MUNICIPAL SOLID WASTE MANAGEMENT WITH COST MINIMIZATION AND EMISSION CONTROL OBJECTIVES

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ABSTRACT

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Proper management of municipal solid waste (MSW) has been a crucial aspect of every society due to its social, environmental, and economic impacts. Operations research techniques have frequently focused on cost minimization objectives in locational planning of municipal solid waste management (MSWM) systems. However, transportation constitutes an integral part of this system producing a considerable amount of greenhouse gas (GHG) emissions. Therefore, sustainable management of MSW systems with GHG emissions minimization considerations is necessary to preserve the resources and protect the environment. In this thesis, we investigate the interplay between system cost and carbon dioxide (CO_2) emissions resulting from transportation activities in locational planning of MSWM system by minimizing them in a bi-objective mixed integer linear programming model. The amount of emitted CO_2 is assumed to be proportional to fuel consumption of vehicles which is calculated by a microscopic model incorporating various factors such as vehicle speed, load, and technical characteristics. The proposed model is applied to MSWM system of Ankara to introduce transfer stations (TSs). Two extensions of the current

system are examined, namely, the extended and hybrid systems, where MSW is only transported through TSs in the former, while direct shipments are also allowed in the latter. For both extensions, it is observed that with no or little increase in system cost, considerable savings in CO_2 emissions can be achieved. Moreover, simulation analyses are performed to investigate the impact of speed variations on resulting CO_2 emissions and system cost.

Keywords: Municipal solid waste management, green transportation, CO_2 emission, facility location, bi-objective optimization

ÖZ

MALİYET AZALTMA VE EMİSYON KONTROLÜ HEDEFLERİ İLE BELEDİYE KATI ATIK YÖNETİMİ

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Belediye katı atıklarının (BKA) doğru yönetimi, sosyal, çevresel ve ekonomik etkileri nedeniyle her toplumun çok önemli bir konusu olmuştur. Yöneylem araştırması teknikleri sıklıkla belediye katı atık yönetimi (BKAY) sistemlerinin bölgesel planlamasında maliyet azaltma hedeflerine odaklanmıştır. Oysa, taşımacılık bu sistemin ayrılmaz bir parçası olarak kayda değer miktarda sera gazı emisyonu üretmektedir. Bu nedenle, sera gazı emisyonlarını enazlamak düşüncesiyle bu sistemin sürdürülebilir yönetimi, kaynakları ve çevreyi korumak için gereklidir. Bu tez çalışmasında, BKAY sisteminin yerleşim planlamasında sistem maliyeti ile taşımacılık faaliyetlerinden kaynaklanan karbondioksit (CO_2) emisyonu arasındaki etkileşimi araştırmak için onları bir iki-hedefli karışık tamsayılı doğrusal programlama modelinde enazlamaya çalışıyoruz. Salınan CO_2 miktarının, aracın hızı, yükü ve teknik özellikleri gibi çeşitli faktörleri içeren bir mikroskobik model ile hesaplanan yakıt tüketimiyle doğru orantılı olduğu varsayılmıştır. Önerilen model, Ankara BKAY sisteminde transfer istasyonları (Tİ'ler) açmak için uygulanmıştır. Mevcut sistemin iki uzantısı, yani, BKA'nın yalnızca Tİ'lerle taşındığı genişletilmiş sistem, ve doğrudan gönderilere de

izin verilen hibrit sistem, incelenmiştir. Her iki uzantı için, sistem maliyetinde hiç veya az bir artışla birlikte, CO_2 emisyonunda önemli tasarruflar sağlanabileceği gözlenmiştir. Ayrıca, hız değişimlerinin ortaya çıkan CO_2 emisyonu ve sistem maliyeti üzerindeki etkisini araştırmak için simülasyon analizleri yapılmıştır.

Anahtar Kelimeler: Belediye katı atık yönetimi, Yeşil taşımacılık, CO_2 emisyonu, Tesis yerseçimi; iki-hedefli optimizasyon

To my mother...

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LIST OF ABBREVIATIONS

SWM	Solid Waste Management
MSW	Municipal Solid Waste
MILP	Mixed Integer Linear Programming
MSWM	Municipal Solid Waste Management
GHG	Greenhouse Gas
FC	Fuel Consumption
TSs	Transfer Stations
P&T	Processing and Treatment
SL	Sanitary Landfill
CMEM	Comprehensive Modal Emission Model
GIS	Geographical Information Systems
NLMIP	Non-Linear Mixed Integer Programming
NLP	Non-Linear Programming
Int.P	Interval Programming
IBPP	Interval-Based Possibilistic Programming

CHAPTER 1

INTRODUCTION

1.1 Motivation and Problem Definition

The increasing amount of solid waste worldwide as a result of urbanization, industrialization, and economic growth, and its subsequent impacts on communities has made solid waste management (SWM) one of the crucial issues for societies to consider. The growing unsustainable consumption behaviors as well as unconcerned deployment of natural resources throughout societies result in generation of additional levels of solid waste creating threatening issues regarding environmental degradation, human health, and natural resources exhaustion [42].

