
- To minimize the cost of transportation of waste
- To minimize the GHG emissions in transportation of waste while considering Fuel consumption rate of vehicles
- To minimize the GHG emissions of waste activities by considering the waste segregation ratios
- To optimize the designed multi objective model using Interactive Multi Objective Fuzzy Programming
- To test the proposed model by using a case study of Saaf Suthra Sheher

1.4 Summary of the Chapter

The importance of designing a supply chain network design for waste management is highlighted based on choices made at the end of life cycle of a product. Amount of waste dumped in landfills has been increasing and causing massive pollution. This has caused air, land and water pollution which leads to water scarcity and different diseases. By considering a green supply chain network and different waste management activities, a supply chain network for waste management is to be designed. The existing literature also highlights the gaps for waste sortation and uncertain amount of waste production in. The objective of studying saving emissions needs to be considered to study the effect of different waste management activities on environment. The interactive multi objective is used for optimizing the designed network.

Chapter 2: Literature Review

In the following chapter extensive study of literature of green supply chain network design, waste management, value capturing from waste and different methodologies is done. Table at the end of the chapter shows the research gap in this study.

2.1 Literature Review

In the following chapter extensive study of literature of green supply chain network design, waste management, value capturing from waste and different methodologies is done.

2.1.1 Green Supply Chain Network Design

In this ever-growing competitive business world, supply chains are considered the backbone of every business. A fitting supply chain network design assists in linking different tiers of the supply chain and helps in increasing profit and customer satisfaction (Barzinpour and Taki, 2018). This norm of Supply Chain network design does not include environmental sustainability, which is very important ongoing research due to global warming these days. Green supply chain network design can cater to all three areas, profit maximization, customer satisfaction, and reducing the environmental effect of the whole supply chain. The past literature has excluded the environmental effect of any supply chain network, but researchers have moved towards studying the environmental consequences of supply chain networks in recent decades.

A well-designed green supply chain network can generate good results economically and environmentally. This designed network should be able to provide effective and coherent management to get effectual results of profit maximization and environmental sustainability (Barzinpour and Taki, 2018).Wang et al. (2011) studied the relationship between total cost and environmental effect by multi-objective optimization model. Elhedhli and Merrick (2012) studied the relationship between vehicle weight and CO_2 emissions with concave function. Chen et al. (2021) studied the literature regarding Green Supply Chain Management and studied the Green Supply Chain Network design under uncertainty. Boronoos et al. (2021) proposed the model to study Green Supply Chain Network design to minimize cost, CO2 emissions, and robustness costs in forward as well as reversed supply chains. This study was in the electronic industry.

A key model to study how supply chains affect the environment is supply chain network design (SCND). Environmental sustainability may not be compatible with the conventional emphasis on cost reduction and improved responsiveness. Among other relevant factors, a company's reputation is influenced by its social responsibility and environmental integrity. Additionally, a sustainable supply chain is now essential to an organization's success rather than just a luxury (Waltho et al., 2019). SCND models unavoidably become more complex when more components—such as multiple periods, inventory decisions, transportation routes, and certain operation-related practices—are added to better resemble reality. GHG emission reporting is not an exception. Even though some activities have a linear effect on emissions, others are more difficult to model, particularly when they are paired with environmental policies. We can carry forward with research and implementation of these researches to have a better environment.

2.1.2 Waste Management

Waste management is an important part of the environmental management system. In every country, its government manages every type of waste in the environment and it is the most impactful municipal service. Standard operating procedures are set for people to follow. Governments try to maintain the cost, service level, and environmental effects that change drastically (Hoornweg and Bhada-Tata, 2012). Usually, the economic status of a country impacts its solid waste management practices (Srivastava et al., 2014). The increase in population has rapidly affected the generation of waste from the start of this century. When waste is produced more than the capacity of landfills, it is released into the environment (Brahney et al., 2020). In 2012 World Bank projected that 1.3 million tons of waste is produced from urban settlements, which will be doubled by 2025 (Hoornweg and Bhada-Tata, 2012).

Waste increases environmental risks if it isn't taken care of properly. Moving towards sustainability is the utmost necessity in today's age. With the emergence of COVID-19, the challenge of waste management has increased twofold as the need for personal protective equipment plastic packaged food, and disposable items related to everyday necessity increased. Wuhan suffered a rapid increase from 40 to 50 tons of waste per day to 247 tons of waste per day(Si and Li). This sudden increase needed fast collection and recycling of waste, which was disturbed due to lockdowns causing labor shortages(Plus, 2020). This triggered an environmental crisis as current practices of waste management were not enough to deal with it (Vanapalli et al., 2021). Developing countries are suffering more than developed countries, as the latter have more secure practices than the former (Sharma et al., 2020). The traditional methods of using landfill incineration are once again replacing sustainable methods of reuse and recycling because it will increase the contamination risk of disease (Klemeš et al., 2020).

Waste has been classified in different categories for its management by different countries according to their own standard operating procedures of waste management. Adedibu (1985) stated that residential environments are where domestic solid waste is produced but municipal solid waste is generated in public parks and streets. Municipal waste does not constitute of hazardous waste and mostly consist of domestic waste i.e., paper, plastic, food waste, glass and gardening waste (Heinen, 1995). In USA this waste is considered as municipal solid waste (United States. Environmental Protection Agency. Office of Solid et al., 1994). Mexicana (1994) states that except for the hazardous and potentially hazardous waste generated in hospitals, clinics, laboratories, and research centers, along with the industrial waste that is not derived from the industrial process itself, MSW is defined by Mexican environmental legislation as being generated by municipal activities, so it does not require special techniques for control.

Various methods have been developed and researched for reducing environmental impact of waste management. Reduce, reuse and recycle are the best strategies for boosting sustainability of environment (Koul et al., 2022) but there is still lack of comprehensive approaches to manage and observe municipal solid waste, globally. Preventing waste is also a great way to reduce waste in environment and sustainability of waste (Wan et al., 2019). Life cycle assessment has widely been used for studying environmental impact of different methods used for municipal waste management in decision making and strategy planning (Zhang et al., 2021). Researchers have been working on reducing the environmental impact of waste management activities using vehicle routing problem and value capturing of waste.

2.1.3 Value capturing from waste

Shifting from linear economy to circular economy requires understanding potential of waste for value creation. The approach of circular economy is in line with sustainable environment and economic development for economic growth (Schulze, 2016). For sustainable environment more focus is on the waste management to prevent its impact on environment. Yang et al. (2017) proposed the concept of "value uncaptured". Capturing value from waste is one of the known method for sustainable environment and economic development by maximizing the resource efficiency and minimizing its overall impact on environment (Zacho et al., 2018).

A user usually discards any item when it is not needed. Cardboards, paper, and glass etc. are usually collected for recycling. Waste is usually contaminated due to not being segregated properly so it loses its value that can be generated from it. Three principals of reduce, reuse and recycle are of foremost priority to move forward towards sustainability (Das et al., 2019). Reducing waste at the source is also very crucial these days by following the waste management hierarchy (Maskuriy et al., 2020). It includes prevention, re-use, recycling and recovery before disposing off any item. The European WFD made waste management hierarchy priority before management of waste (Wuttke, 2018).

For capturing most value from waste, Zacho et al. (2018) states that circular economy ranks following methods fit for maximizing resource utilization and minimizing its effects of environment: 1) Prevention, 2) Reuse, 3) Recycling, 4) Energy recovery and 5) Disposal. Preparing waste to increase its potential for reuse and recycle is one of the most dominant activity to increase resource efficiency and minimizing environmental impact. Various methods have been researched on in various industries to prepare waste to increase its potential. In manufacturing industry, process mapping is one enhancement to maximize the material use. This method helps us to understand the use of waste that is going to produced beforehand and prepare for its reuse, recycle, incineration or proper dumping (Rybicka et al., 2015).Soini et al. (2018) states that best practice of circular economy effects all three dimensions of sustainability.

2.1.4 Vehicle Routing for Waste Management

Waste generation has sparked widespread public concern in modern countries, not only because of the quantitative increase in trash output, but also because of the rising complexity of various products and components. Trash collection is a critical function in the reverse logistics system, and how to collect waste efficiently is an area that need improvement. Waste collection is an essential part of waste management. Waste collection is defined as follows by the Organization for Economic Co-operation and Development (OECD) in 1997: "Waste collection is the collecting and transportation of waste to a location for treatment or disposal by municipal agencies or similar institutions, as well as public or private corporations, specialized enterprises, or the general government. Municipal garbage collection might be selective, that is, for a certain type of product, or undifferentiated, that is, for all types of waste at the same time"(Klimisch et al., 1997).

Waste collection problems are usually considered as arc routing problems without time windows. This case also pertains to municipal waste collection from residential areas (Kim et al., 2006). The classic objective of Vehicle routing is minimization of cost. Vehicle routing problem is the most studied combinatorial optimization problem, used to optimize routes performed by set of vehicles to serve a set of customers (Toth and Vigo, 2002). It was first applied in the field of waste collection and transportation (Beltrami and Bodin, 1974). Optimization of waste collection and transportation has been happening from previous decade by using different modeling methods and different methodologies. Using GIS (Ni-Bin Chang, 1997) studied the best route and schedule in solid waste collection system. Comparing GIS and Linear programming with existing waste collection routes Rızvanoğlu et al. (2020) suggested the best result. (Bing et al., 2014) solved vehicle routing for collection of house hold plastic waste by keeping eco-efficiency as performance indicator, using a tabu search algorithm.

Babaee Tirkolaee et al. (2019) proposed simulated annealing to optimize municipal waste collection with objectives of minimizing cost of transportation, cost of vehicles and penalty cost for deviating from time windows. By proposing modified particle swarm optimization model Hannan et al. (2018) optimized the routes for a capacitated vehicle routing problem in collection of solid waste. De Bruecker et al. (2018) used model enhancement approach for optimizing shifts and routes for minimizing cost of collecting and transporting waste, also minimizing labor cost.

Most of research has not taken time windows in account, but to increase efficiency of a work, completing the task in specified time windows is necessary. Kim et al. (2006) used Solomon’s insertion algorithm to solve vehicle routing problem with time windows to lower the number of vehicles and minimizing time in a real-world situation where workload balance is also considered. A roll-on roll-off vehicle routing problem with time windows is studied by (Juyoung Wy 2013), proposing large neighborhood search based iterative heuristics. Louati (2016) developed an effective vehicle routing model to optimize routes while minimizing cost, distance and emissions while taking time windows, multiple trips and inhomogeneous fleets in account. Nurprihatin Filscha (2020) developed waste collection vehicle routing model while taking spilt delivery, time windows, multiple trips and heterogeneous fleet into consideration.

Municipal waste and solid waste can also contain hazardous materials. Transporting these material is also a risky process. ReVelle et al. (1991) modeled a multi-objective transportation model to minimize the burden and transportation risk alongside assigning the facilities. To minimize the total cost and risk of vehicle routing of an explosive waste Zhao and Zhu (2016), designed a multi-depot vehicle routing problem. A modified lexicographic weighted Tche by cheff method is proposed to solve this bi-objective problem. Mariagrazia

Dotoli (2017) solved a waste scheduling and transportation model for hazardous waste. Taking COVID-19 situation into consideration Emre Eren (2021), originate a multi objective model using linear programming to optimize the routes along increasing safety score.

Biggest aspect of climate change is Global warming, which is caused by the increase of greenhouses gases in atmosphere. While transporting the waste GHG gasses are eliminated to the atmosphere from vehicles. To reduce the amount of GHG emissions, researchers have introduced the objective function of minimizing GHG emissions or minimizing CO_2 in their research. Jose Carlos Molina (2019) designed waste collection routes for a single landfill using eco efficiency as a performance indicator. To reduce system cost and CO_2 emission, Mohsenizadeh et al. (2020) proposed bi-objective optimization model for municipal solid waste management. Hailin Wu (2020) constructed a priority considered green vehicle routing problem to minimize distance of routes and emission of greenhouse gasses. Chance constrained low carbon vehicle routing problem is modeled in (Wu et al., 2020a).

Vehicle Routing is a NP-hard problem. Using heuristic to solve it, is common. Benjamin and Beasley (2010) presented two metaheuristics algorithms, tabu search and variable neighborhood search. Simulated annealing is used by (Babaee Tirkolaee et al., 2019) to solve the problem. Hannan et al. (2018) has used particle swarm optimization (PSO) to solve the VRP problem. Hailin Wu (2020) has used local search hybrid algorithm (LSHA), particle swarm optimization (PSO) and simulated annealing to solve the problem defined. There are many other methods including exact method, metaheuristic, real time solution and simulation and classic heuristic (Braekers et al., 2016).

In conclusion there are a lot of research of algorithms to solve waste collection problem. Most of these algorithms are single algorithms. Single algorithms have less efficiency than hybrid algorithms. Research on hybrid algorithms is a recent event. They increase the efficiency of the result.

2.1.5 Interactive Multi Objective Fuzzy Programming

The distribution planning decision (DPD) entails optimizing the transportation plan for assigning commodities and/or services from a collection of sources to various destinations throughout a supply chain. The DPD problem is essentially a subset of the regular linear programming (LP) issue that may be solved using the simplex approach. Furthermore, several particular solution methods, such as the stepping stone approach and the modified distribution (MODI) method, make DPD problems much easier to solve than the LP method (Kumar et al., 2019). When using any of the standard LP or current solution methods to address DPD problems, the objective function and model inputs are generally expected to be deterministic/crisp. Most real-world DPD situations have imprecise/fuzzy environment coefficients and model parameters, such as available supply, predicted demand, and corresponding cost/time coefficients, because some information is inadequate and/or unavailable across the planning horizon. Traditional deterministic LP and special solution algorithms, obviously, cannot tackle all imprecise/fuzzy DPD programming situations.

The investigation demonstrated the existence of an analogous ordinary LP form for the fuzzy decision-making paradigm presented by (Chakraborty et al., 2023).Zimmermann's fuzzy linear programming (FLP) has now evolved into a number of fuzzy optimization algorithms for addressing DPD problems in fuzzy settings. Using crisp cost coefficients and fuzzy supply and demand values, Haque et al. (2022) established an FLP model for handling transportation challenges. Furthermore, Sakthivel et al. (2022) established the concept of optimal transportation issue solution using fuzzy coefficients expressed as L-R fuzzy numbers, and devised an algorithm for achieving the optimal solution. Furthermore, Nagar et al. (2019) developed an algorithm for solving the integer fuzzy transportation issue with fuzzy supply and demand volumes by maximizing the combined satisfaction of the fuzzy goal and constraints. Anuradha et al. (2019) devised a parametric method for calculating an auxiliary parametric solid transportation problem (PSTP) connected to the main problem. To discover a decent fuzzy solution to the PSTP, an evolutionary approach was used. Related research on the application of fuzzy programming methods to address fuzzy DPD problems include (Singh and Singh, 2022), (Kane et al., 2021) and (Gupta and Arora, 2021).

In the case of practical TPD challenges, the decision maker (DM) typically deals with competing objectives that regulate the utilization of limited resources inside organizations. The DM, in particular, must simultaneously optimize these competing aims within a context of hazy aspiration levels. Minimizing total distribution/transportation costs, number of rejected items, and delivery time/distance, for example, and/or maximizing total profits, relative safety, and customer service level (Abd El-Wahed, 2001), (Clímaco et al., 1993, Isermann, 1979) and (Li and Lai, 2000). Zimmermann (1978) was the first to apply his FLP approach to a multi-objective linear programming (MOLP) issue using linear membership functions to describe fuzzy objectives in 1978. The DM was considered to have fuzzy objectives for each of the objective functions in this MOLP problem, such as "the objective function should be substantially less than and/or equal to some values." (Chen and Tsai, 2001), (Dubois et al., 1996), (Hannan, 1981), (Kuwano, 1996), (Leberling, 1981), (Luhandjula, 1982), and (Sakawa and Yano, 1988) have all published research on fuzzy goals programming (FGP).

Furthermore, academics have created a number of FGP algorithms for solving multi-objective DPD problems. Bit et al. (1993) provided an additive fuzzy programming model for the transportation planning problem that took into account weights and priorities for all non-equivalent objectives. Li and Lai (2000) presented a fuzzy compromise programming method for obtaining a non-dominated compromise solution for multi-objective transportation decision problems using the marginal evaluation for individual objectives and the global evaluation for all objective functions. Furthermore, Abd El-Wahed (2001) developed a fuzzy programming approach for determining the optimal compromise solution of a multi-objective DPD problem by assessing the degree of similarity of the compromise solution to the ideal solution using a family of distance functions. (Das et al., 1999), (Hussein, 1998), and (Verma et al., 1997) conducted studies on solving DPD issues with fuzzy multiple objectives.

2.2 Literature Contribution Table

Table 1 shows the literature contribution table for the existing literature of supply chain network design for waste management factors like waste segregation, emissions from waste, environmental objectives and methodology.

	Segregation of Waste		No. Of vehicles		Objective Function					
Author Year	**At source**	**At Sortation Centers**	**Decision Variable**	**Parameter**	**% of Waste Segregation**	**GHG emission of Vehicles**	**Total Cost of Transportation**	**Total Time of the Process**	**Impact of Segregation of waste**	**Methodology**
(Wu et al., 2020a)				✓		✓	✓			PSOSA
(Wu et al., 2020b)				✓		✓	✓			Particle Swarm Optimization
(Olapiriyakul et al., 2019)				✓		✓	✓			Branch and Bound Method
(Babaee Tirkolaee et al., 2019)				✓		✓	✓	✓		Simulated Annealing
(Babaee Tirkolaee et al., 2019)				✓		✓	✓			Fuzzy Optimization
(Rathore et al., 2022)				✓		✓		✓		Particle Swarm Optimization
(Aliahmadi et al., 2021)				✓			✓	✓		Augmented Ɛ Constraint Method
(Eghbali et al., 2022)	✓			✓		✓			✓	LP Metric Method
Proposed Research		✓	✓		✓	✓	✓		✓	Interactive Multi Objective Fuzzy Programming

Table 1-1:Literature contribution Table for the existing literature for Supply Chain Network Design for Waste Management

2.3 Research Gap

An in-depth analysis has been performed of the existing literature regarding the green supply chain network design of waste management, waste segregation, waste production and emissions from waste and transportation. The literature review shows the need for designing a green supply chain network design has potential for saving emissions from waste and minimizing GHG of transportation process. The minimization of GHG function includes vehicle fuel consumption rates and amount of waste a vehicle carries. The minimization of cost of transportation function includes cost of vehicle selection and transportation cost between each node. The consideration of factors such as uncertain waste production and uncertain emissions based on waste also address the research gap. The consideration of saving emission from waste management activities using waste segregation is major contribution to existing literature.

2.3.1 Proposed Framework

To fill the research gaps identified by conducting literature review, a multi objective model is proposed for waste management that can serve as a decision support tool for a waste management supply chain. The proposed model is based on the objectives of cost minimization of transportation, GHG minimization of transportation and maximizing saving emissions from waste management activities. The proposed framework for waste management is also optimized for a waste management company using the Interactive multi-objective fuzzy programming.

2.4 Summary of the chapter

In this chapter, an in-depth analysis of existing literature review is performed which starts with basic understanding of green supply chain network design and how it is achieved. Waste management, value capturing from waste and vehicle routing for waste management is also studied. The three objectives minimizing cost of transportation, minimizing GHG emissions and maximizing emission saving is discussed as well as the discussion on Interactive multi objective fuzzy programming is also studied. After in depth analysis a green supply chain network design for random waste generation is proposed. The network is designed based on the objectives of cost minimization of transportation, minimization of GHG emissions due to transportation and maximizing saving of emission from waste and is then optimized using Interactive multi-objective fuzzy programming technique.

Chapter 3: Development of Mathematical Model

Following chapter is about development of the mathematical model after the description of the problem. The detailed description of the mathematical model is done and problem is explained.

3.1 Problem Description

A mathematical model is proposed for designing a supply chain network for waste management under the consideration of multiple objectives. The mathematical model is solved using the three objectives of minimizing cost of transportation of waste, minimizing GHG emissions of the transportation process and minimizing GHG emission from waste by taking waste segregation ratios for respective waste management activities. The most important goal of this research is to propose a supply chain network for waste management which will help in taking decisions based on (1) segregation of waste, (2) Fuel consumption rate of vehicles and (3) number of vehicles required for the whole process of transferring the waste. Figure 3.1 shows generic waste management supply chain.

Figure 3-1:Generic Supply Chain of Waste Management

The multi-objective model proposed for designing a supply chain network for a sustainable supply chain for waste is multi period model for waste collection and segregation. The model proposed in this research includes multi tiers, which include waste collection sites, vehicle depots, sortation centers, recycling centers, incineration centers and landfill. Figure 2 shows the generic structure of waste management supply chain. A waste management supply chain starts from vehicle depot sites from where vehicles move towards waste collection sites. Waste collected is moved toward sortation centers where waste is sorted in different categories and then waste is moved towards the respected activity associated with the waste type. These activities include recycling of waste, incineration of different types of waste and moving the remaining waste to landfill.

The supply chain considered in this research has no consideration for vehicles or road conditions, which usually effects the fuel consumption rate of vehicles and in result effects the cost and GHG emissions of vehicle. Waste segregation ratios has been defined to calculate the GHG emissions saved by waste segregation. For analysis purpose, a constant amount of GHG from waste during different activities is considered. Due to random generation of waste number of vehicles moving towards waste collection points is considered variable.

3.2 Model Assumptions

- Waste generated at collection points is random and known.
- Waste collection vehicles are homogenous.
- Empty vehicles move from vehicle depot i to waste collection sites j.
- Vehicles will move with load capacity based on volume of waste from waste sites j to sortation center k.
- Vehicle can only visit one site at a time.
- Constant GHG emissions are considered for type of waste in each activity to calculate the GHG emissions.

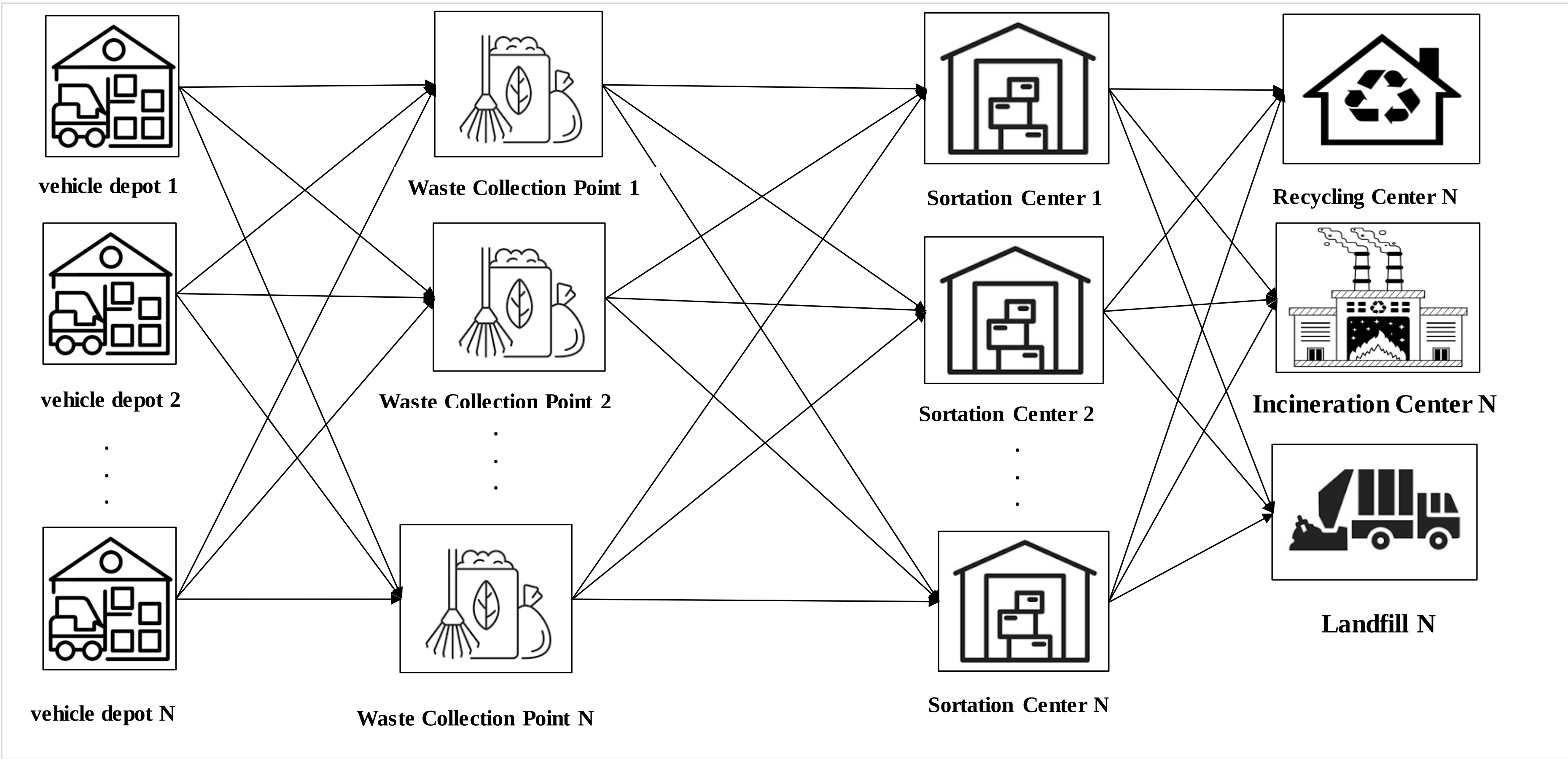

Figure 3-2:Network structure of a Waste Management Supply Chain

3.3 Notations

Table 3-1: Sets for the mathematical model

i	Vehicle Depot	$i = 1, 2, 3, ..., I$
j	Waste Collection point	$j = 1, 2, 3, ..., J$
k	Sortation center	$k = 1, 2, 3, ..., K$
l	Recycling center	$l = 1, 2, 3, ..., L$
m	Incineration center	$m = 1, 2, 3, ..., M$
n	Landfill	$n = 1, 2, 3, ..., N$
t	Time period	$t = 1, 2, 3, ..., T$

Table 3-2: Decision Variables for the mathematical model

Q_{kl}^{t}	Quantity of waste at moving from sortation center k to recycling center l in time period t (kg)
Q_{km}^{t}	Quantity of waste at moving from sortation center k to incineration center m in time period t (kg)
Q_{kn}^{t}	Quantity of waste at moving from sortation center k to landfill n in time period t (kg)
X_{ij}^{t}	No of vehicles moving from vehicle depots i to wastes sites j in time period t
X_{jk}^{t}	No of vehicles moving from waste sites j to sortation centers k in time period t
X_{kl}^{t}	No of vehicles moving from sortation center k to recycling center l in time period t
X_{km}^{t}	No of vehicles moving from sortation center k to incineration centers m in time period t

X_{kn}^{t}	No of vehicles moving from sortation center k to landfill n in time period t
Y_i	If vehicle v is moved from vehicle depots then 1, otherwise 0

Table 3-3: Parameters for mathematical model

d_{ij}	Distance between nodes i and j, where $i = 1,2,3...,I$ and $j = 1,2,3,...,J$ (km)
d_{jk}	Distance between nodes j and k, where $j = 1,2,3,...,J$ and $k = 1,2,3,...,K$ (km)
d_{kl}	Distance between node k and l, where $k = 1,2,3,...,K$ and $l = 1,2,3,...,L$ (km)
d_{km}	Distance between node k and m, where $k = 1,2,3,...,K$ and $m = 1,2,3,...,M$ (km)
d_{kn}	Distance between node k and n, where $k = 1,2,3,...,K$ and $n = 1,2,3,...,N$ (km)
F	Fixed cost of vehicle selection (PKR)
Q_j^t	Amount of waste discharged at node j in time period t, where $j = 1,2,3,...,J$ (kg)
C_v	Maximum capacity of vehicle, where $v = 1,2,3,...V$ (kg)
C_k	Maximum capacity of sortation center node k, where $k = 1,2,3,...,K$ (kg)
C_l	Maximum capacity of Recycling center at node l, where $l = 1,2,3,...,L$ (kg)
C_m	Maximum capacity of incineration center at node m, where $m = 1,2,3,...,M$ (kg)
C_n	Maximum capacity of Landfill at node n, where $n = 1,2,3,...,N$ (kg)

ℓ	Emission coefficient of Vehicles $(kgCO_2 / L)$
α	Avoided emission due to secondary material usage/ recycle at node f, where $f = 1, 2, 3, ...F$ (kg)
β	Avoided emissions due to incineration at node f, where $f = 1, 2, 3, ...F$ (kg)
λ	Emission due to landfilling at node f, where $f = 1, 2, 3, ...F$ (kg)
a	Fuel consumption rate per unit distance with empty vehicle (L / km)
b	Fuel consumption rate per unit distance at full load (L / km)
φ	Percentage of segregated waste that should move towards Recycling center
ε	Percentage of segregated waste that should move towards Incineration Center
ω	Percentage of segregated waste that should move towards Landfill
V	Number of vehicles available

3.4 Mathematical Model

The following chapter consists of mathematical model in this study. All objectives are explained and discussed in detail.

3.4.1 Objective 1: Minimize cost of Transportation of waste

To find the cost incurred in transportation process of waste collection and transportation total distance traveled by vehicles in between all nodes is multiply by the fuel consumption rates of vehicles and fuel price. Cost of vehicle selection is also added.

Equation (3.1) shows the initial equation for cost minimization of transportation of waste management supply chain. It includes two parts i.e., (1) Cost of selection of vehicle and (2) cost of transportation of waste between all nodes. Total nodes in the problem statement are four.

$$MinTC = \left(\sum_{i=1}^{I} \sum_{j=1}^{J} X_{ij}^{t} \times a \times p \times d_{ij} \right) + (\sum_{i=1}^{I} \sum_{j=1}^{J} Y_i \times F) + \left(\sum_{j=1}^{J} \sum_{k=1}^{K} X_{jk}^{t} \times b \times p \times d_{jk} \right)$$

$$+ \left(\sum_{k=1}^{K} \sum_{l=1}^{L} X_{kl}^{t} \times b \times p \times d_{kl} \right) + \left(\sum_{k=1}^{K} \sum_{m=1}^{M} X_{km}^{t} \times b \times p \times d_{km} \right) + \left(\sum_{k=1}^{K} \sum_{n=1}^{N} X_{kn}^{t} \times b \times p \times d_{kn} \right) \quad (3.1)$$

Objective function $(MinTC)$ i.e., equation (3.1) explain the cost of transportation of waste from vehicle depots i to waste management facilities i.e., recycling centers, incineration centers and landfill. This process also includes waste sites j and sortation centers k. Full vehicle load as volume capacity is assumed in transportation of waste. The cost of petrol p is included. Fuel consumption rates at empty vehicle and full load capacity are included as well.

i) Cost of transportation between vehicle depot and waste collection centers

The cost incurred when vehicles move from vehicle depots i to waste sites j.It include fuel consumption rate of vehicle at carried load b, price of fuel p, distance between nodes d_{jk} and number of vehicles moving from vehicle depots to waste sites X_{ij}^{t}. Number of vehicles moving depends on amount of waste collected at wastes sites j.Equation (3.2) shows the cost of transportation between vehicle depot i and waste collection centers j.

$$c_{ij} = \left(\sum_{i=1}^{I} \sum_{j=1}^{J} X_{ij}^{t} \times a \times p \times d_{ij} \right) \quad (3.2)$$

ii) Cost of transportation between waste collection centers and sortation center

The cost incurred when vehicles moves from waste sites j to sortation center k after collecting waste include fuel consumption rate of vehicle at empty load a, price of fuel p, distance between nodes d_{ij} and number of vehicles moving from waste sites to sortation center X_{jk}^{t}. Equation (3.3) shows the cost of transportation between and waste sites j to sortation center k.

$$c_{jk} = \left(\sum_{j=1}^{J} \sum_{k=1}^{K} X_{jk}^{t} \times b \times p \times d_{jk} \right) \quad (3.3)$$

3.4.1.3 Cost of vehicle selection

The fixed cost of vehicle selection is included by fixed cost of vehicle selection F multiplied by binary variable of vehicle selection Y_i. Equation (3.4) shows cost of vehicle selection at node i.

$$c_i^v = \sum_{i=1}^{I} Y_i \times F \tag{3.4}$$

iii) Cost of transportation between sortation center and recycling center

The cost incurred when vehicles moves from sortation center k to recycling center l after sortation of waste include fuel consumption rate of vehicle at load b, price of fuel p, distance between nodes d_{kl} and number of vehicles moving from sortation center to recycling center X_{kl}^t. Equation (3.5) shows the cost of transportation between sortation centers k to recycling centers l.

$$c_{kl} = \left(\sum_{k=1}^{K} \sum_{L=1}^{L} X_{kl}^t \times b \times p \times d_{kl} \right) \tag{3.5}$$

iv) Cost of transportation between sortation center and incineration center

The cost incurred when vehicles moves from sortation center k to incineration center m after sortation of waste. It includes fuel consumption rate of vehicle at load b, price of fuel p, distance between nodes d_{km} and number of vehicles moving from sortation center to incineration center X_{km}^t. Equation (3.6) shows the cost of transportation between sortation center k to incineration center m.

$$c_{km} = \left(\sum_{k=1}^{K} \sum_{m=1}^{M} X_{km}^t \times b \times p \times d_{km} \right) \tag{3.6}$$

v) Cost of transportation between sortation center and incineration center

The cost incurred when vehicles moves from sortation center k to landfill n after sortation of waste. It includes fuel consumption rate of vehicle at load b, price of fuel p, distance between nodes d_{kn} and number of vehicles moving from sortation center to landfill X^t_{kn}. Equation (3.7) shows the cost of transportation between sortation center k to landfill n.

$$c_{kn} = \left(\sum_{k=1}^{K} \sum_{n=1}^{N} X^t_{kn} \times b \times p \times d_{kn} \right) \tag{3.7}$$

3.4.2 Objective 2: Minimize the GHG emission from the vehicle used in the transportation process

A report published by Ministry of Land, Infrastructure, Transport and tourism of Japan showed relationship between distance traveled per Liter by vehicle and it's weight as shown by following figure, stating that the distance traveled per volume unit of fuel used is strongly correlated to the vehicle's gross weight"(Xiao et al., 2012).

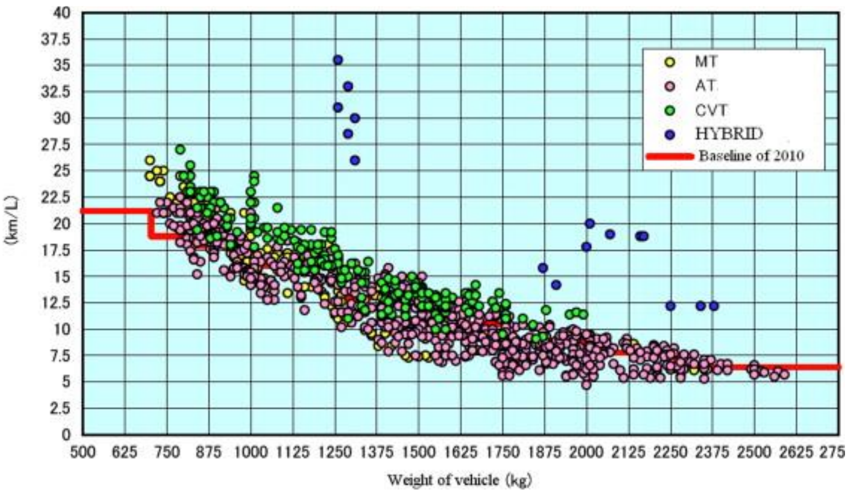

Figure 3-3:Data on Vehicles' running Distance per liter to their weights

Following figure 5 is derived from figure 4 and shows FCR dependent on weight of vehicle. X-coordinate shows the weight of vehicle in kg and Y-coordinate shows the Fuel consumption rate in L/Km.

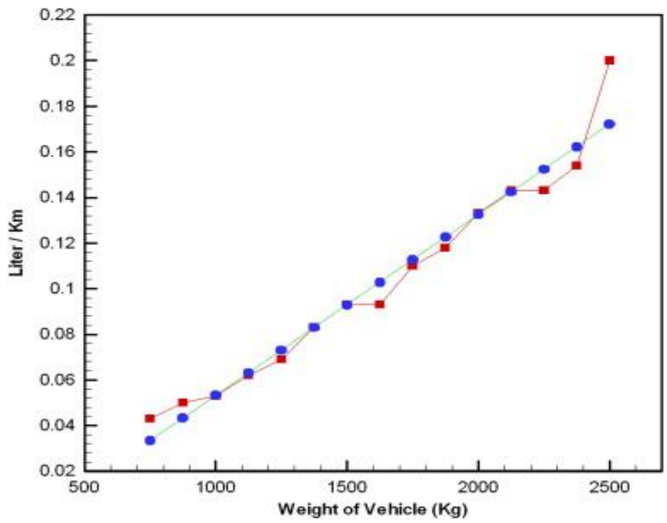

Figure 3-4:FCR Vs Combination of weight of vehicle and Load on it

For calculating GHG emissions first we calculated FCR (Fuel Consumption Rate) using linear regression. R^2 is a statistical measure with a value between 0 and 1 showing how well a regression line approximates real data points. With higher value of R-squared generally implying better predicted results and having R^2=0.985 shows that there is linear relationship between FCR (Fuel Consumption Rate) and Vehicle's Gross Weight.

By using, following linear regression equation (1) we will calculate the FCR (Fuel Consumption Rate) of a vehicle.

$$y = ax + b \tag{1}$$

In this equation y represents the dependent variable as x represents the independent variable, a represents the slope and b represents intercept. Without losing generalization, we divide vehicle's gross weight in two parts i.e., Q_0 and Q_L, that represents vehicle's weight with no load and carried load respectively. By putting these values, we get the equation (2) for FCR (Fuel Consumption Rate) of carried load.

$$\rho(Q_L) = a(Q_L + Q_0) + b \tag{2}$$

By defining the maximum weight, the vehicle can carry often referred as maximum capacity of vehicle C_v, full load FCR (Fuel Consumption Rate) as ρ^* and no load FCR (Fuel Consumption Rate) as ρ_0, we get equations (3) and (4) as follows.

$$\rho_0 = aQ_0 + b \tag{3}$$

$$\rho^* = a(Q_0 + C_v) + b \tag{4}$$

By solving equations (3) and (4) we will get the value for slope a, that is as follows in equation (5).

$$a = \frac{\rho^{*} - \rho_0}{C_v} \tag{5}$$

Now putting this value of a in equation (2), we will get the FCR (Fuel Consumption Rate) for Q_L. This is defined as shown in following equation (6).

$$\rho(Q_L) = \rho_0 + \frac{\rho^{*} - \rho_0}{C_v} Q_L \tag{6}$$

In this model, we have used this equation to calculate the GHG (Green House Gas) emissions of transportation as shown in the following equation of mathematical model (3.8).

$$MinGHG = e\left[\begin{array}{l} \left(\sum_{i=1}^{I}\sum_{j=1}^{J}(X_{ij}^{t}\times d_{ij})\times a + \frac{(b-a)}{C_v}\times Q_L\right) + \left(\sum_{j=1}^{J}\sum_{k=1}^{K}(X_{jk}^{t}\times d_{jk})\times a + \frac{(b-a)}{C_v}\times Q_L\right) + \\ \left(\sum_{k=1}^{K}\sum_{l=1}^{L}(X_{kl}^{t}\times d_{kl})\times a + \frac{(b-a)}{C_v}\times Q_L\right) + \left(\sum_{k=1}^{K}\sum_{m=1}^{M}(X_{km}^{t}\times d_{km})\times a + \frac{(b-a)}{C_v}\times Q_L\right) + \\ \left(\sum_{k=1}^{K}\sum_{n=1}^{N}(X_{kn}^{t}\times d_{kn})\times a + \frac{(b-a)}{C_v}\times Q_L\right) \end{array}\right] \tag{3.8}$$

Objective Function $(MinGHG)$ i.e., equation (3.8) explain GHG emissions from vehicles in transportation process of waste. Quantity of waste moving towards at waste sites j, sortation centers k and waste management facilities l,m and n i.e., recycling center, incineration center and landfill, is direct related to GHG emissions. Equation (3.8) shows the relationship between distance (d), fuel consumption rate of vehicles at full load (b) and no-load (a), maximum load carried by vehicle Q_L, maximum load a vehicle can carry (C_v) and no. of vehicle moving from one node to other (X). Emission coefficient e is multiplied to get the value of GHG in Kg.

i) GHG emissions of vehicle from Vehicle Depots i to Waste Sites j

The GHG emissions emitted from vehicles during transportation process when vehicles move from vehicle depot i to waste sites j is calculated by equation. The equation (3.9) take number of vehicles (X_{ij}^{t}), distance between nodes (d_{ij}), fuel consumption rate of vehicles at full load (b) and no-load (a), maximum load carried by vehicle Q_L and maximum load a vehicle can carry (C_v).

$$G_{ij} = \left(\sum_{i=1}^{I} \sum_{j=1}^{J} (X_{ij}^{t} \times d_{ij}) \times a + \frac{(b-a)}{C_v} \times Q_L \right) \quad (3.9)$$

ii) GHG emissions of vehicle from Waste Sites j to Sortation Center k

The GHG emissions emitted from vehicles during transportation process when vehicles move from waste sites j to sortation center k is calculated by equation. The equation (3.10) take number of vehicles (X_{jk}^{t}), distance between nodes (d_{jk}), fuel consumption rate of vehicles at full load (b) and no-load (a), maximum load carried by vehicle Q_L and maximum load a vehicle can carry (C_v).

$$G_{jk} = \left(\sum_{j=1}^{J} \sum_{k=1}^{K} (X_{jk}^{t} \times d_{jk}) \times a + \frac{(b-a)}{C_v} \times Q_L \right) \quad (3.10)$$

iii) GHG emissions of vehicle from Sortation Center k to recycling center l

The GHG emissions emitted from vehicles during transportation process when vehicles move from sortation center k to recycling center l is calculated by equation. The equation (3.11) take number of vehicles (X_{kl}^{t}), distance between nodes (d_{kl}), fuel consumption rate of vehicles at full load (b) and no-load (a), maximum load carried by vehicle Q_L and maximum load a vehicle can carry (C_v).

$$G_{kl} = \left(\sum_{k=1}^{K} \sum_{l=1}^{L} (X_{kl}^{t} \times d_{kl}) \times a + \frac{(b-a)}{C_v} \times Q_L \right) \quad (3.11)$$

iv) GHG emissions of vehicle from Sortation Center k to incineration center m

The GHG emissions emitted from vehicles during transportation process when vehicles move from sortation center k to incineration center m is calculated by equation. The equation (3.12) take number of vehicles (X_{kl}^{t}), distance between nodes (d_{kl}), fuel consumption rate of vehicles at full load (b) and no-load (a), maximum load carried by vehicle Q_L and maximum load a vehicle can carry (C_v).

$$G_{km} = \left(\sum_{k=1}^{K} \sum_{m=1}^{M} (X_{km}^{t} \times d_{km}) \times a + \frac{(b-a)}{C_v} \times Q_L \right) \tag{3.12}$$

v) GHG emissions of vehicle from Sortation Center k to landfill n

The GHG emissions emitted from vehicles during transportation process when vehicles move from sortation center k to landfill n is calculated by equation. The equation (3.13) take number of vehicles (X_{kl}^{t}), distance between nodes (d_{kl}), fuel consumption rate of vehicles at full load (b) and no-load (a), maximum load carried by vehicle Q_L and maximum load a vehicle can carry (C_v).

$$G_{kn} = \left(\sum_{k=1}^{K} \sum_{n=1}^{N} (X_{kn}^{t} \times d_{kn}) \times a + \frac{(b-a)}{C_v} \times Q_L \right) \tag{3.13}$$

3.4.3 Objective 3: Maximize saving Emissions from waste management activities

$$MaxEI = (\sum_{k=1}^{K} \sum_{l=1}^{L} \alpha \times Q_{kl}^{t}) - (\sum_{k=1}^{K} \sum_{m=1}^{M} \beta \times Q_{km}^{t}) - (\sum_{k=1}^{K} \sum_{n=1}^{N} \lambda \times Q_{kn}^{t}) \tag{3.14}$$

Objective Function $(MinEI)$ i.e., equation (3.14) calculates the effect of waste management activities on environment. CO_2 emissions saved by recycling and incineration can minimize the effect of emissions from landfills. Segregation of waste is most important factor in this objective. Communities can make standard operating procedure for waste segregation to minimize the effect of waste on environment. This objective function only calculates effect in terms of atmosphere but significant decrease in land pollution can also be seen by proper waste management activities.