According to Badran and El-Haggar [6], solid waste divides into three main categories: municipal, industrial, and agricultural. Among these categories, municipal solid waste (MSW) is of particular importance due to its variable composition and constant generation by the public, demanding timely and efficient handling with high levels of economic and operational tactics.

The definition of MSW varies based on the strategies that have been used in its management practices. Eurostat [1] defines MSW as a waste which is generally produced by households in addition to the waste generated by commerce, offices, and public institutions. According to United States Environmental Protection Agency (USEPA) [55], MSW includes waste from residential (incorporating multi-family housing waste), commercial, and institutional sources (e.g., schools, businesses, and hospitals) and excludes industrial, construction, and hazardous waste. Moreover, McDougall et al. [37] classify MSW as commercial and household wastes which comprises a comparatively small share of solid waste, however having critical political impacts.

Decision making methodologies have studied SWM systems by focusing on their various aspects, namely economic, environmental, social, technical, and political. However, there is no work in the literature which incorporates all of such aspects together [23] and one of the main difficulties is to include different aspects simultaneously into a decision making process.

SWM involve strategic, tactical, and operational level decisions where operations research techniques can be utilized to tackle integrated decision making problems in this context [23]. Operations research techniques widely employ mixed integer linear programming (MILP) and are commonly centered around economic aspects. However, incorporating various aspects in different decision making levels within a multi-objective optimization framework is imperative to maintain a comprehensive management of solid waste.

Modeling a SWM system from operations research perspective requires studying it as a multi-echelon supply chain in which activities such as generation, collection, transportation, sorting, recovery, recycling, treatment, and landfilling take place [23]. A SWM system can be decomposed into two sub-systems, namely, regional SWM system and collection system [23]. The collection system involves regular activities regarding collecting solid waste from the sources of generation, mostly on a daily basis, by municipalities, private contractors, or other responsible local authorities. Besides, regional system is in charge of general treatment and disposal of the collected solid waste through a connected chain of facilities. The regional SWM system benefits from economies of scale and leads to lower operational and transportation costs. The network design, a strategic level decision, is related to the regional planning of SWM system, while districting, fleet deployment, scheduling, and routing within the regional SWM system or collection system are among the tactical and operational level decisions [23].

The concern over health and safety of SWM systems has always been an issue in societies [37]. Moreover, during the last few decades an emerging attention has been paid to the sustainable management of solid waste [55]. Sustainable management of solid waste requires performing the related operations in the most productive and environmentally friendly manner as well as extracting the value of solid waste as much as possible to preserve the natural resources, slow down the climate change, and cut the burden on the surrounding environment without impairing publics' quality of life [55]. Noted that, the term "sustainability" composes of three dimensions, namely, economic feasibility, environmental friendliness, and social acceptability where a sustainable SWM system should operate satisfying all three dimensions [37].

Extracting the value of solid waste effectively and increasing its recovery rate require installation of novel technologies and inclusion of new facilities within the SWM systems. Such adjustments would improve environmental sustainability of SWM systems at the expense of additional costs. McDougall et al. [37] suggest that an integrated SWM can deliver both economic efficiency and environmental friendliness. An integrated SWM management system is composed of various interrelated facilities (i.e., recovery, treatment, and disposal) which can deal with various types of solid waste, provided an efficient collection and sorting scheme is handling collection of solid waste from different sources [37].

The principals applying to integrated SWM systems can be utilized for municipal solid waste management (MSWM) systems as well. MSW account for one of the most heterogeneous categories of solid waste in contrast to other classes, e.g., industrial and construction, which are comparatively homogeneous [37]. In this study, the focus is centered around effective design and management of MSW systems due to their high social, political, environmental, and economic profiles. The employed methods in MSWM systems can also be utilized for effective management of other sources of solid waste because of their less complex nature compared to MSW [37].

The variable composition of MSW with respect to temporal, local, and seasonal factors as well as diverse range of included materials demand availability of different set of treatment options in an MSWM system. In addition, remote regional treatment plants and sanitary landfills have emerged in MSWM systems due to land shortage near urban centers, environmental considerations, public oppositions, and regulations in order to protect the environment and prevent potential human health risks. Emergence of regional large-scale facilities has provided the possibility of dealing with different sets of MSW streams depending on the situation, promoting economic efficiency because of the relevant economies of scale [53].

Introduction of new regional facilities within MSWM systems that are distantly located from urban areas have changed the conventional structure of MSWM systems. Thus, longer transportation routes have appeared between existing and newly introduced facilities [58]. Accordingly, transportation, which is an integral element of MSWM systems, gains more importance than before as a result of the increase in frequency and duration of vehicle trips. Subsequently, there is a need to include adverse environmental, atmospheric, and societal impacts of transportation activities in different decision making levels of MSWM systems.