3.4.4 Constraints for Mathematical Model

This section explains the constraint of the mathematical model and their conditions. All the constraints are discussed in detail.

3.4.4.1 Demand Constraint

i) Required Number of vehicles to move towards waste sites j

$$\sum_{j=1}^{J} X_{ij}^{t} \geq \frac{Q_j^t}{C_v} \qquad \forall i, \forall t \tag{3.15}$$

Equation (3.15) calculates required number of vehicles at waste sites j by dividing known value of waste collected by capacity of a vehicle. Quantity of waste collected at j very in every time period.

ii) Required Number of vehicles to move towards Sortation Center k

$$\sum_{k=1}^{K} X_{jk}^{t} \geq \frac{Q_{jk}^t}{C_v} \qquad \forall j, \forall t \tag{3.16}$$

Equation (3.16) calculates number of vehicles moving from wastes sites j to sortation center k by dividing Waste collected by vehicles capacity. Number of vehicles moving from vehicle depots i to waste sites j will all move towards sortation center k .

iii) Required Number of vehicles to move towards Recycling Center l

Equation (3.17) calculates required number of vehicles at recycling facility l by dividing quantity of waste moving by capacity of a vehicle.

$$\sum_{l=1}^{L} X_{kl}^{t} \geq \frac{Q_{kl}^t}{C_v} \qquad \forall k, \forall t \tag{3.17}$$

iv) Required Number of vehicles to move towards Incineration Center m

Equation (3.18) calculates required number of vehicles moving towards incineration center m by dividing quantity of waste segregated for incineration center by capacity of a vehicle.

$$\sum_{m=1}^{M} X_{km}^{t} \geq \frac{Q_{km}^t}{C_v} \qquad \forall k, \forall t \tag{3.18}$$

v) Required Number of vehicles to move towards Incineration Center n

Equation (3.19) calculates required number of vehicles moving towards landfill n by dividing quantity of waste segregated for landfill by capacity of a vehicle.

$$\sum_{n=1}^{N} X_{kn}^{t} \geq \frac{Q_{kn}^{t}}{C_v} \quad \forall k, \forall t \tag{3.19}$$

3.4.4.2 Supply Constraint of vehicles

Equation (3.20) calculates the number of vehicles available at vehicle depots i. Number of vehicles available at node i should be greater than or equal to vehicles required at waste sites j.

$$\sum_{j=1}^{J} X_{ij}^{t} \geq Y_i \times V \quad \forall i, \forall t \tag{3.20}$$

3.4.4.3 Transshipment Constraints of waste

Equation (3.21) shows that full Quantity of waste (Q_j^t) moving from node j (waste sites) should be transferred to node k (sortation centers).

$$Q_j^t = \sum_{k=1}^{K} Q_{jk}^{t} \quad \forall j, \forall t \tag{3.21}$$

Equation (3.22) shows that quantity moved to waste management facilities i.e., recycling centers (Q_{kl}^t), incineration centers (Q_{km}^t) and landfill (Q_{kn}^t) should be equal or less than to the quantity of waste sorted at node k (Q_{jk}^t).

$$\sum_{j=1}^{J} Q_{jk}^{t} = \sum_{l=1}^{L} Q_{kl}^{t} + \sum_{m=1}^{M} Q_{km}^{t} + \sum_{n=1}^{N} Q_{kn}^{t} \quad \forall k, \forall t \tag{3.22}$$

3.4.4.4 Percentage of Waste Sortation

Equations (3.23), (3.24) and (3.25) calculates the quantity of waste distributed after sortation. φ shows the percentage of waste moving towards recycling center. After sortation of waste maximum amount of waste should be moved to recycling. Recycling the waste save emissions that will otherwise go into environment and will cause air pollution as well as land pollution. Incineration of waste is also done for different materials such as paper and glass. Landfilling should only be used for the materials which cannot be recycled and which will cause more harm if incinerated and emit harmful gasses.

$$\sum_{l=1}^{L} Q_{kl}^{t} \geq \sum_{j=1}^{J} Q_{jk}^{t} \times \varphi \qquad \forall k, \forall t \tag{3.23}$$

$$\sum_{m=1}^{M} Q_{km}^{t} \leq \sum_{j=1}^{J} Q_{jk}^{t} \times \varepsilon \qquad \forall k, \forall t \tag{3.24}$$

$$\sum_{n=1}^{N} Q_{kn}^{t} \geq \sum_{j=1}^{J} Q_{jk}^{t} \times \omega \qquad \forall k, \forall t \tag{3.25}$$

3.4.4.5 Capacity of sortation center

Equation (3.26) describes that quantity of waste arriving at sortation center at node k (Q_{jk}^{t}) should be less than or equal to capacity of sortation center (C_k) at node k.

$$\sum_{j=1}^{J} Q_{jk}^{t} \leq C_k \qquad \forall k, \forall t \tag{3.26}$$

3.4.4.6 Capacity constraint of facilities

Equations (3.27), (3.28) and (3.29) define the capacity constraints of waste management facilities at nodes l, m and n. All waste supplied from sortation centers to different facilities i.e., Q_{kl}^{t}, Q_{km}^{t} and Q_{kn}^{t} should be less than the capacity of the facilities i.e., capacity of recycling center C_l, capacity of incineration center C_m and capacity of landfill C_n.

$$\sum_{k=1}^{K} Q_{kl}^{t} \leq C_l \quad \forall l, \forall t \tag{3.27}$$

$$\sum_{k=1}^{K} Q_{km}^{t} \leq C_m \quad \forall m, \forall t \tag{3.28}$$

$$\sum_{k=1}^{K} Q_{kn}^{t} \leq C_n \quad \forall n, \forall t \tag{3.29}$$

3.4.4.7 Types of variables

$$Y_i \in \{0,1\} \tag{3.30}$$

$$X_{ij}^t, X_{jk}^t, X_{kl}^t, X_{km}^t, X_{kn}^t, Q_{jk}^t, Q_{kl}^t, Q_{km}^t, Q_{kn}^t \geq 0 \tag{3.31}$$

Equation (3.30) shows that Y_i is a binary variable. It represents selection of vehicle. Its value should be either 0 or 1. Equation (3.31) shows that all other variables should be non-negative.

3.5 Summary of the chapter

In this chapter a multi-objective mathematical model is designed for a green supply chain network design for waste management. The proposed mathematical model takes into consideration (1) waste collected at waste sites, (2) capacity of vehicles, (3) capacity of waste management facilities, (4) waste segregation ratios and (5) emission from waste. The mathematical model has three objective functions, i.e., (1) Minimization of cost of transportation, (2) Minimization of GHG emissions from transportation and (3) Maximizing Emission saving from waste management activities. The objective function minimization of transportation cost constitutes of (1) cost of vehicle selection and (2) cost of transportation of waste to all nodes. The second objective minimization of GHG emission due to transportation constitutes of vehicle fuel consumption rates and weight of waste vehicle carries. The third objective of maximizing saving emissions from waste management activities constitutes of three parts i.e., (1) emissions saved due to recycling center, (2) emissions due to incineration and (3) emissions that will occur due to landfill. In this objective segregation of waste is also an important part. Recycling more waste will save more emissions. All three objectives are solved under demand constraint of vehicles, supply constraint of waste, capacity constraint of vehicles as well as facilities and segregation constraint of waste.

Chapter 4: Case Study

According to recent estimates, Pakistan generates 30 million metric tons of municipal solid waste (MSW) per year. Furthermore, fast population expansion, urbanization, and economic development are expected to result in a significant increase in the coming years. Around half of the waste created is collected. However, the rate varies by location, ranging from 80% in larger cities to 0% in most rural areas (Mihai and Grozavu 2019). In terms of trash disposal, managed landfill sites are nearly non-existent. Typically, urban waste is left uncollected or dumped on open land. Pakistan urgently requires a waste road map for policymakers in order to achieve progress towards better health for its people, minimize contamination of land and water sources, more efficiently measure greenhouse gas (GHG) emissions, and improve aesthetics.

The country's present municipal waste management system is far from ideal. Municipalities offer the majority of the services, which are limited to partial collection and open dumping or burning. Here is a snapshot to serve as a baseline for the development of the road map and a more sustainable system. There has been no accurate national study to quantify the total amount of garbage generated in the country, although estimates collected from various sources are provided in figure 4-1.

	Waste Quantity				
	Generated	**Collected**	**Transported**	**Treated**	**Disposed of**
Settlement Area	Daily (kg per capita per day)		Yearly (million metric tons per year)		(% of waste generated)
Large Cities (11)	0.55	9.44	80	20	80-100
Medium sized and samall cities	0.42	4.44	50-70	10	90-100
Rural communities	0.33	13.72	20	20	80-100
Total		**27.58**			

Figure 4-1: Waste Generation, Treatment and Disposal Estimates of Pakistan

4.1 Saaf Suthra Sheher

A real time case study of saaf suthra sheher, a waste management initiative is used to analyze the proposed mathematical model for the supply chain network design for sustainable waste management. Saaf Suthra Sheher is a privately-owned company which has contracts with hospitals, hotels, home owners and society owners in Islamabad. Company pays the partners for waste by rate of per kg. The partners are trained for waste segregations. Basic waste that is collected from partners are segregated into three parts i.e., paper, plastic and glass. This waste is segregated into 25-30 categories in the sortation center of the company.

Some parameter values are taken from the existing literature and published sources. The numerical example is based on the case of saaf suthra sheher. The research is being conducted at a medium level with the consideration one vehicle depot, five waste collection centers, one sortation center, one recycling center, one incineration center and one landfill. This initiative is based in Islamabad and the centers of recycling and incineration and landfill in Rawalpindi. Figure 6 shows the supply chain network of saaf suthra sheher in Islamabad, Pakistan. The waste is collected from different sectors of Islamabad. The sectors taken in this research are F11, I8, G13 and F7. Waste is collected from these sectors where residents have sorted waste into three basic categories i.e., paper, plastic and glass. Vehicles are moved from vehicle depot centers after estimating the waste generated and then taken to sortation center. In sortation center waste is categorized in more categories and sorted. This waste is then moved towards different recycling center, incineration center or landfill.

The municipal waste has food waste in too but saaf suthra sheher does not take that. Its only focus is on recyclables. Some part of waste i.e., paper waste is taken into incineration center where it is used for energy purpose. Some of the waste is upcycled, and recycled and only a small part is taken to landfill. For research purpose we have taken into consideration only five areas of Islamabad. The vehicles that are being used for transporting the waste is Hyundai Shehzore Porter H-100. The payload capacity of vehicle is 1000 kgs (Automotive, 2021) and its fuel efficiency is 8 kilometers per liter (Fairwheels, 2021). The fuel type used in Hyundai Shehzore Porter H-100 is diesel and its price considered in the numerical example is PKR 272 per liter as of 2^{nd} April, 2023.

The basic categories of waste that are collected is paper, plastic, metal, glass and tetra packs. This is further segregated into various categories to supply to different factories for recycling. Mixed waste is not accepted i.e., recycling waste with food and wet waste. The collected waste is further segregated into 25-30 categories. The recyclables are supplied to factories that process them for recycling. For example, Paper is recycled into boxboard, plastic into polyester Fiber and pellets, Tetra Paks into corrugated roofing material. Metal and glass and recycled back into the same materials.

Following snapshot in figure 4-1 shows the supply chain network map of the company. Vehicle depots and sortation center is at Bahria Enclave and waste sites are in Islamabad. The waste sites are F11, I8, G13 and F7. The recycling center, incineration center and landfill are in Rawalpindi. Vehicles move from vehicle depots at Bahria Enclave to waste sites at Islamabad that are F11, I8, G13 and F7. After collecting waste from waste sites, the vehicles move towards sortation center for sortation of waste that is located at Bahria Enclave as well. After the waste is sorted according to categories, vehicles are loaded and then move towards the facilities accordingly that is recycling center, incineration center and landfill. Following tables show the distances between all the nodes in Supply Chain of Saaf Suthra Sheher.

Table 4-1: Distance matrix between Vehicle Depots and Waste Sites (Km)

Name	**F11**	**I8**	**G13**	**F7**
Vehicle Depot 1	31	21.8	34.7	24
Vehicle Depot 2	33	23.8	36.7	26

This table 4-1 represents the details of distances between vehicle depots and the waste collection sites that are taken in this research. The distances are shown in km. These distances are between vehicle depots that are situated are Bahria Enclave and Waste sites F11, I8, G13 and F7.

Table 4-2: Distance matrix between Waste Sites and Sortation Center (Km)

Name	**Sortation Center**
F11	31
I8	21.8
G13	34.7
F7	24

The table 4-2 represents the distance between waste sites and sortation centers. The distances are taken in km. The waste sites are F11, I8, G13 and F7 situated in Islamabad and sortation center is situated in Bahria Enclave. The waste is collected from the respective waste site and it is moved towards the sortation center. The waste is usually taken in form of five categories. The following table 7 shows the categories of waste that is collected from waste sites. Waste is moved towards sortation center and at sortation center it is sorted into 20-25 more categories.

Table 4-3: Category of Waste Collected

Category	Type
Category 1	Paper
Category 2	Plastic
Category 3	Metal
Category 4	Glass
Category 5	Tetra Pack

When the waste is collected and moved towards sortation center, the collected waste is sorted more in to 20-25 categories and moved towards the respective facilities. The facilities are recycling center, incineration center and landfill. The following table 8 shows the distance between sortation center and respective facilities (recycling center, incineration center and landfill).

Table 4-4: Distance matrix between Sortation Center and Facilities (km)

Name	Recycling Center	Incineration Center	Landfill
Sortation Center	39	42	44

The company has contract with the household owners, society owners and hostel owners. The waste is collected and sorted afterward it is sold to recycling center and incineration center. The company is using 25 vehicles for the overall process and it’s cost for six time periods had been up to PKR 900,000.

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4.2 Summary of the chapter

In this chapter the case study of Saaf Suthra Sheher is explained in terms of the respected research. The distances between every node is mentioned in tables. The case study explains the type of waste and waste management activities. The waste management activities are explained and sortation of waste is elaborated for the waste management system. It’s a real-life example of waste management supply chain and analysis of cost, GHG emissions and emissions saving is done through Interactive Multi-Objective Fuzzy Programming.

The case study will help us in understanding the results and implication of the mathematical model and will help in understanding the future recommendations and implementation of its and suggestions to make the supply chain more sustainable.

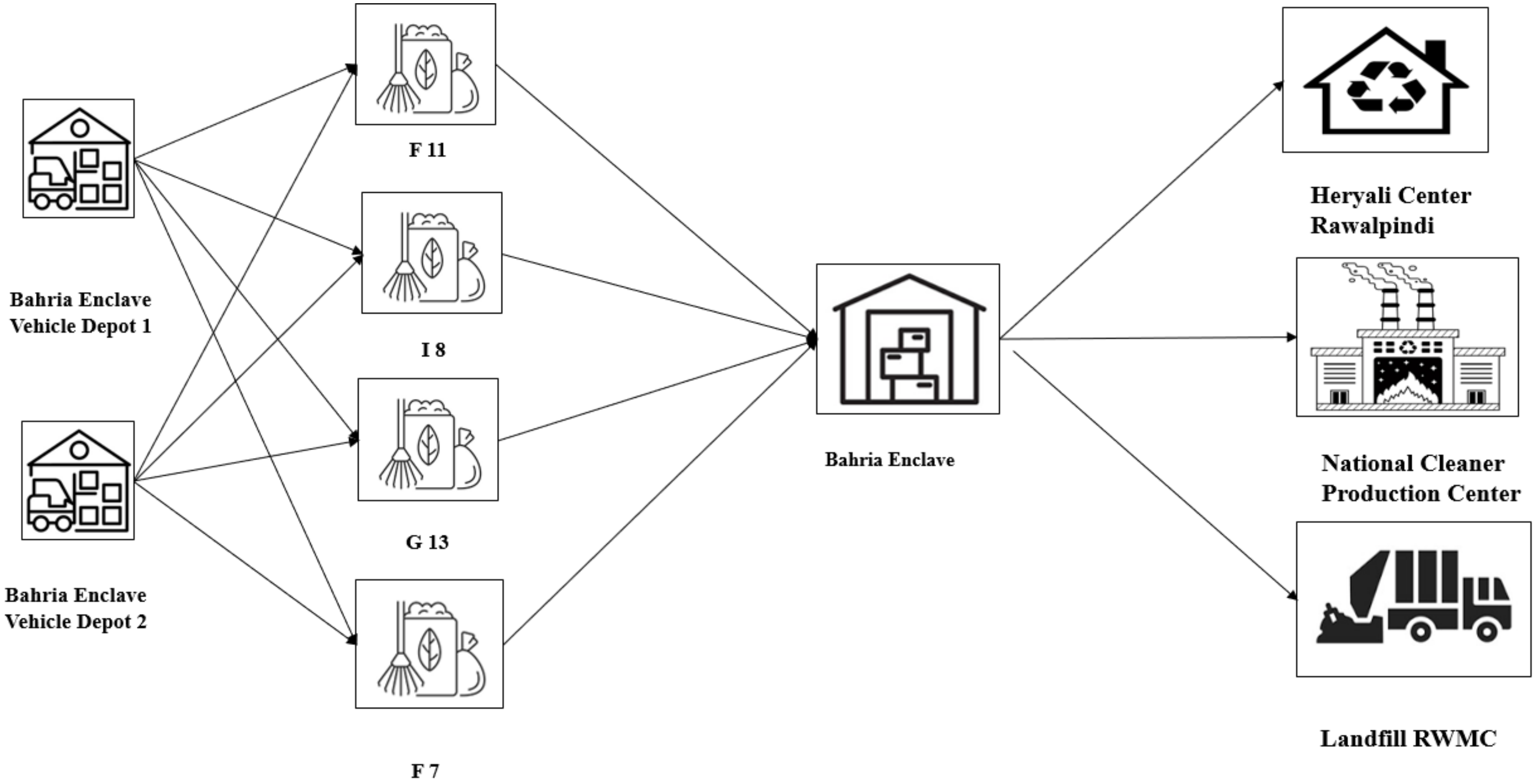

Figure 4-1: Supply chain network for waste management of Saaf Suthra Sheher

Chapter 5: Research Methodology

5.1 Interactive Fuzzy multi-objective Optimization

For the multi-objective model designed in the research for waste management supply chain, the coding is done on MATLAB 2022a. The coding for the designed model is done using the problem-based coding technique on MATLAB, for three objectives and various constraints. The three objectives of the proposed model include: (1) Cost minimization of Transportation of Waste, (2) Minimization of GHG emissions from transportation, and (3) Saving Emissions Maximization. The supply chain network design for waste management in this research is a multi-objective model and, on such models, various multi-objective techniques have been applied (Ahmadini et al., 2021). Due to inclusion of multi objectives and constraints in mathematical to objective functions that are also optimal, chance of inaccuracy of value given by decision maker is high, and uncertainty should be incorporated in the model to minimize the level of inaccuracy in the values (Abdelfattah, 2021).

As shown in figure 8, the flowchart of steps involved in interactive fuzzy programming. By following steps for interactive fuzzy programming in the flowchart, the designed multi-objective supply chain for waste management is optimized. The supply chain network designed for waste management is based on three objectives of cost minimization, GHG minimization and maximization of saved emissions. The proposed multi-objective model for waste management is optimized using interactive fuzzy programming. In the first step of IFP the decision variables, constraints and objectives are expressed using fuzzy sets and fuzzy relationships. In next step membership functions and fuzzy rules are applied then to define the relationship between decision variables and objectives.

Defuzzification of fuzzy objectives is done to make crisp objectives and formulating of fuzzy objectives and constraints as mathematical programming problem is done. Each objective function is optimized as single objective problem. Positive Ideal solution and Negative Ideal solution for each objective function is defined. Membership Functions are defined. Multi objective Mixed Integer linear programing is converted into Mixed integer Linear Programming and it is solved. Convergence and optimization of results is done based on decision maker's feedback and iterations are performed until decision maker gets satisfactory results and convergence criteria is met.

In stating of the methodology, the conventional multi-objective optimization model is constructed and additional constraints are built. The next step calculated the minimum and maximum value of every objective function. Then fuzzy multi-objective optimization model is formulated and weights of coefficients are selected and assigned. After this the interactive process is started.

In the interactive process, new weighting coefficients are assigned and fuzzy optimization model is solved using suitable algorithm. The collaborative sensitive analysis is done and it is tested that the satisfaction level and collaborative sensitivity degree meet the designer's preference. If not, then new design preference is set and new threshold value is set. In this process new weights are assigned and the process is repeated till the results satisfy the designer.

5.2 Numerical Example

A numerical example of Saaf Suthra Sheher is considered to analyze the proposed mathematical model for green supply chain network design for waste management. The parameter values for analysis purpose are taken from literature, published sources as well as real scenarios. The numerical example is based on the case of a saaf suthra sheher. The research is conducted at a medium level with consideration of having two vehicle depots, four waste sites, one sortation center and one recycling center. Figure 8 shows the supply chain network for saaf suthra sheher taken in this study. The locations of vehicle depots, waste sites, sortation center, recycling center, incineration center and landfill are known and fixed. The waste sites are responsible for waste generation demand.

Vehicles move from vehicle depots and collect waste from waste sites and take it into sortation center. After sorting of waste vehicles carry waste to respective waste management facilities. Hence, cost of transportation will be incurred between all nodes. GHG emission of transportation is also incurred between all nodes due to waste transportation. The recycling center is responsible for recycling of waste, incineration center takes paper waste mostly for incineration and remaining waste is dumped in landfill.

Some parameter values are taken from the existing literature and published sources. The numerical example is based on the case of saaf suthra sheher. The research is being conducted at a medium level with the consideration one vehicle depot, five waste collection centers, one sortation center, one recycling center, one incineration center and one landfill. This initiative is based in Islamabad and the centers of recycling and incineration and landfill in

Rawalpindi. Figure 6 shows the supply chain network of saaf suthra sheher in Islamabad, Pakistan. The waste is collected from different sectors of Islamabad. The sectors taken in this research are F11, I8, G13 and F7. Waste is collected from these sectors where residents have sorted waste into three basic categories i.e., paper, plastic and glass. Vehicles are moved from vehicle depot centers after estimating the waste generated and then taken to sortation center. In sortation center waste is categorized in more categories and sorted. This waste is then moved towards different recycling center, incineration center or landfill.

5.3 Summary of the chapter

This chapter explains the methodology used in this research and its application of the proposed Multi objective model and case study of Saff Suthra Sheher. The methodology will help us in understanding the results and help us in analysis of different scenarios.

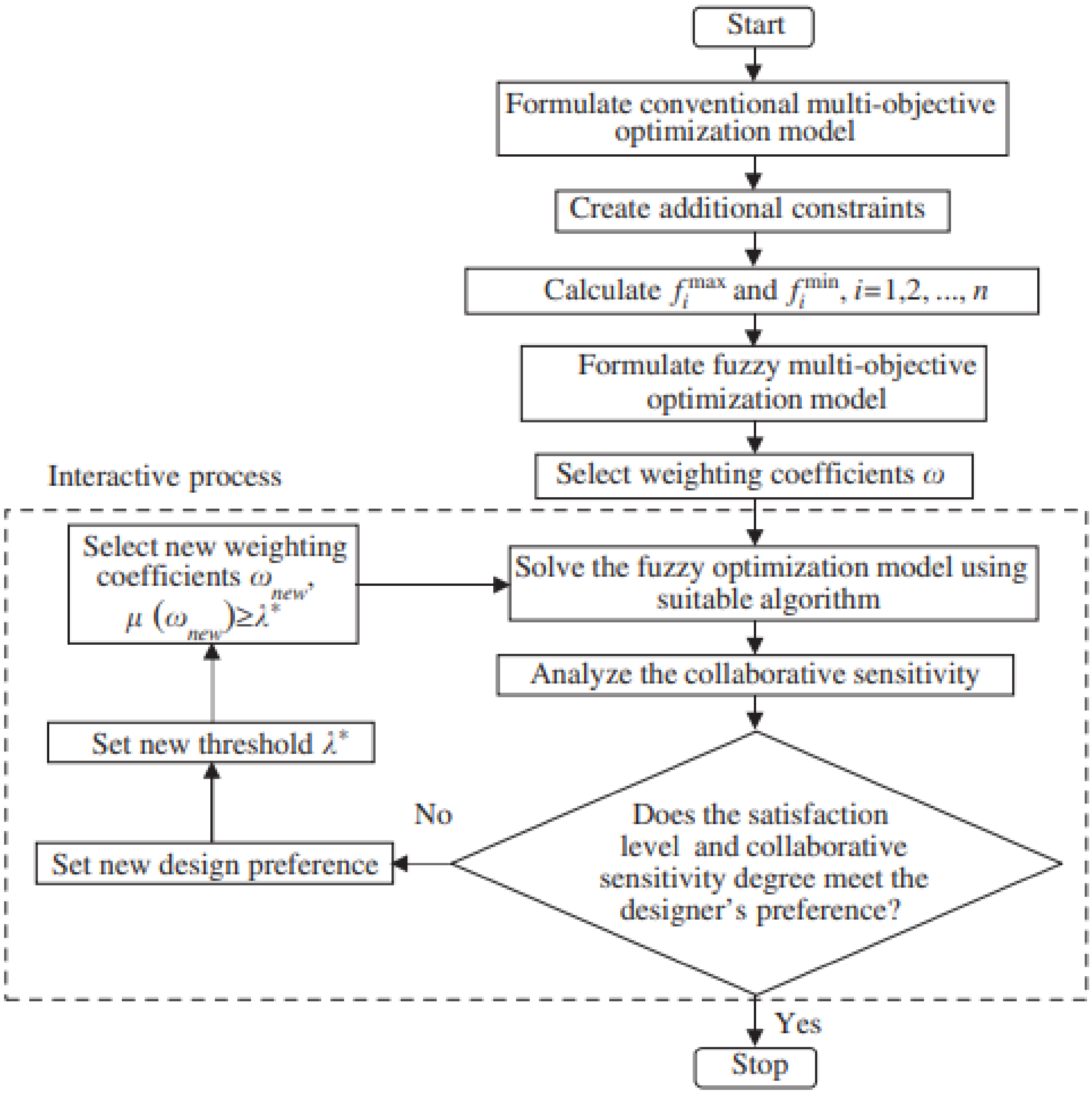

Figure 5-1: Flowchart of Interactive Fuzzy Programming

Chapter 6: Results and Discussion

Following chapter includes the analysis of the results and different scenarios. The optimal solutions and different scenarios are compared and discussed.

6.1 Results and Discussion

The multi-objective mathematical model proposed for designing a sustainable supply chain network for waste transportation and management has been solved using MATLAB R2022a coding tool on a personal laptop with specifications of Intel(R) Core (TM) i5-7300U CPU @ 2.60GHz 2.70 GHz and 8GB RAM and was then optimized using the Interactive Fuzzy programming for optimization. The model is solved for two vehicle depots, four waste sites, two sortation centers, two recycling centers, one incineration centers and one landfill. The model is solved for total three objective functions, X constraints and Y decision variables. Model is solved using collected data and optimal values for (1) minimization of cost of transportation, (2) minimization GHG of transportation process and (3) and minimization of effect of waste management activities. The model is also solved using Goal Programming and results are compared.

6.1.1 Optimal number of vehicles for waste transportation

Two vehicle depots located in Bahria Enclave, Islamabad are responsible for providing vehicles for the transportation of waste from four waste sites located in Islamabad Capital Territory. These areas are F11, I8, G13 and F7. The houses which have signed the contract gets the waste in designed categories and the waste is recorded and the amount of waste generated there is usually a constant amount. The vehicles can carry 50 kgs by volume by mass ratio. They vehicles need to move according to amount of waste calculated. Following table 6-1 shows number of vehicles moving to each waste sites from vehicle depots. The model has reduced the number of required vehicles from 25 to 16.

Table 6-1:No. of vehicles moving from Vehicle Depots i to Waste sites j

X_{ij}	Time Period=1			
	Waste Site 1	**Waste Site 2**	**Waste Site 3**	**Waste Site 4**
Vehicle Depot 1	4	0	0	4
Vehicle Depot 2	0	5	3	0
	Time Period =2			
	Waste Site 1	**Waste Site 2**	**Waste Site 3**	**Waste Site 4**
Vehicle Depot 1	4	0	0	4
Vehicle Depot 2	0	5	3	0
	Time Period =3			
	Waste Site 1	**Waste Site 2**	**Waste Site 3**	**Waste Site 4**
Vehicle Depot 1	4	0	0	4
Vehicle Depot 2	0	5	3	0
	Time Period =4			
	Waste Site 1	**Waste Site 2**	**Waste Site 3**	**Waste Site 4**
Vehicle Depot 1	4	0	0	4
Vehicle Depot 2	0	5	3	0
	Time Period =5			
	Waste Site 1	**Waste Site 2**	**Waste Site 3**	**Waste Site 4**
Vehicle Depot 1	4	0	0	4
Vehicle Depot 2	0	5	3	0
	Time Period =6			
	Waste Site 1	**Waste Site 2**	**Waste Site 3**	**Waste Site 4**
Vehicle Depot 1	4	0	0	4
Vehicle Depot 2	0	5	3	0

Vehicles that moves from vehicle depots i to waste sites j collect the waste and move to sortation center k to get the waste sorted. The waste sites are located at F11, I8, G13 and F7. The vehicle depots and sortation center are located in Bahria Enclave. The company has contract with house owners, hotel owner and society owners. The waste is collected from waste sites once a week and the society owners, house owners or hotel owners inform company about the weight and volume of collected waste. So, the optimal quantity of vehicles that are moving from vehicle depots to waste sites depends on the collected quantity of waste.

Vehicle depot 1 is providing vehicles for waste sites 1 and 4, that are F11 and F7. Vehicle depot 2 is providing vehicles for waste sites 2 and 3, that are I8 and G13. This happens in every time period. Collected waste is moved back after the vehicles are loaded and this waste in unloaded in sortation center. The sortation center is located in Bahria Enclave. Following table shows the number of vehicles moving toward the waste sortation center. It's the same vehicles that moved to the waste sites.

Table 6-2: No. of vehicles moving from Waste sites to Sortation center

X_{jk}	**Sortation Center**					
	Time Period=1	**Time Period =2**	**Time Period=3**	**Time Period=4**	**Time Period=5**	**Time Period =6**
Waste Site 1	4	4	4	4	4	4
Waste Site 2	5	5	5	5	5	5
Waste Site 2	3	3	3	3	3	3
Waste Site 4	4	4	4	4	4	4

When the waste is sorted the waste is moved into three more sites that are recycling centers, incineration center and Recycling center. Location of recycling center is Heryali Center TMA Rawalpindi, location of incineration center is National Cleaner Production Center, H34H+GMC, Morgah, Rawalpindi and location of landfill is Landfill RWMC, F5GW+PCG, Losar Chakbeli Khan Road, Rawalpindi, Islamabad Capital Territory.

The waste is moved from sortation center k towards recycling center l, incineration center m and landfill n after sortation. The waste is sorted according to the required percentage and measured. Hence the optimal number of vehicles are moved towards the respective facility that are recycling center, incineration center and landfill. Following tables shows the number of vehicles moving from sortation center to respective facilities (recycling center, incineration center and landfill).

Table 6-3: No of vehicles moving from Sortation Center to Recycling Center

X_{kl}		**Recycling Center**
Sortation Center	**Time Period =1**	9
	Time Period =2	9
	Time Period =3	9
	Time Period =4	9
	Time Period =5	9
	Time Period =6	9

Table 6-4: No. of vehicles moving from Sortation center to Incineration center

X_{km}		**Incineration Center**
Sortation Center	**Time Period =1**	4
	Time Period =2	4
	Time Period =3	4
	Time Period =4	4
	Time Period =5	4
	Time Period =6	4

Table 6-5: No of Vehicles moving from sortation center to Landfill

X_{kn}		**Landfill**
Sortation Center	**Time Period =1**	3
	Time Period =2	3
	Time Period =3	3
	Time Period =4	3
	Time Period =5	3
	Time Period =6	3

Figure 6-1 shows the flow chart of optimal number of vehicles selected.

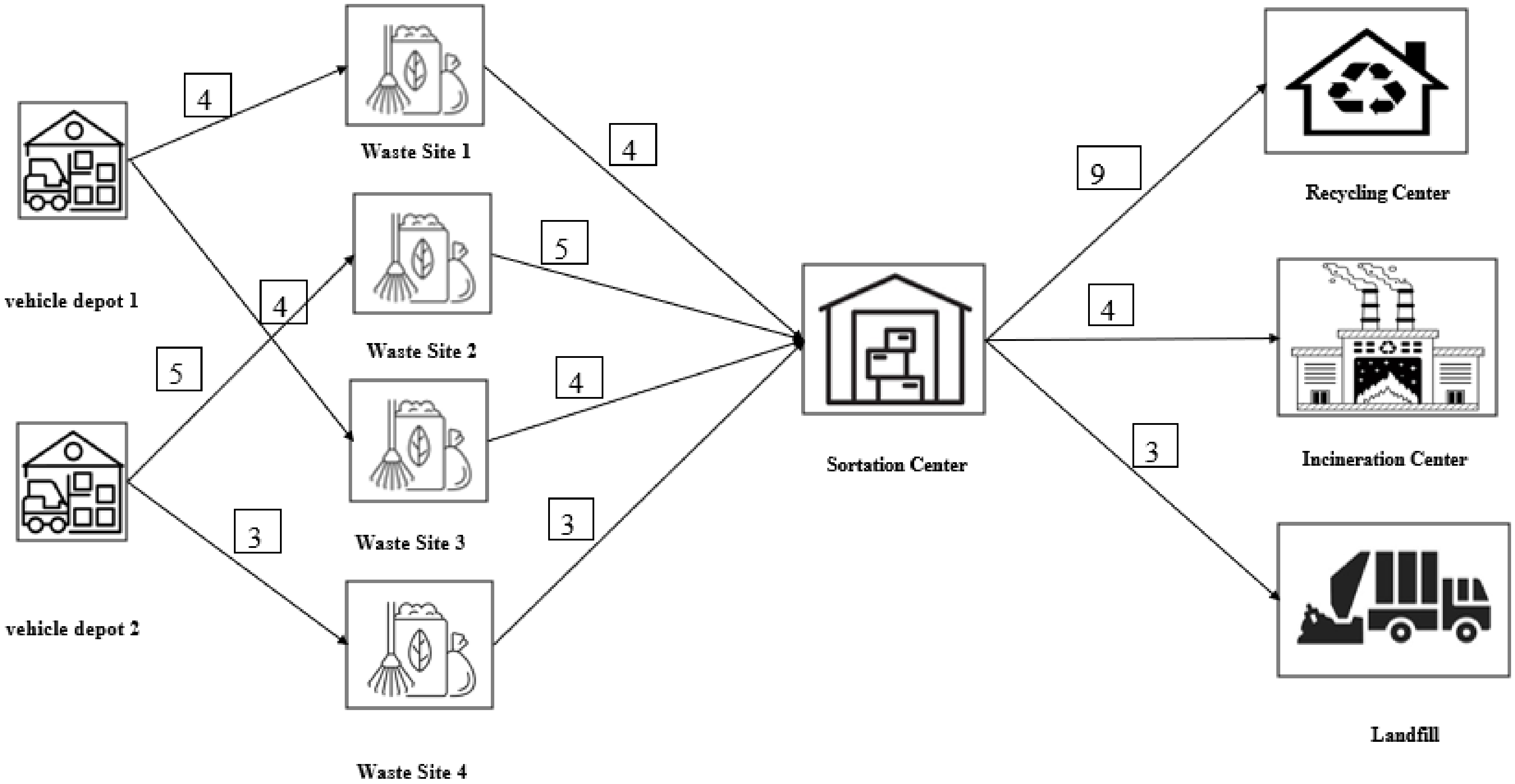

Figure 6-1: Flowchart of optimal numbers of vehicles

6.1.2 Optimal Waste Quantities for Waste Management Activities

Quantity of waste collected at waste sites j is known and all the waste is moved towards sortation center k after sorting it into categories. The quantity of waste that is considered in the case study is taken in kgs. The vehicles take waste according to designated weight of the vehicle and transfer into sortation center. The five categories are sorted into 20-25 categories and moved towards the designated facilities. Quantity of waste moved towards sortation center from waste sites are shown in following table in respective time period.

Table 6-6: Quantity of waste moving from Waste Sites to Sortation center in kg

Q_{jk}	**Sortation Center** (k)					
(j)	**Time Period=1**	**Time Period =2**	**Time Period =3**	**Time Period =4**	**Time Period =5**	**Time Period =6**
Waste Site 1	200	200	200	200	200	200
Waste Site 2	250	250	250	250	250	250
Waste Site 3	150	150	150	150	150	150
Waste Site 4	200	200	200	200	200	200

The above-mentioned waste is the approximated waste that is collected from the waste sites. At sortation center k, waste is sorted out into three categories and it is transported to recycling center, incineration center and landfill. Following tables show the optimal quantity of waste that is transported after being sorted.

Table 6-7: Optimal quantity of waste moving to recycling center in kg

Q_{kl}		**Recycling Center** (l)
Sortation Center (k)	**Time Period =1**	450
	Time Period =2	450
	Time Period =3	450
	Time Period =4	450
	Time Period =5	450
	Time Period =6	450

This waste is sorted and categorized as recyclable waste and it’s more than 50 percent of the collected waste. The recycling waste is moved towards the Heryali recycling center located in Rawalpindi. This value is in kgs. The company sell the waste to recycling center on per kg rate. The following table shows the quantity of waste that is moved towards incineration center after sortation.

Table 6-8:Optimal quantity of waste moving towards Incineration center in kg

Q_{km}		**Incineration Center** (m)
Sortation Center (k)	**Time Period =1**	200
	Time Period =2	200
	Time Period =3	200
	Time Period =4	200
	Time Period =5	200
	Time Period =6	200

This waste is sorted and categorized as incinerable waste and it’s less than 30 percent of the collected waste. The incinerated waste is moved towards the Incineration center located in Rawalpindi. This value is in kgs. The company sell the waste to incineration center on per kg rate. The following table shows the quantity of waste that is moved towards landfill after sortation.

Table 6-9: Optimal Quantity of waste moving towards landfill in kg

Q_{kn}		Recycling Center (n)
Sortation Center (k)	**Time Period =1**	150
	Time Period =2	150
	Time Period =3	150
	Time Period =4	150
	Time Period =5	150
	Time Period =6	150

This waste is sorted and categorized as landfill waste and it’s less than 20 percent of the collected waste. This waste is moved towards the Incineration center located in Rawalpindi. This value is in kgs. Figure 6-2 shows the flow chart of optimal waste quantity.

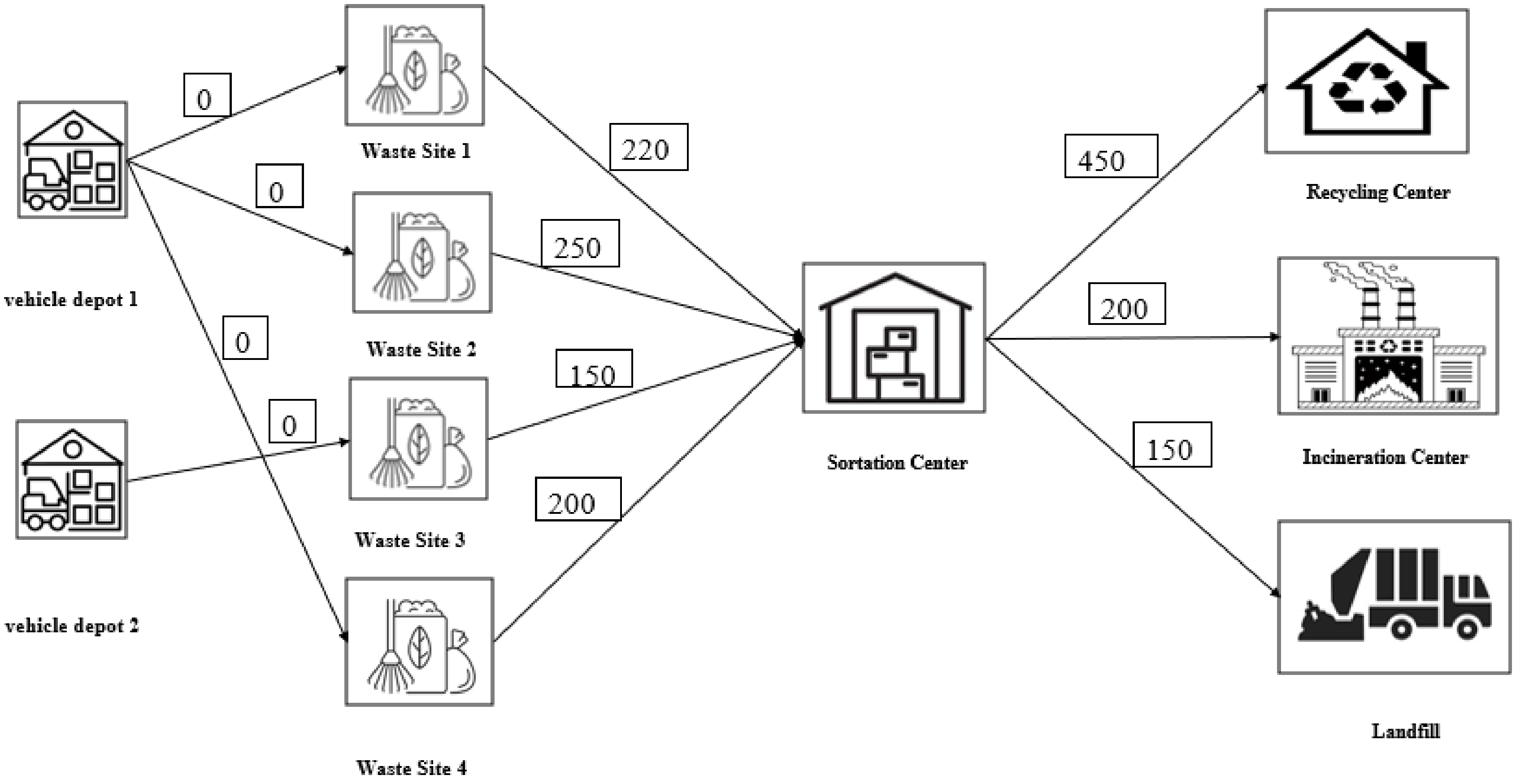

Figure 6-2:Flowchart of optimal waste quantity

6.1.3 Cost Minimization

In the model, the cost minimization function for a waste supply chain consists of; (1) cost of selection of vehicle and (2) cost of transportation of waste between nodes of supply chain network. A total cost of PKR 585,670 is incurred in transporting of waste throughout the supply network in whole six time periods. For one time period it becomes PKR 97,612. This cost has six components. One component shows the value of maintenance cost other components calculates the transportation cost of waste between nodes. This cost is less than the cost that company has been facing for six time periods.

6.1.3.1 Cost incurred in Waste Supply Chain

The results are showing that a major contribution of 23.28%, PKR 136,340 is made to the total cost value by cost incurred while vehicles moving from vehicle depots to the waste sites in total six time periods. Cost for one time period is PKR 22,723.3. This cost can be minimized by moving vehicle depots nearer to the waste sites. Cost of moving waste from four waste sites towards sortation center is 23.28%, PKR 136,340 for six time periods. Cost for one time period is PKR 22,723.3. This cost can be reduced by proper streamlined allocation of waste, enhancing quality of roads, proper vehicle utilization and proper allocation of routes. Cost of moving waste towards waste management facilities i.e., recycling center, incineration center and landfill are 32.92% (PKR 192,830), 17.52% (PKR 120,600) and 12.20% (PKR 71,457). These costs are cumulative for six time periods. For single time period the costs are PKR 32,138.3, PKR 17,100 and PKR 11,909.6 respectively for recycling center, incineration center and landfill. Last component of cost is the cost of maintenance of vehicles. This constitutes of 3.07% that is PKR 18,000 for six time periods. The cost of maintenance for a single time period is PKR 3,000.

Figure 6-3 shows the graphical representation of all the costs incurred during transportation of waste throughout supply network of waste management activities. This figure shows the distribution in terms of six time periods. The pie chart shows the components of cost and their contribution in cost of the supply chain of waste management.

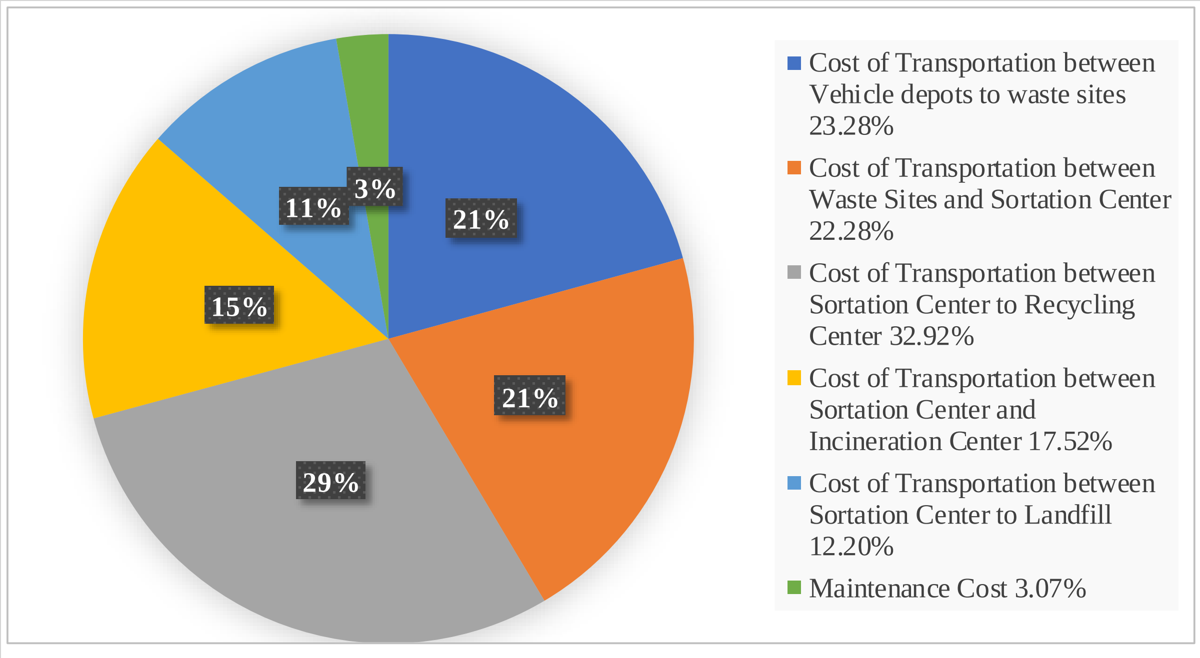

Figure 6-3: Cost incurred in Waste Transportation (PKR)

6.1.4 Minimization of Green House Gases due to Transportation

In the model, the second objective of minimization of GHG emissions is solved. The optimal value of the function is 5,057.5 KgCO_2. Since the vehicles are not moving in their full capacity this value will increase under full capacity but more waste will be moved, so overall value of GHG emissions will be decreased. GHG emission when vehicle move from vehicle depots to waste sites is 32.10% that is 1,623.43 KgCO_2/L for six time periods. For single time period the value is 270.57 KgCO_2/L. These emissions can be saved by moving vehicle depots nearer to the waste sites. GHG emissions when vehicles move towards sortation center are 31.78% of the total emissions in the supply network i.e., 1,607.03 KgCO_2/L for six time periods. GHG emissions for single time period in this node is 267.83 KgCO_2/L. These emissions can be reduced by utilizing the capacity of the vehicles and moving more waste using less vehicles. The Green House Gas Emissions while transferring waste towards facilities that are recycling, incineration and landfill are 18.92% i.e., 956.66 KgCO_2/L, 10.13% i.e., 512.13 KgCO_2/L and 7.08% i.e., 357.7 KgCO_2/L, respectively for six time periods. The values for GHG of transportation for single time period in these nodes are 159.4 KgCO_2/L, 85.3 KgCO_2/L and 59.65 KgCO_2/L respectively. Following figure 11 shows the results of GHG emissions of transportation of supply chain of waste management. The figure 6-4 shows the values with respect to six time periods.

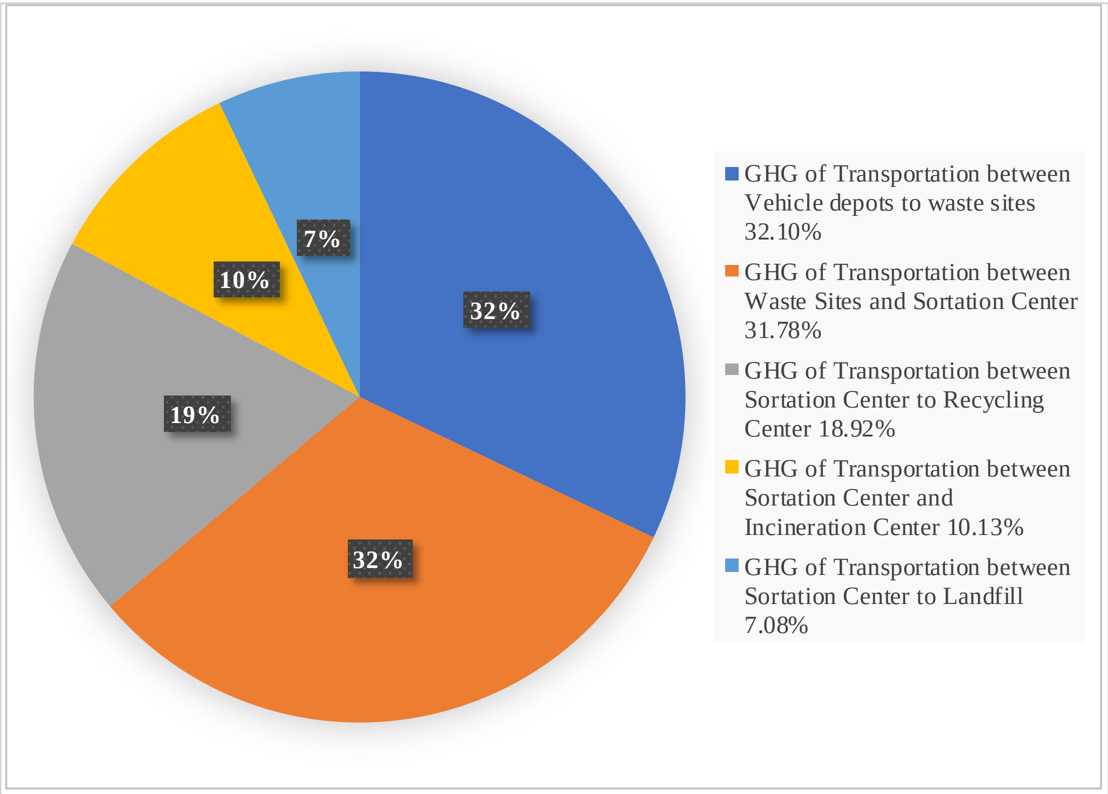

Figure 6-4: GHG Emissions in Transportation Process in kg CO_2

6.1.5 Maximizing emissions saving

The third objective maximizing emission saving of waste by waste management activities is solved and recycling is assigned more than 50% of the waste and the value it saves 2970 kg CO_2 by recycling 450 kgs of waste. Incineration releases 1260 kg CO_2 by incinerating 300 kgs of waste. Landfill releases 330 kg CO_2 by 50 kg of waste. So total emissions saved by this are 1380 kg CO_2. Following figure 6-5 shows the emissions caused by different waste management activities. The total emissions saved are calculated by subtracting emissions caused by incineration and landfill from the emissions saved by recycling.

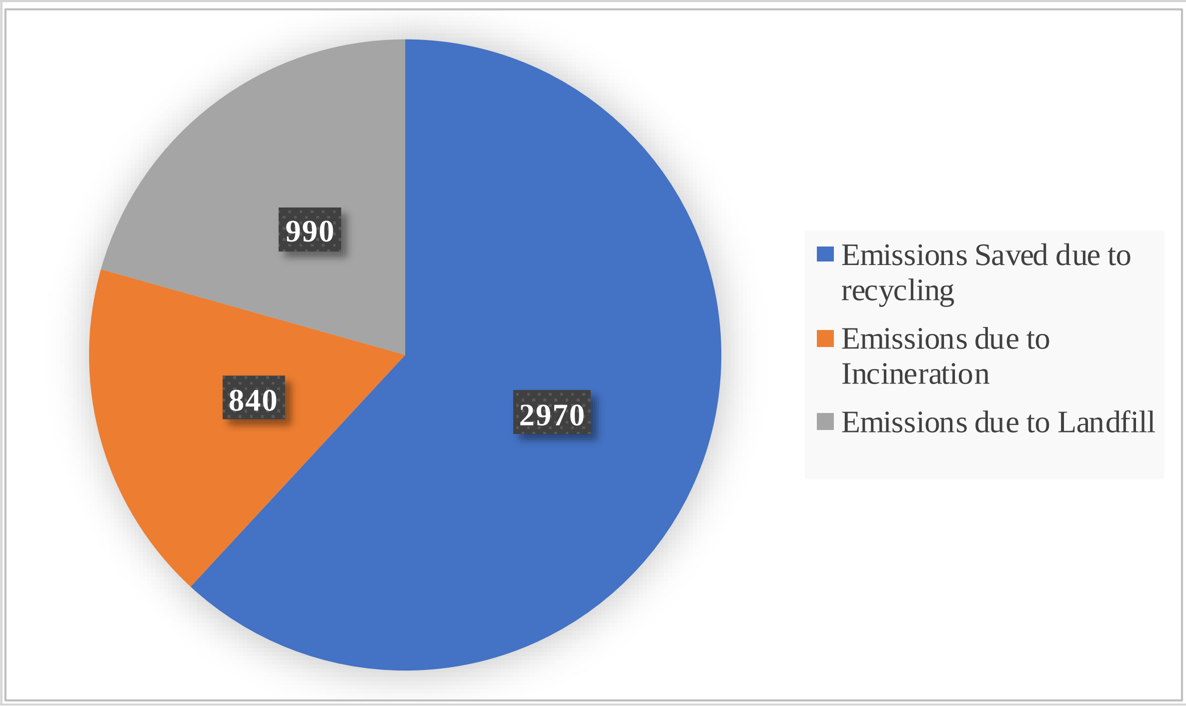

Figure 6-5: Emissions saved by waste management activities in kg CO_2

6.2 Analysis of scenarios

The comparison of different scenarios is done in this section to study the effect of segregation of waste.

6.2.1 When 100% waste moves to Landfill (Scenario 1)

Following table shows the result and comparison between following two conditions:

1. When 50% of waste is recycled, 30% incinerated and 20% is landfilled
2. When 100 % of waste is landfilled

Table 6-10: Comparison of first scenario

Scenario	**50% Recycling 30% Incineration 20 % Landfill**	**100% Landfill**
Cost (PKR)	585,770	298,970
GHG (kg CO_2)	5,057.5	5226.5
Emission Saving (kg CO_2)	1,140	-5,280

Following graphs show the comparison of scenario with respect to each objective. Figure 6-6 shows the comparison between first objective of our model that is cost of transportation. For 50% recycling, 30% incineration and 20 % landfill the cost is PKR 585,770, and the cost for 100% landfilling is PKR 298,970. It is less than first condition but segregation is not being done.

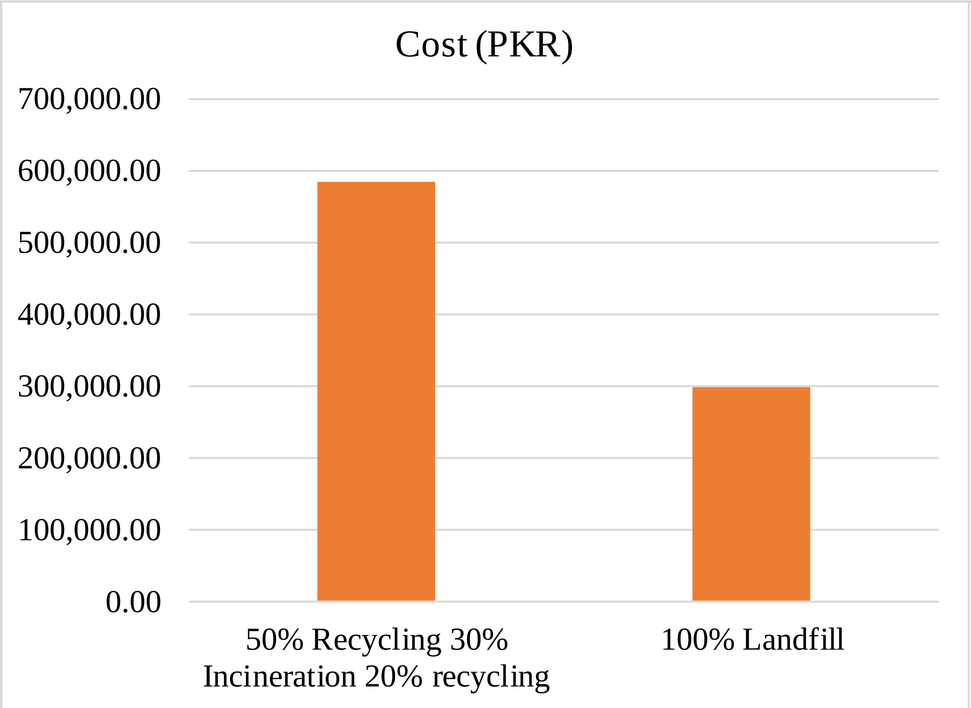

Figure 6-6: Comparison of cost in scenario 1

Figure 6-7 shows the comparison between second objective that is Greenhouse gas emissions of transportation. For 50% recycling, 30% incineration and 20 % landfill the GHG emissions are 5,057.5 kg CO_2, and the Greenhouse gas emissions for 100% landfilling is 5,226 kg CO_2. Landfilling causes more Greenhouse gas emissions in transportation.

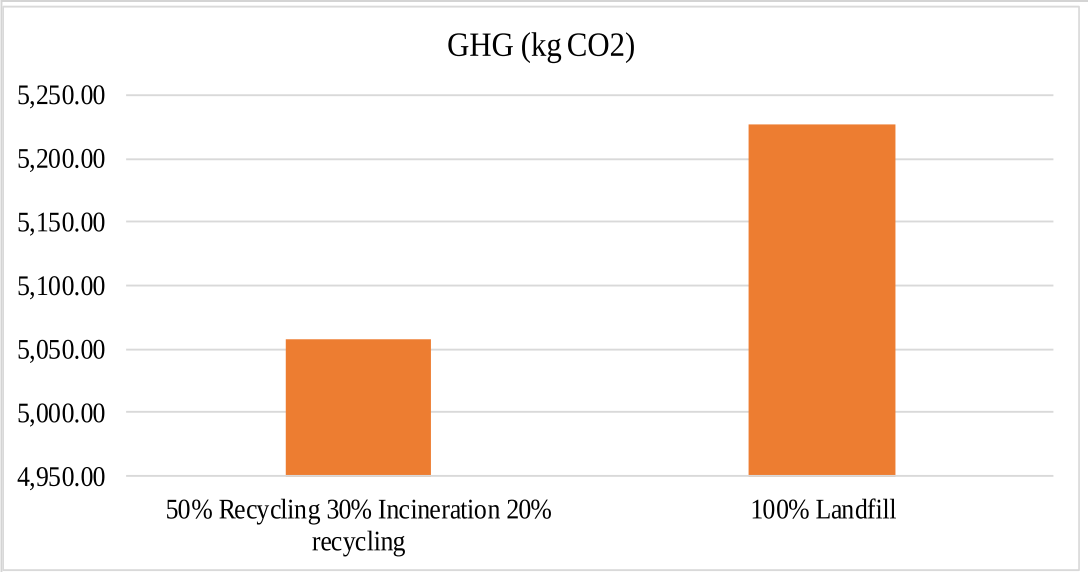

Figure 6-7: Comparison of GHG of transportation in scenario 1

Following figure 6-8 shows the comparison between the values of third objective function that is maximizing emission savings by waste management activities. For 50% recycling, 30% incineration and 20 % landfill the emissions saved by waste management activities are 1,140 kg CO_2, and the emissions emitted in environment by 100% landfilling are 5,280 kg CO_2.

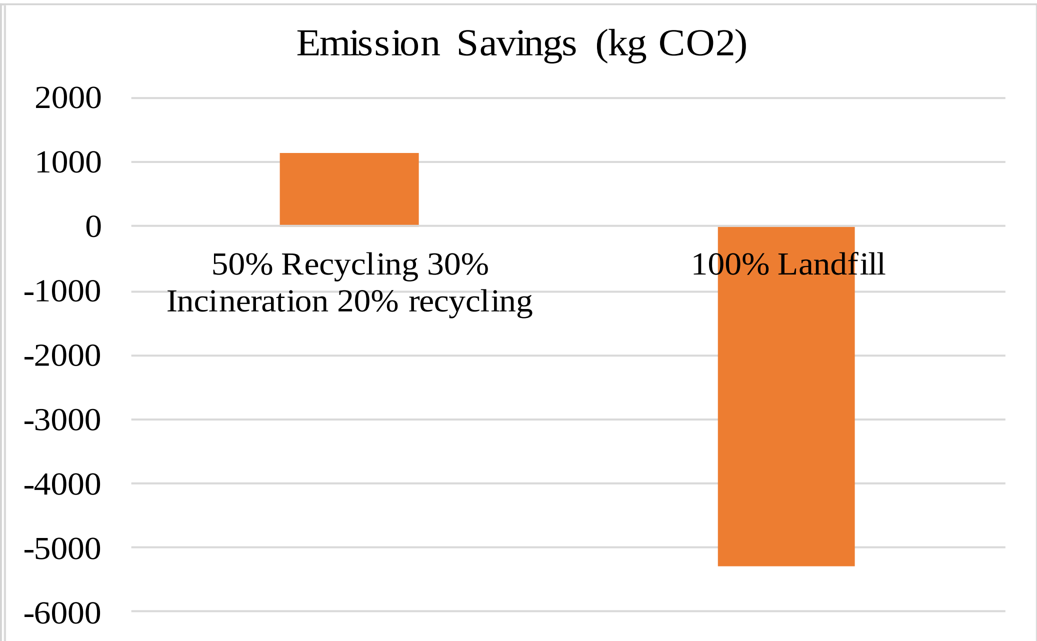

Figure 6-8: Comparison of Emission Saving in scenario 1

6.2.2 When 100% waste is recycled (Scenario 2)

Following table shows the result and comparison between following two conditions:

1. When 50% of waste is recycled, 30% incinerated and 20% is landfilled
2. When 100 % of waste is recycling

Table 6-11: Comparison of Scenario 2

Scenario	**50%Recycling 30% Incineration 20 % Landfill**	**100% Recycling**
Cost (PKR)	585,770	640,990
GHG (kg CO_2)	5,057.5	5,033
Emission Saving (kg CO_2)	1,140	5,280

Following graphs show the comparison of scenario with respect to each objective. Figure 6-9 shows the comparison between first objective of our model that is cost of transportation. For 50% recycling, 30% incineration and 20 % landfill the cost is PKR 585,780, and the cost for 100% recycling is PKR 640,990. It is more than first condition.

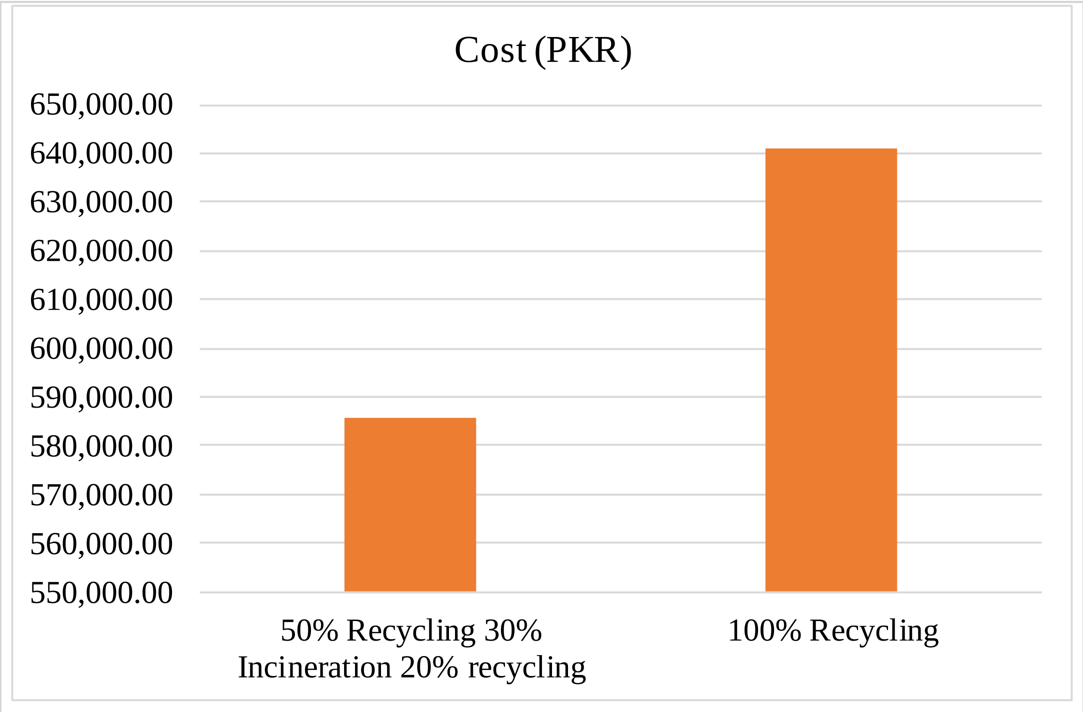

Figure 6-9: Comparison of cost of transportation in scenario 2

Figure 19 shows the comparison between second objective that is Greenhouse gas emissions of transportation. For 50% recycling, 30% incineration and 20 % landfill the GHG emissions are 5,057.5 kg CO_2, and the Greenhouse gas emissions for 100% landfilling is 5,033 kg CO_2. Recycling will cause more Greenhouse gas emissions in transportation.

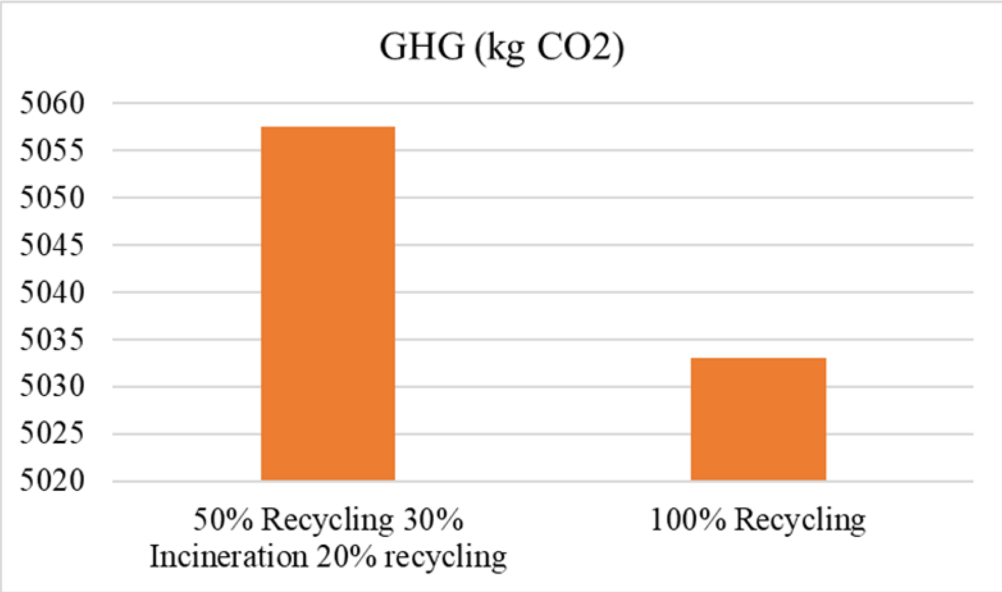

Figure 6-10: Comparison of GHG emissions of transportation in scenario 2

Following figure 6-11 shows the comparison between the values of third objective function that is maximizing emission savings by waste management activities. For 50% recycling, 30% incineration and 20 % landfill the emissions saved by waste management activities are 1,140 kg CO_2, and the emissions saved by 100% recycling are 5,280 kg CO_2.

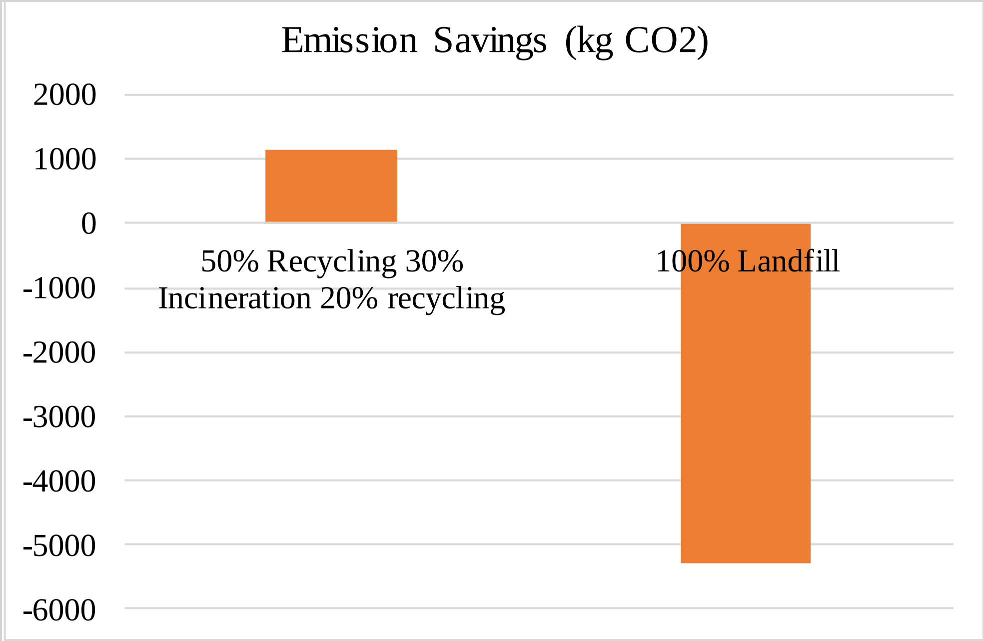

Figure 6-11: Comparison between emission savings of scenario 2

6.2.3 When 100% waste is incinerated (Scenario 3)

Following table shows the result and comparison between following two conditions:

1. When 50% of waste is recycled, 30% incinerated and 20% is landfilled
2. When 100 % of waste is incinerated

Table 6-12:Comparison of scenario 3

Scenario	**50%Recycling 30% Incineration 20 % Landfill**	**100% Incinerated**
Cost (PKR)	585,770	709,390
GHG (kg CO_2)	5,057.5	5371.6
Emission Saving (kg CO_2)	1,140	-3,360

Following graphs show the comparison of scenario with respect to each objective. Figure 6-12 shows the comparison between first objective of our model that is cost of transportation. For 50% recycling, 30% incineration and 20 % landfill the cost is PKR 585,770, and the cost for 100% incinerated is PKR 709,390. It is more than first condition.

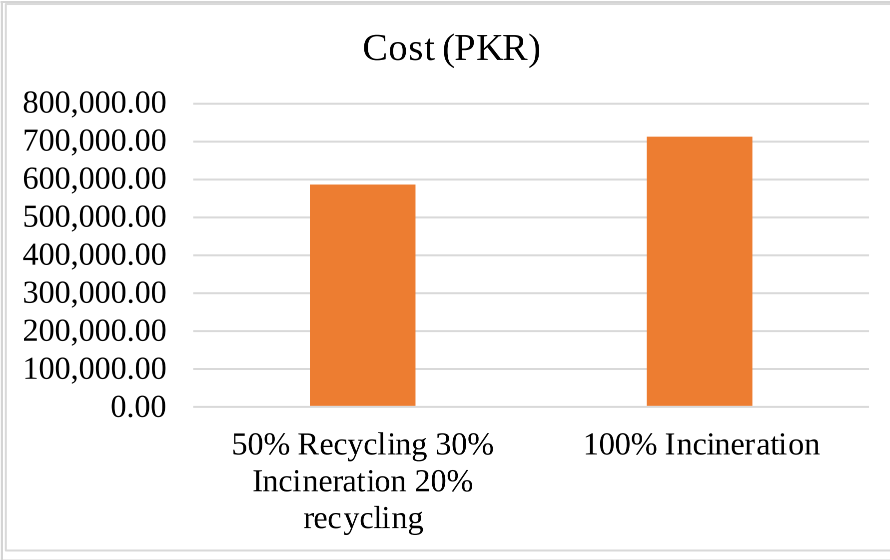

Figure 6-12: Comparison of cost of transportation in scenario 3

Figure 6-13 shows the comparison between second objective that is Greenhouse gas emissions of transportation. For 50% recycling, 30% incineration and 20 % landfill the GHG emissions are 5,057.5 kg CO_2, and the Greenhouse gas emissions for 100% landfilling is 6,223.5 kg CO_2. Recycling will cause more Greenhouse gas emissions in transportation.

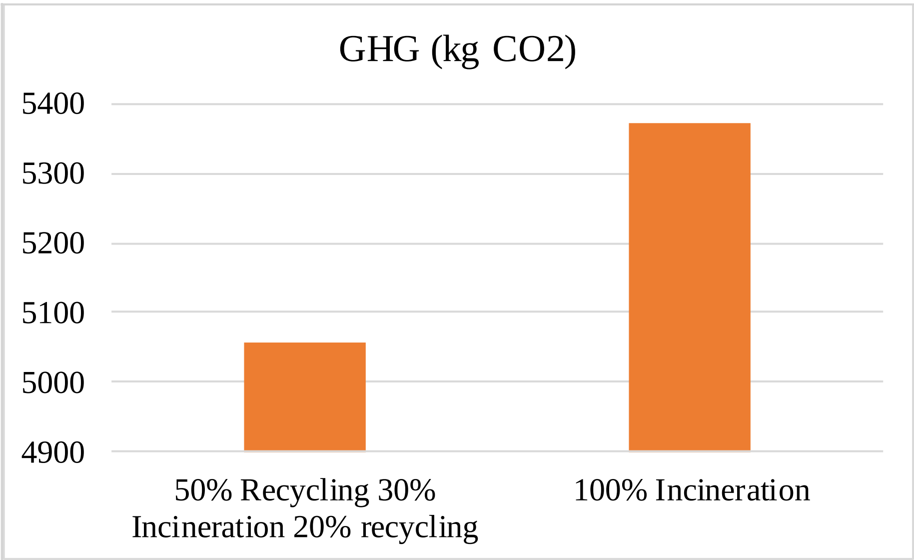

Figure 6-13:Comparison of GHG of transportation in scenario 3

Following figure 6-14 shows the comparison between the values of third objective function that is maximizing emission savings by waste management activities. For 50% recycling, 30% incineration and 20 % landfill the emissions saved by waste management activities are 1,140 kg CO_2, and the emissions emitted in environment by 100% incineration are 3,360 kg CO_2.

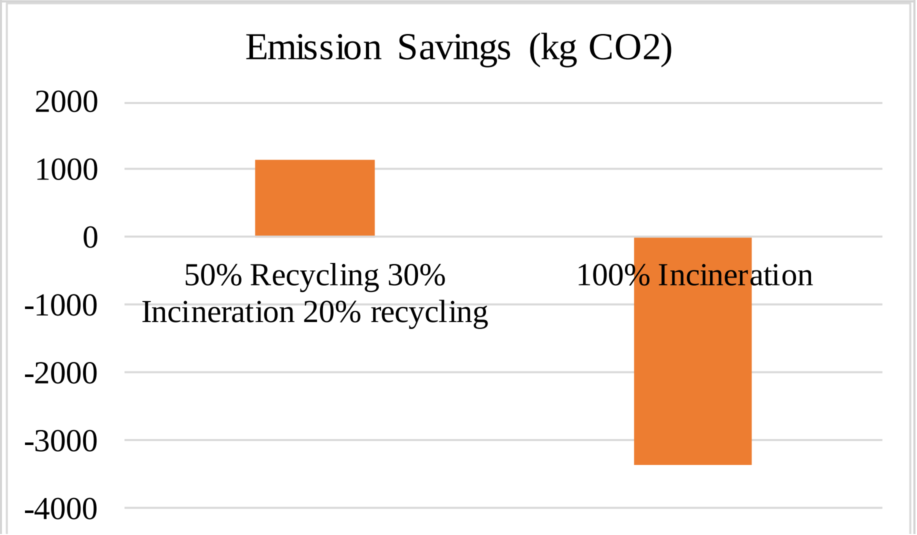

Figure 6-14:Comparison of emission saving from waste management activities in scenario 3

6.2.4 When 50% waste is incinerated (Scenario 4)

Following table shows the result and comparison between following two conditions:

1. When 50% of waste is recycled, 30% incinerated and 20% is landfilled
2. When 150% of waste is incinerated and 50% is recycled

Table 6-13:Comparison of scenario 4

Scenario	50%Recycling 30% Incineration 20 % Landfill	50%Recycling 50% Incineration
Cost (PKR)	585,770	675,190
GHG (kg CO_2)	5,057.5	5,202.3
Emission Saving (kg CO_2)	1,140	960

Following graphs show the comparison of scenario with respect to each objective. Figure 6-15 shows the comparison between first objective of our model that is cost of transportation. For 50% recycling, 30% incineration and 20 % landfill the cost is PKR 585,770, and the cost for 50% incinerated and 50% is recycled is PKR 675,190. It is more than first condition.

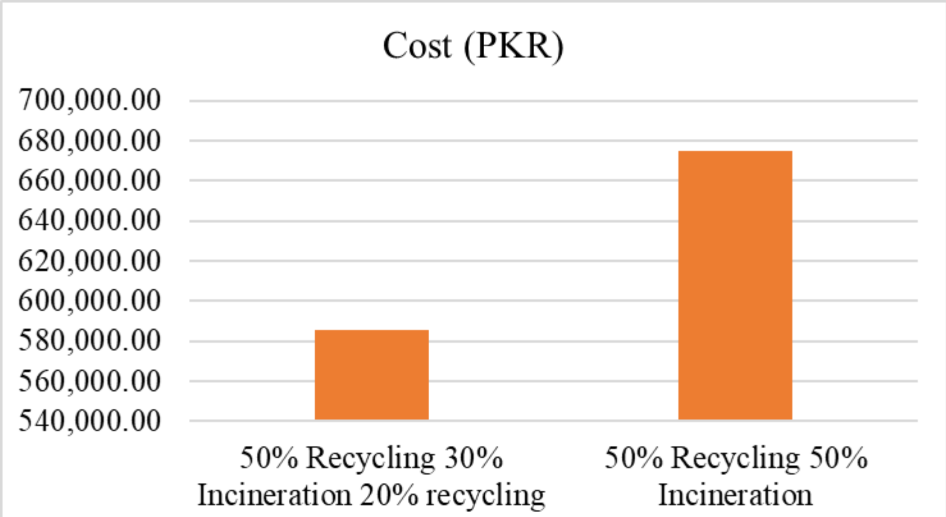

Figure 6-15:Comparison of cost of transportation in scenario 4

Figure 6-16 shows the comparison between second objective of our model that is Greenhouse gas emissions of transportation. For 50% recycling, 30% incineration and 20 % landfill the Greenhous gas emissions are 5,057.5 kg CO_2, and the greenhouse gas emissions when 50% incinerated and 50% is recycled are 5,202 kg CO_2. It is more than first condition.

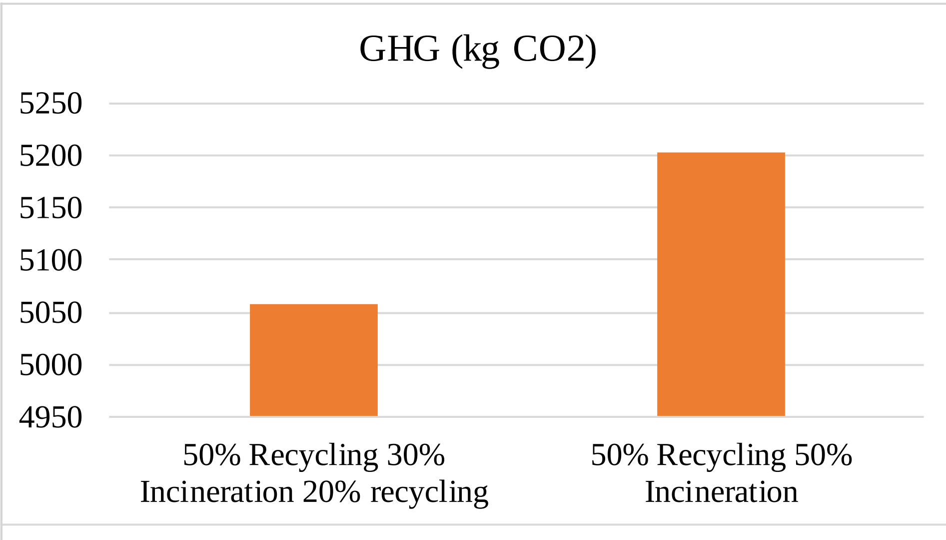

Figure 6-16: Comparison between GHG emissions of transportation in scenario 4

Following figure 6-17 shows the comparison between the values of third objective function that is maximizing emission savings by waste management activities. For 50% recycling, 30% incineration and 20 % landfill the emissions saved by waste management activities are 1,140 kg CO_2, and the emissions saved by 50% incinerated and 50% is recycled are 960 kg CO_2.

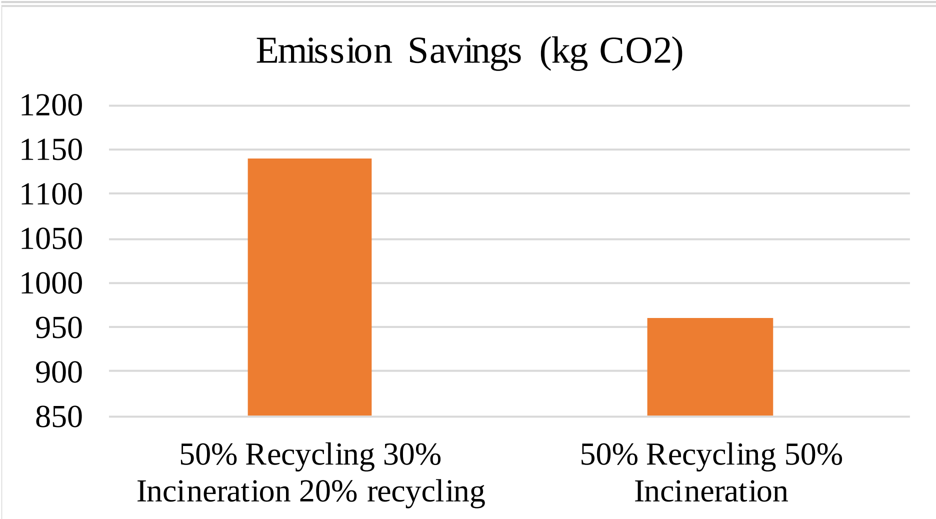

Figure 6-17: Comparison of emission saved due to waste management activities in scenario 4

6.3 Sensitivity Analysis

A sensitivity analysis is conducted on some key parameters whose values are changed by a certain percentage to see the effect of that change on the optimal values of cost minimization function, GHG minimization function and saving emissions maximization as shown in table. The percentage changes considered to see the changes in optimal function values are -50%, -25%, +25%, and +50%. The parameters changed include distance between nodes, carried load and segregation ratio of recycling.

Table 6-14: Sensitivity analysis results for key parameters

Parameter	Percentage Change in Parameter	Percentage Change in Cost	Percentage Change in GHG emissions of Transportation	Percentage Change in Emissions Saved
Distance Between Nodes	50%	35.09%	33.18%	0%
	25%	6.12%	16.75%	0%
	-25%	-6.60%	-16.75%	0%
	-50%	-35.00%	-33.18%	0%
Carried Load	50%	19.32%	9.3%	0%
	25%	9.2%	4.5%	0%
	-25%	-9.2%	-4.5%	0%
	-50%	-19.20%	-9.3%	0%
Segregation Ratio of Recycling	50%	28.08%	12.67%	52.25%
	25%	11.12%	4.43%	21.56%
	-25%	-11.12%	-4.43%	-21.56%
	-50%	-28.08%	-12.67%	-52.25%

6.3.1 Analysis of change in distance

Following figures explain the sensitivity analysis by measures of each objective function with respect to changing of each parameter. Figure 13 shows the percentage change in cost of transportation by changing the distance by 50%, 25%, -25% and -50%. The change in value of cost of transportation is 35.09%, 6.12%, -6.12% and -35% respectively.

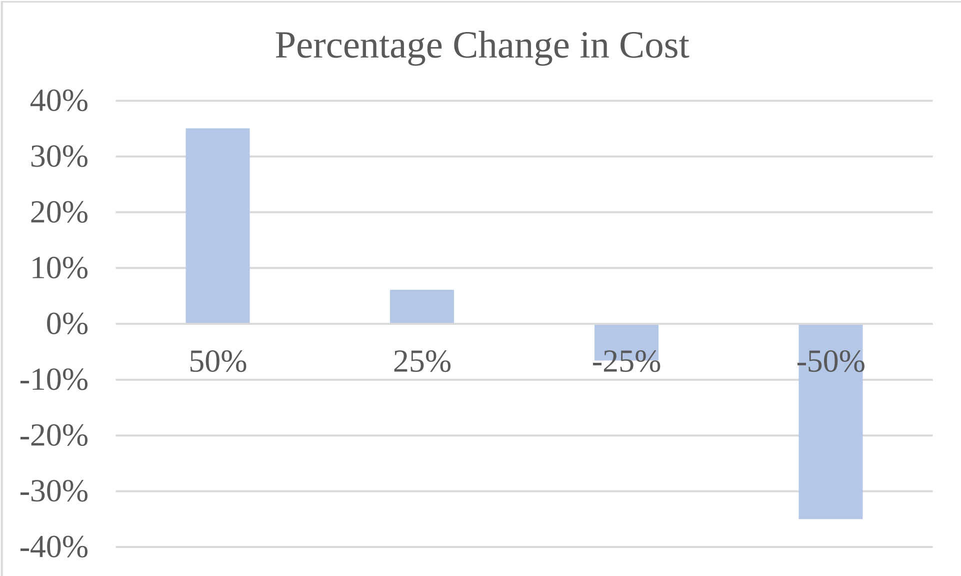

Figure 6-18: Change in Cost by Changing Distance

Following figure 6-19, shows the change in Green House Gas emissions of transportation by changing the distance by 50%, 25%, -25% and -50%. The percentage change is 33.18%, 16.75%, -16.75% and -33.18% respectively.

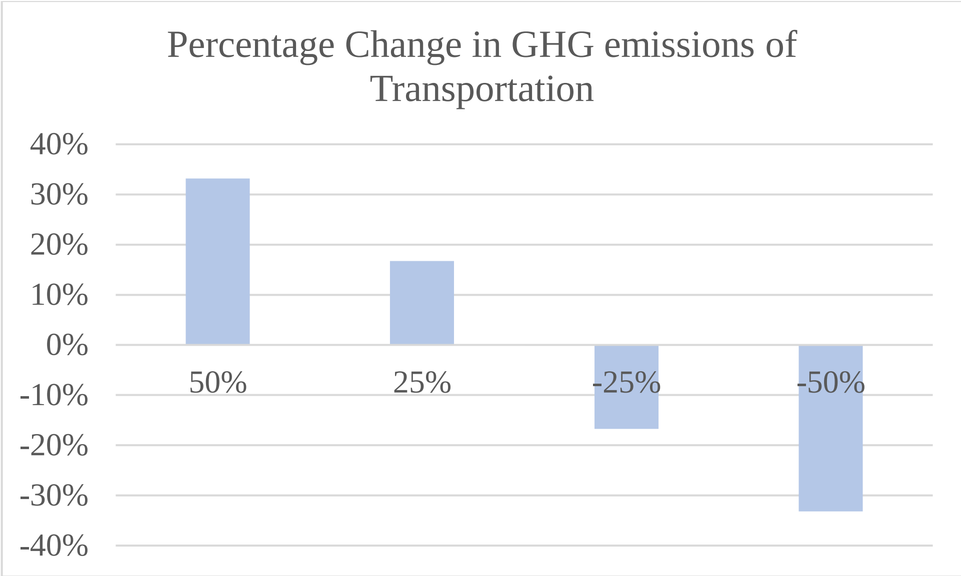

Figure 6-19: Change in GHG by changing distance

Changing distance does not have any impact on the third objective that is maximizing emission saving by waste management activities. The effect is shown in table 18 as 0 percent but graph is not shown here.

6.3.2 Analysis of change in load

Following figures show the change in value of objective functions cost of transportation and GHG of transportation by changing the load that is carried by vehicle. The first figure in this section figure 15 shows the changes by percentage in cost of transportation by changing the value of load carried by vehicles by 50%, 25%, -25% and -50%. The values are 19.32%, 6.9%, -6.9% and -19.20% respectively.

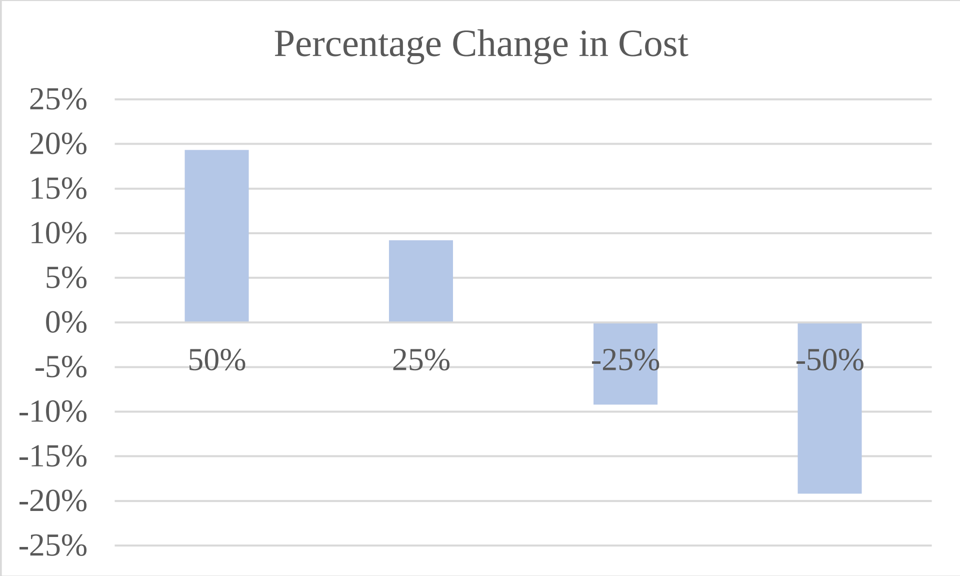

Figure 6-20: Change in Cost e by Changing Load

Following figure 6-21 shows the changes in second objective Green House Gas emission from transportation by changing the value of load carried by vehicles by 50%, 25%, -25% and -50%. The result of this analysis is 9.3%, 4.5%, -4.5% and 9.3%, respectively.

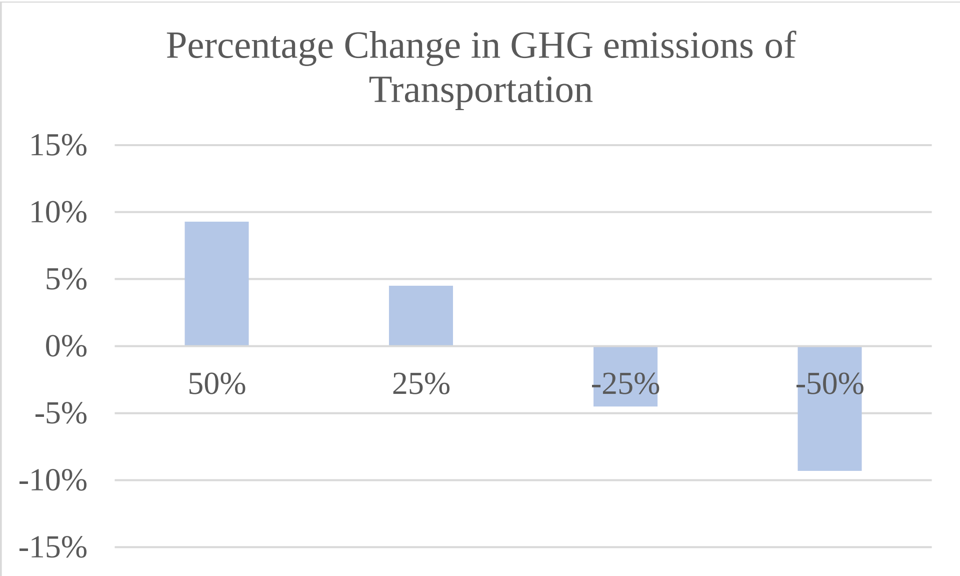

Figure 6-0-21: Change in GHG by changing in Load

There is no effect of changing the load on the third objective that is maximizing the emission saving by waste management activities. The effect is shown in table 19 by zero percent so no graph is plotted here.

6.3.3 Analysis of change in segregation ratio of recycling

Following figures show the change in value of objective functions cost of transportation and GHG of transportation and maximizing the emissions saving by waste management activities by changing the segregation ratio of recycling. The first figure in this section figure 6-22 shows the changes by percentage in cost of transportation by changing the segregation ratio of recycling by 50%, 25%, -25% and -50%. The values are 28.08%, 11.2%, -11.2% and -28.08% respectively.

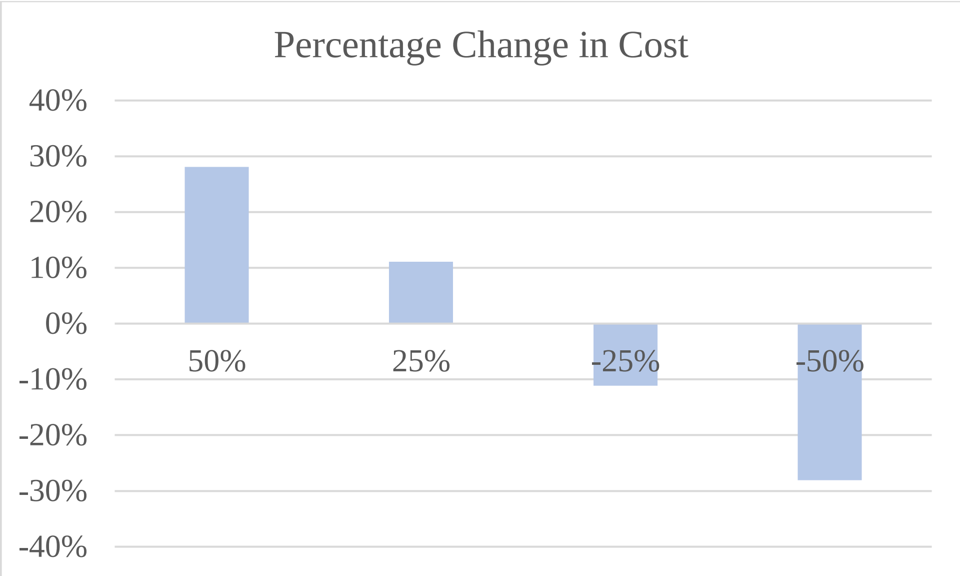

Figure 6-22: Change in Cost by Changing Segregation Ratio of Recycling

Following figure 6-33 shows the changes in second objective Green House Gas emission from transportation by changing the segregation ratio of recycling by 50%, 25%, -25% and -50%. The value in percentage change are 12.67%, 4.43%, -4.43% and -12.67%, respectively.

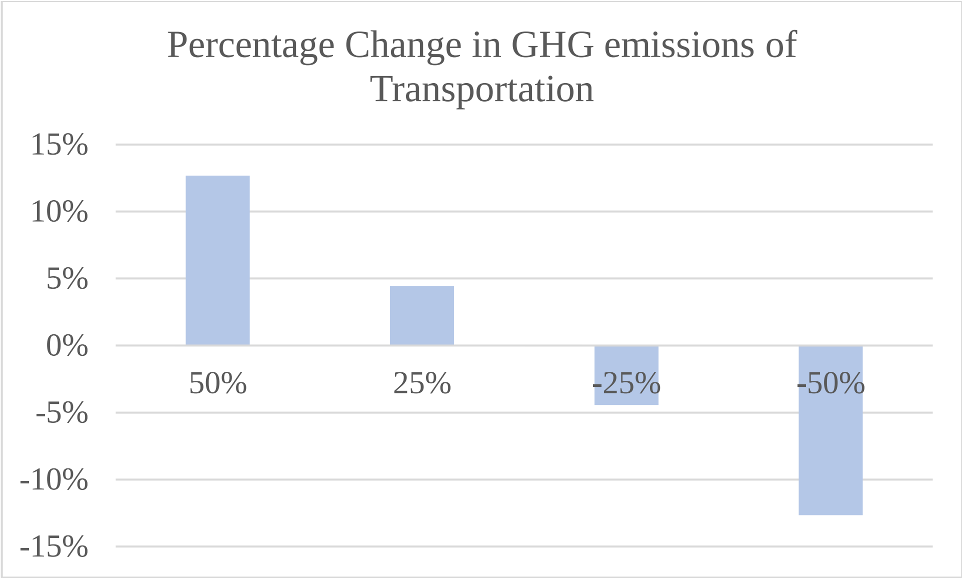

Figure 6-23: Change in GHG by changing Ratio of Recycling

Following figure 6-24 shows the change in third objective emission saved by waste management activities by changing the value of segregation ratio of recycling by 50%, 25%, -25% and -50%. The percentage value changed is 52.25%, 21.56%, -21.56% and -52.25%, respectively.

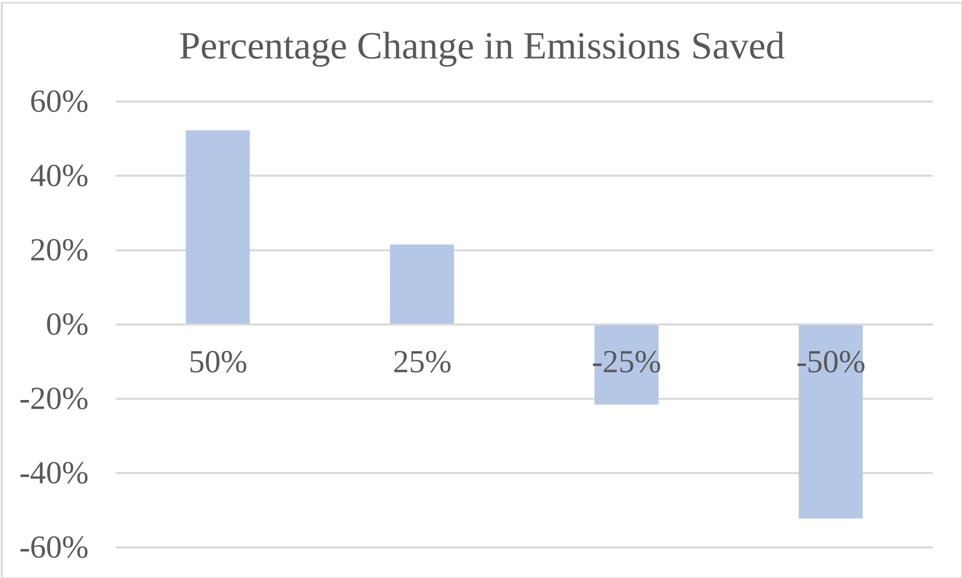

Figure 6-24: Change in emission saved by changing Ratio of recycling

6.4 Summary of the chapter

The proposed multi-objective model for designing a green supply chain network design for waste management is solved and optimized using MATLAB R2022a. The results showed that an optimal cost of transportation of 800 kg waste in six time periods is PKR 686,830. Cost for one time period is PKR 30,628.3. This cost can be minimized by moving vehicle depots nearer to the waste sites. Cost of moving waste from four waste sites towards sortation center is 22.76%, PKR 1563,00 for six time periods. Cost for one time period is PKR 26,050. This cost can be reduced by proper streamlined allocation of waste, enhancing quality of roads, proper vehicle utilization and proper allocation of routes. Cost of moving waste towards waste management facilities i.e., recycling center, incineration center and landfill are 27.21% (PKR 186,890), 17.61% (PKR 120,930) and 3.02% (PKR 20,765). These costs are cumulative for six time periods. For single time period the costs are PKR 31,148.3, PKR 20,115 and PKR 3,460.6 respectively for recycling center, incineration center and landfill. Last component of cost is the cost of maintenance of vehicles. This constitutes of 2.65% that is PKR 18,186 for six time periods. The cost of maintenance for a single time period is PKR 3,031.

The optimal value of the function is 5,655.9 $KgCO_2$. Since the vehicles are not moving in their full capacity this value will increase under full capacity but more waste will be moved, so overall value of GHG emissions will be decreased. GHG emission when vehicle move from vehicle depots to waste sites is 38.49% that is 2,176.83 $KgCO_2$/L for six time periods. For single time period the value is 362.80 $KgCO_2$/L. These emissions can be saved by moving vehicle depots nearer to the waste sites. GHG emissions when vehicles move towards sortation center are 32.53% of the total emissions in the supply network i.e., 1,839.8 $KgCO_2$/L for six time periods. GHG emissions for single time period in this node is 306.64 $KgCO_2$/L. These emissions can be reduced by utilizing the capacity of the vehicles and moving more waste using less vehicles. The Green House Gas Emissions while transferring waste towards facilities that are recycling, incineration and landfill are 16.43% i.e., 929.44 $KgCO_2$/L, 10.66% i.e., 602.85 $KgCO_2$/L and 1.89% i.e., 106.9 $KgCO_2$/L, respectively for six time periods. The values for GHG of transportation in these nodes are 154.9 $KgCO_2$/L, 100.5 $KgCO_2$/L and 17.81 $KgCO_2$/L respectively.

The third objective maximizing emission saving of waste by waste management activities is solved and recycling is assigned more than 50% of the waste and the value it saves 2970 kg CO_2 by recycling 450 kgs of waste. Incineration releases 1260 kg CO_2 by incinerating 300 kgs of waste. Landfill releases 330 kg CO_2 by 50 kg of waste. So total emissions saved by this are 1380 kg CO_2. Other analysis on the basis of different scenarios is also done. After in-depth analysis and results, a sensitivity analysis is also performed on some major parameters by changing their values by -50%, +50%, -25% and +25%. The parameter whose values are changed to see the results are distance between nodes, cost of vehicle selection and capacity of vehicle.

Chapter 7: Comparison of Methodologies

In this chapter interactive multi-objective fuzzy programming is compared with goal programming and results are discussed.

7.1 Comparison of Methodology

The designed green supply chain network design for waste management has been optimized using the interactive multi-objective fuzzy programming. For comparison purposes, the interactive multi-objective fuzzy programming has been compared to two other multi-objective approaches (1) Goal Programming, and (2) augmented Ɛ-constraint method. The comparison has been performed on three criterions, (1) Objective functions, (2) number of iterations and (3) computational time. The software used for these approaches is MATLAB R2022a. For criteria objective function, the optimal value of each objective function, minimization of cost of transportation, Minimization of GHG of transportation and maximizing the saving emission due to waste management activities is calculated. The cost is calculated in Pakistani Rupees, the GHG emissions are calculated in Kg, and emissions from waste is also calculated in Kg. The criterions of number of iterations and computational time are checked after the optimal results. The comparing unit of computational time is seconds.

7.2 Goal Programming

In the actual world, multi-criteria decision-making difficulties are common. It allows you to derive an appropriate solution by satisfying many requirements in the model. Each requirement in a goal programming problem has a target value that must be met. Goal programming is straightforward to use (Jayaraman et al., 2017), hence it may be implemented to a wide range of applications such as stock management, human resource management, marketing, quality control, production management, and operation management. Despite the linear programming paradigm, which determines the solution directly by optimizing objectives, goal programming attempts to minimize undesirable deviations between the goal's ambition level and the ideal solution. There are two sorts of constraints in the goal programming problem: system constraints and goal constraints. The system constraints are framed using linear programming, whereas extra constraints are goal constraints. In a lexicographical sense, the goal programming approach minimizes undesirable deviations. This method determines the best solution to a problem by addressing many sub-problems in order of importance for each aim. Priority vice opposite, a sub-problem is handled to minimize undesirable deviation variables from the current goal. Then, the value of the deviation variable becomes a constraint for the next sub-problem, which is addressed to minimize unwanted departure from the next goal on a priority basis (Romero, 2004).

The following equation shows the equations used in goal programming methodology to solve the model.

$$prob.objective = (f1 / fval11) + (f2 / favl22) + (1 - (f3 / fval33)) \quad (7.1)$$

Following table 7-1 shows the difference between the results of goal programming and Interactive multi-objective fuzzy programming.

Table 7-1: Comparison of Methodologies

Methodology	**Value of Cost Function (PKR)**	**Value of GHG of transportation Function kg CO_2**	**Value of Emissions saving through waste management activities function kg CO_2**	**CPU Time (sec)**
Interactive multi-objective fuzzy programming	585,770	5,057.3	1,140	0.51
Goal Programming	660,790	5,075.3	1,380	0.90

Chapter 8: Conclusion

8.1 Conclusion

The amount of waste dumped directly to landfills and improper disposal of waste causes major effects on environment and human health. This leads to land, air and water pollution. Major cause of water scarcity is improper waste management. Burning of waste under uncontrollable conditions causes lungs diseases. Transportation of waste also causes emission of GHG in environment. Finally, improper waste management endangers ecosystems, jeopardizes human health, and exacerbates the current worldwide environmental disaster. Recycling is one of the major contributions towards saving the environment. To counter these issues, a green supply chain network design is presented in this research which has three objective functions i.e., minimizing cost of transportation, minimizing GHG emission due to transportation and maximizing saving of emissions from waste. The distance between all nodes i.e., waste sites, sortation centers, recycling center, incineration center and landfill contribute majorly in cost of transportation as well as in GHG emissions. The segregation of waste at sortation center contributes towards the emission saved. The function of saving emissions constitutes of recycling of waste, incineration of waste and landfilling. Our research contributes towards major recycling of waste for saving of emissions. The designed network is also optimized using Interactive multi-objective fuzzy programming to avoid impractical and unrealistic modeling. A numerical example is considered for the case of Saaf Suthra Sheher and sensitivity analysis is performed.

The ability of the optimized multi-objective model to evaluate the performance of the waste management supply chain determines its effectiveness. It also assists decision-makers in making vital decisions to limit the environmental impact of waste in the aftermath of global warming and its severe consequences. The results of the proposed multi-objective model also confirm the capability of the developed decision assistance tool in terms of meeting the research objectives. The results of optimizing the model shows the factors that are majorly responsible for cost contribution. Six different types of costs are incurred in transportation process. GHG emissions depends on the weight carried by vehicles as well as its fuel consumption rate. The sensitivity analysis shows that changing distance between nodes effects the cost and GHG transportation of waste. A comparison between interactive fuzzy programming, goal programming and augmented Ɛ-constraint method is also performed. This research can be extended in the future considering (1) training of population for waste segregation, (2) taking food waste into account and (3) profit of the waste management company.

This research has its own limitations. We have not considered the all type of waste that is being produced in households. For future research, the food waste from house-holds can be considered and the researcher can work on getting organic fertilizers from food waste. The other limitation of this research is to study the problem on full capacity of vehicles and study the effect on cost and green house gas emissions. In the emission savings objective we have not considered the emissions that are due to transportation. It can be studies in future and overall impact in terms of emissions can be calculated.

8.2 Practical Implications

The proposed multi-objective green supply chain network for waste management is optimized for real case scenario. It can be used as decision support tool for decision makers to take beneficial and critical decisions. It can help in implementing in different policies to reduce the impact of waste on environment and save the environment for our future generations. Waste management companies can generate revenues and work for the betterment of society. The government can imply policies regarding waste management on individual level to reduce the landfilling.

In the scenario of Pakistan, no precautions and action are being taken on national levels. Pakistan faces serious challenge of waste management and faces global warming and land pollution. Higher authorities of Pakistan can follow this model to benefit the country needs and make an impact according to sustainable development goals.

References

ABD EL-WAHED, W. F. 2001. A multi-objective transportation problem under fuzziness. *Fuzzy sets and systems,* 117**,** 27-33.

ABDELFATTAH, W. 2021. A parametric approach to solve neutrosophic linear programming models. *Journal of Information and Optimization Sciences,* 42**,** 631-654.

ADEDIBU, A. A. 1985. A comparative analysis of solid waste composition and generation in two cities of a developing nation. *Environmentalist,* 5**,** 123-127.

AHMADINI, A. A. H., MODIBBO, U. M., SHAIKH, A. A. & ALI, I. 2021. Multi-objective optimization modelling of sustainable green supply chain in inventory and production management. *Alexandria Engineering Journal,* 60**,** 5129-5146.

ALIAHMADI, S. Z., BARZINPOUR, F. & PISHVAEE, M. S. 2021. A novel bi-objective credibility-based fuzzy model for municipal waste collection with hard time windows. *Journal of Cleaner Production,* 296**,** 126364.

ANURADHA, D., JAYALAKSHMI, M., DEEPA, G. & SUJATHA, V. Solution of multi-objective solid transportation problem in fuzzy approach. AIP Conference Proceedings, 2019. AIP Publishing LLC, 020009.

AUTOMOTIVE, P. 2021. https://www.pakautomotive.com/p/hyundai-porter-h-100-car-models-in.html.

BABAEE TIRKOLAEE, E., ABBASIAN, P., SOLTANI, M. & GHAFFARIAN, S. A. 2019. Developing an applied algorithm for multi-trip vehicle routing problem with time windows in urban waste collection: A case study. *Waste Management & Research,* 37**,** 4-13.

BARZINPOUR, F. & TAKI, P. 2018. A dual-channel network design model in a green supply chain considering pricing and transportation mode choice. *Journal of Intelligent Manufacturing,* 29**,** 1465-1483.

BELTRAMI, E. J. & BODIN, L. D. 1974. Networks and vehicle routing for municipal waste collection. *Networks,* 4**,** 65-94.

BENJAMIN, A. M. & BEASLEY, J. E. 2010. Metaheuristics for the waste collection vehicle routing problem with time windows, driver rest period and multiple disposal facilities. *Computers & Operations Research,* 37**,** 2270-2280.

BING, X., DE KEIZER, M., BLOEMHOF-RUWAARD, J. M. & VAN DER VORST, J. G. 2014. Vehicle routing for the eco-efficient collection of household plastic waste. *Waste management,* 34**,** 719-729.

BIT, A., BISWAL, M. & ALAM, S. 1993. Fuzzy programming approach to multiobjective solid transportation problem. *Fuzzy sets and systems,* 57**,** 183-194.

BORONOOS, M., MOUSAZADEH, M. & TORABI, S. A. 2021. A robust mixed flexible-possibilistic programming approach for multi-objective closed-loop green supply chain network design. *Environment, Development and Sustainability,* 23**,** 3368-3395.

BRAEKERS, K., RAMAEKERS, K. & VAN NIEUWENHUYSE, I. 2016. The vehicle routing problem: State of the art classification and review. *Computers & Industrial Engineering,* 99**,** 300-313.

BRAHNEY, J., HALLERUD, M., HEIM, E., HAHNENBERGER, M. & SUKUMARAN, S. 2020. Plastic rain in protected areas of the United States. *Science,* 368**,** 1257-1260.

BUENROSTRO, O., BOCCO, G. & CRAM, S. 2001. Classification of sources of municipal solid wastes in developing countries. *Resources, Conservation and Recycling,* 32**,** 29-41.

CHAKRABORTY, J., MUKHERJEE, S. & SAHOO, L. 2023. Intuitionistic fuzzy multi-index multi-criteria decision-making for smart phone selection using similarity measures in a fuzzy environment. *J. Ind Intell,* 1**,** 1-7.

CHEN, L.-H. & TSAI, F.-C. 2001. Fuzzy goal programming with different importance and priorities. *European journal of operational research,* 133**,** 548-556.

CHEN, N., CAI, J., MA, Y. & HAN, W. 2021. Green supply chain management under uncertainty: a review and content analysis. *International Journal of Sustainable Development & World Ecology***,** 1-17.

CLÍMACO, J. N., ANTUNES, C. H. & ALVES, M. J. 1993. Interactive decision support for multiobjective transportation problems. *European Journal of Operational Research,* 65**,** 58-67.
DAS, S., GOSWAMI, A. & ALAM, S. 1999. Multiobjective transportation problem with interval cost, source and destination parameters. *European Journal of Operational Research,* 117**,** 100-112.
DAS, S., LEE, S. H., KUMAR, P., KIM, K.-H., LEE, S. S. & BHATTACHARYA, S. S. 2019. Solid waste management: Scope and the challenge of sustainability. *Journal of cleaner production,* 228**,** 658-678.
DE BRUECKER, P., BELIËN, J., DE BOECK, L., DE JAEGER, S. & DEMEULEMEESTER, E. 2018. A model enhancement approach for optimizing the integrated shift scheduling and vehicle routing problem in waste collection. *European Journal of Operational Research,* 266**,** 278-290.
DUBOIS, D., FARGIER, H. & PRADE, H. 1996. Refinements of the maximin approach to decision-making in a fuzzy environment. *Fuzzy sets and systems,* 81**,** 103-122.
EDALATPOUR, M., MIRZAPOUR AL-E-HASHEM, S., KARIMI, B. & BAHLI, B. 2018. Investigation on a novel sustainable model for waste management in megacities: A case study in tehran municipality. *Sustainable cities and society,* 36**,** 286-301.
EGHBALI, H., ARKAT, J. & TAVAKKOLI-MOGHADDAM, R. 2022. Sustainable supply chain network design for municipal solid waste management: A case study. *Journal of Cleaner Production,* 381**,** 135211.
ELHEDHLI, S. & MERRICK, R. 2012. Green supply chain network design to reduce carbon emissions. *Transportation Research Part D: Transport and Environment,* 17**,** 370-379.
EMRE EREN, U. R. T. 2021. Safe distance-based vehicle routing problem: Medical waste collection case

study in COVID-19 pandemic *Computers & Industrial Engineering* 157.
FAIRWHEELS 2021. https://fairwheels.com/cars-overviews/19892/hyundai-shehzore-best-selling-truck-is-now-hyundai-porter-h-100-in-pakistan/.
GUPTA, K. & ARORA, R. 2021. Three dimensional bounded transportation problem. *Yugoslav Journal of Operations Research,* 31**,** 121-137.
HAILIN WU, F. T., BO YANG 2020. Optimization of Vehicle Routing for Waste Collection and Transportation. *International Journal of Environmental Research and Public Health,* 17**,** 26.
HANNAN, E. L. 1981. Linear programming with multiple fuzzy goals. *Fuzzy sets and systems,* 6**,** 235-248.
HANNAN, M., AKHTAR, M., BEGUM, R., BASRI, H., HUSSAIN, A. & SCAVINO, E. 2018. Capacitated vehicle-routing problem model for scheduled solid waste collection and route optimization using PSO algorithm. *Waste management,* 71**,** 31-41.
HAQUE, S., BHURJEE, A. & KUMAR, P. 2022. Multi-objective non-linear solid transportation problem with fixed charge, budget constraints under uncertain environments. *Systems Science & Control Engineering,* 10**,** 899-909.
HEINEN, J. T. 1995. A review of, and research suggestions for, solid-waste management issues: The predicted role of incentives in promoting conservation behaviour. *Environmental Conservation,* 22**,** 157-166.
HOORNWEG, D. & BHADA-TATA, P. 2012. What a waste: a global review of solid waste management.
HUSSEIN, M. L. 1998. Complete solutions of multiple objective transportation problems with possibilistic coefficients. *Fuzzy Sets and Systems,* 93**,** 293-299.
ISERMANN, H. 1979. The enumeration of all efficient solutions for a linear multiple-objective transportation problem. *Naval Research Logistics Quarterly,* 26**,** 123-139.
JAYARAMAN, R., COLAPINTO, C., LA TORRE, D. & MALIK, T. 2017. A Weighted Goal Programming model for planning sustainable development applied to Gulf Cooperation Council Countries. *Applied Energy,* 185**,** 1931-1939.

JOSE CARLOS MOLINA, I. E., JESUS RACERO 2019. Reducing pollutant emissions in a waste collection vehicle routing problem using a variable neighborhood tabu search algorithm: a case study. *TOP*.

JUYOUNG WY , B.-I. K., SEONGBAE KIM B 2013. The rollon–rolloff waste collection vehicle routing problem with time windows. *European Journal of Operational Research,* 224**,** 466-476.

KANE, L., SIDIBE, H., KANE, S., BADO, H., KONATE, M., DIAWARA, D. & DIABATE, L. 2021. A simplified new approach for solving fully fuzzy transportation problems with involving triangular fuzzy numbers. *Journal of fuzzy extension and applications,* 2**,** 89-105.

KIM, B.-I., KIM, S. & SAHOO, S. 2006. Waste collection vehicle routing problem with time windows. *Computers & Operations Research,* 33**,** 3624-3642.

KLEMEŠ, J. J., VAN FAN, Y., TAN, R. R. & JIANG, P. 2020. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. *Renewable and Sustainable Energy Reviews,* 127**,** 109883.

KLIMISCH, H.-J., ANDREAE, M. & TILLMANN, U. 1997. A systematic approach for evaluating the quality of experimental toxicological and ecotoxicological data. *Regulatory toxicology and pharmacology,* 25**,** 1-5.

KOUL, B., YAKOOB, M. & SHAH, M. P. 2022. Agricultural waste management strategies for environmental sustainability. *Environmental Research,* 206**,** 112285.

KUMAR, R., EDALATPANAH, S., JHA, S. & SINGH, R. 2019. A Pythagorean fuzzy approach to the transportation problem. *Complex & intelligent systems,* 5**,** 255-263.

KUWANO, H. 1996. On the fuzzy multi-objective linear programming problem: Goal programming approach. *Fuzzy Sets and Systems,* 82**,** 57-64.

LEBERLING, H. 1981. On finding compromise solutions in multicriteria problems using the fuzzy min-operator. *Fuzzy sets and systems,* 6**,** 105-118.

LI, L. & LAI, K. K. 2000. A fuzzy approach to the multiobjective transportation problem. *Computers & Operations Research,* 27**,** 43-57.

LOUATI, A. 2016. Modeling municipal solid waste collection: A generalized vehicle routing model with multiple transfer stations, gather sites and inhomogeneous vehicles in time windows. *Waste Management,* 52**,** 34-49.

LUHANDJULA, M. 1982. Compensatory operators in fuzzy linear programming with multiple objectives. *Fuzzy sets and systems,* 8**,** 245-252.

MARIAGRAZIA DOTOLI, N. E. 2017. A Vehicle Routing Technique for Hazardous Waste Collection. *IFAC Papers Online,* 50**,** 5.

MASKURIY, R., SELAMAT, A., ALI, K., MARESOVA, P., KREJCAR, O., KUCA, K. & MOHD, S. Man-made Disaster Prevention using Waste Management Hierarchy and Disaster Management Cycle. IOP Conference Series: Earth and Environmental Science, 2020. IOP Publishing, 012004.

MEXICANA, N. 1994. Secretaría de comercio y fomento industrial. *Materiales,* 3**,** 5.

MOHSENIZADEH, M., TURAL, M. K. & KENTEL, E. 2020. Municipal solid waste management with cost minimization and emission control objectives: A case study of Ankara. *Sustainable Cities and Society,* 52**,** 101807.

NAGAR, P., SRIVASTAVA, A. & SRIVASTAVA, P. K. 2019. Optimization of species transportation via an exclusive fuzzy trapezoidal centroid approach. *Mathematics in Engineering, Science & Aerospace (MESA),* 10.

NI-BIN CHANG, H. Y. L., Y.L.WEI 1997. GIS TECHNOLOGY FOR VEHICLE ROUTING AND SCHEDULING IN SOLID WASTE COLLECTION SYSTEMS. *Journal of Enviornmental Engineering,* 123**,** 9.

NURPRIHATIN FILSCHA, L. A. 2020. Waste Collection Vehicle Routing Problem Model with Multiple Trips, Time Windows, Split Delivery, Heterogeneous Fleet and Intermediate Facility. *ENGINEERING JOURNAL-THAILAND,* 24**,** 55-64.

OLAPIRIYAKUL, S., PANNAKKONG, W., KACHAPANYA, W. & STARITA, S. 2019. Multiobjective optimization model for sustainable waste management network design. *Journal of Advanced Transportation,* 2019.

PLUS, A. C. 2020. Municipal waste management and COVID-19. *Retrieved from ACR Plus: https://www. acrplus. org/en/municipal-waste-management-covid-19# italy*.
RATHORE, P., CHAKRABORTY, S., GUPTA, M. & SARMAH, S. 2022. Towards a sustainable organic waste supply chain: A comparison of centralized and decentralized systems. *Journal of Environmental Management,* 315**,** 115141.
REVELLE, C., COHON, J. & SHOBRYS, D. 1991. Simultaneous siting and routing in the disposal of hazardous wastes. *Transportation Science,* 25**,** 138-145.
RıZVANOĞLU, O., KAYA, S., ULUKAVAK, M. & YEŞILNACAR, M. İ. 2020. Optimization of municipal solid waste collection and transportation routes, through linear programming and geographic information system: a case study from Şanlıurfa, Turkey. *Environmental monitoring and assessment,* 192**,** 1-12.
ROMERO, C. 2004. A general structure of achievement function for a goal programming model. *European Journal of Operational Research,* 153**,** 675-686.
RYBICKA, J., TIWARI, A., DEL CAMPO, P. A. & HOWARTH, J. 2015. Capturing composites manufacturing waste flows through process mapping. *Journal of Cleaner Production,* 91**,** 251-261.
SAKAWA, M. & YANO, H. 1988. An interactive fuzzy satisficing method for multiobjective linear fractional programming problems. *Fuzzy sets and systems,* 28**,** 129-144.
SAKTHIVEL, K., GUNASEKAR, T., THIRAVIDARANI, J. & MANIKANDAN, S. 2022. Solving Assignment Problem In Fuzzy Environment By Using New Ranking Technique In Trapezoidal Fuzzy Number. *JOURNAL OF ALGEBRAIC STATISTICS,* 13**,** 1256-1262.
SCHULZE, G. 2016. Growth within: A circular economy vision for a competitive Europe. *Ellen MacArthur Foundation and the McKinsey Center for Business and Environment***,** 1-22.
SHARIF, N. S., PISHVAEE, M. S., ALIAHMADI, A. & JABBARZADEH, A. 2018. A bi-level programming approach to joint network design and pricing problem in the municipal solid waste management system: A case study. *Resources, Conservation and Recycling,* 131**,** 17-40.
SHARMA, H. B., VANAPALLI, K. R., CHEELA, V. R. S., RANJAN, V. P., JAGLAN, A. K., DUBEY, B., GOEL, S. & BHATTACHARYA, J. 2020. Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. *Resources, conservation and recycling,* 162**,** 105052.
SI, Z. H. & LI, Y. Medical Waste Treatment in Wuhan from Emergency to Stability," Xin Hua Net, 2020.
SINGH, S. & SINGH, S. 2022. A method for solving bi-objective transportation problem under fuzzy environment. *Meta-heuristic Optimization Techniques: Applications in Engineering,* 10**,** 37.
SOINI, K., JURGILEVICH, A., PIETIKÄINEN, J. & KORHONEN-KURKI, K. 2018. Universities responding to the call for sustainability: A typology of sustainability centres. *Journal of Cleaner Production,* 170**,** 1423-1432.
SRIVASTAVA, R., KRISHNA, V. & SONKAR, I. 2014. Characterization and management of municipal solid waste: a case study of Varanasi city, India. *Int. J. Curr. Res. Acad. Rev,* 2**,** 10-16.
TOTH, P. & VIGO, D. 2002. *The vehicle routing problem,* SIAM.
UNITED STATES. ENVIRONMENTAL PROTECTION AGENCY. OFFICE OF SOLID, W., EMERGENCY, R., UNITED STATES. OFFICE OF SOLID WASTE, M. & INDUSTRIAL SOLID WASTE, D. 1994. *Characterization of Municipal Solid Waste in the United States: 1994 Update,* US Environmental Protection Agency, Solid Waste and Emergency Response.
VANAPALLI, K. R., SHARMA, H. B., RANJAN, V. P., SAMAL, B., BHATTACHARYA, J., DUBEY, B. K. & GOEL, S. 2021. Challenges and strategies for effective plastic waste management during and post COVID-19 pandemic. *Science of The Total Environment,* 750**,** 141514.
VERMA, R., BISWAL, M. & BISWAS, A. 1997. Fuzzy programming technique to solve multi-objective transportation problems with some non-linear membership functions. *Fuzzy sets and systems,* 91**,** 37-43.

WALTHO, C., ELHEDHLI, S. & GZARA, F. 2019. Green supply chain network design: A review focused on policy adoption and emission quantification. *International Journal of Production Economics,* 208**,** 305-318.
WAN, C., SHEN, G. Q. & CHOI, S. 2019. Waste management strategies for sustainable development.
WANG, F., LAI, X. & SHI, N. 2011. A multi-objective optimization for green supply chain network design. *Decision support systems,* 51**,** 262-269.
WU, H., TAO, F., QIAO, Q. & ZHANG, M. 2020a. A chance-constrained vehicle routing problem for wet waste collection and transportation considering carbon emissions. *International journal of environmental research and public health,* 17**,** 458.
WU, H., TAO, F. & YANG, B. 2020b. Optimization of vehicle routing for waste collection and transportation. *International Journal of Environmental Research and Public Health,* 17**,** 4963.
WUTTKE, J. 2018. The Circular Economy Package of the European Union. *Factor X: Challenges, Implementation Strategies and Examples for a Sustainable Use of Natural Resources***,** 251-262.
XIAO, Y., ZHAO, Q., KAKU, I. & XU, Y. 2012. Development of a fuel consumption optimization model for the capacitated vehicle routing problem. *Computers & operations research,* 39**,** 1419-1431.
YANG, M., EVANS, S., VLADIMIROVA, D. & RANA, P. 2017. Value uncaptured perspective for sustainable business model innovation. *Journal of Cleaner Production,* 140**,** 1794-1804.
ZACHO, K. O., MOSGAARD, M. & RIISGAARD, H. 2018. Capturing uncaptured values—A Danish case study on municipal preparation for reuse and recycling of waste. *Resources, Conservation and Recycling,* 136**,** 297-305.
ZHANG, C., SU, H., BAEYENS, J. & TAN, T. 2014. Reviewing the anaerobic digestion of food waste for biogas production. *Renewable and Sustainable Energy Reviews,* 38**,** 383-392.
ZHANG, J., QIN, Q., LI, G. & TSENG, C.-H. 2021. Sustainable municipal waste management strategies through life cycle assessment method: A review. *Journal of Environmental Management,* 287**,** 112238.
ZHAO, J. & ZHU, F. 2016. A multi-depot vehicle-routing model for the explosive waste recycling. *International Journal of Production Research,* 54**,** 550-563.
ZIMMERMANN, H.-J. 1978. Fuzzy programming and linear programming with several objective functions. *Fuzzy sets and systems,* 1**,** 45-55.