Transportation imposes numerous burdens on the environment and societies such as natural resources depletion, air pollution and greenhouse gas (GHG) effect, noise, land wear, acidification, human and ecosystem toxicity [33]. As a result, the quality of life of the people, especially those living in urban areas, has been jeopardized by logistics activities due to the emission of GHGs. Among the GHG emissions, mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [56], have significant adverse effects on social and physical health of public directly and indirectly via atmospheric pollution, ozone layer depletion, and global warming potentials just to name a few.

According to USEPA [56], transportation sector accounts for the leading contributor to United States (US) GHG emissions by holding a 28% share. Besides, between 1990 and 2016, transportation sector had the largest increase in GHG emissions among all economic sectors. This issue can be attributed to increasing logistics activities by cars and heavy and light-duty vehicles. Additionally, in 2016, CO_2 emission accounted for one of the most prominent GHG emissions from US transportation sector with more than 95% share.

Such observations justify incorporation of social and environmental side effects of logistics activities into the strategic and tactical planning of supply chains. The green network design is one of the strategies that aims to reduce the harmful effects of logistics activities on the environment [15]. However, quantification of fuel consumption (FC) and resultant GHG emission is a relatively complicated process entailing inclusion of various factors such as speed, travel distance, and load.

Demir et al. [12] categorize approaches in the literature for calculation of FC with respect to their complexity. They put FC models in order as factor, macroscopic, and microscopic models, respectively. In factor models, the collected data regarding travel distance or fuel consumption are simply multiplied by an emission factor [15]. Macroscopic models consider average aggregate network parameters, e.g., average speed, and calculate emissions accordingly, while microscopic models calculate the emission more precisely with respect to instantaneous measurement of parameters [12].

Green network design of MSWM systems and subsequent reductions in GHG emissions associated with transportation activities account for one of the steps towards sustainable management of these systems. Furthermore, incorporation of green aspects of logistics activities in strategic decision making of MSWM systems is of particular importance as it assists us to understand the effects of long-term decisions such as facility location and capacity selection, MSW streams allocation, and vehicle selection on the environment along with assessing trade-offs between economic and environmental objectives. Moreover, an efficient strategic planning of MSW systems entails holding a holistic view over the entire system which is also an essential factor for integrated management of MSW [37].

In this thesis, the green network design of the regional MSWM system is going to be studied. By "green network design", we intend to design the logistics network of a regional MSWM system with the explicit goal of minimizing resultant CO_2 emission. In other words, we investigate the impact of CO_2 emission from transportation activities on locational planning of a regional MSWM system utilizing a microscopic emission model.

1.2 Proposed Methods and Models

This thesis focuses on the strategic planning of the regional integrated MSWM system by incorporating the impact of CO_2 emission from logistics activities into the decision making process. For this purpose, we evaluate the locational planning of a regional MSWM system while holding an entire picture over systems' components and functions.

A bi-objective facility location-allocation problem is considered and an MILP model is proposed to determine the optimal locations of transfer stations (TSs), processing and treatment (P&T) facilities, and sanitary landfills (SL) in an MSWM system; allocate MSW flows to such facilities; quantify the required number of vehicle trips; and determine the travel speeds of vehicles. Two objective functions are minimized namely, the total daily system cost, composed of fixed and variable costs of facilities, variable transportation cost, fuel cost, and possible monetary benefits of facilities, as well as CO_2 emission from transportation activities.

We implement a microscopic approach for quantifying FC and subsequent CO_2 emissions of vehicles by implementing the comprehensive modal emission model (CMEM) [7] which takes into account vehicle's speed, load, travel distance, and technical characteristics. Moreover, we assume that the paths connecting entities of the MSWM logistics network are split into a number of distinct segments with respect to different speed limits imposed by local or governmental legislations directly and by traffic congestion indirectly. Such an assumption is necessary due to the fact that a vehicle cannot drive with a homogeneous speed entirely on a given path; because the driving speed of vehicle dependents on different factors such as geographical, local, temporal, weather, imposed speed limits, traffic characteristics, driver behavior, and physical condition of the road. Consequently, our proposed model explicitly evaluates the travel speed of a vehicle on every road segment with respect to its optimum FC rate and segment-wise speed limits.

In order to generate the efficient solutions of the proposed model, the ϵ-constraint method [57] is implemented. Afterwards, the proposed model is applied to the MSWM system of Ankara by utilizing Geographical Information System (GIS) tools to investigate the sustainability benefits obtained by introducing TSs into the current system. Two extensions of the current system are considered; the extended one, where MSW is only transported through TSs and the hybrid one, where direct shipments are allowed in addition to indirect shipments through TSs. Even though the total daily system cost and CO_2 emission from transportation activities are conflicting objectives, we have shown that for the Ankara case, CO_2 emission can be decreased by a large amount with little or no increase in the system cost.

Eventually, the impact of speed variations of vehicles on the resulting CO_2 emissions and system cost is investigated by performing simulation analyses. The Monte Carlo simulation experiments indicate that inclusion of vehicle speed as a random variable does not yield considerable changes in the resulting CO_2 emission and system cost.

1.3 Contributions and Novelties

Our study aims to propose a green optimization approach for locational planning of the regional MSWM systems and offers the following contributions to the existing literature:

- Our model investigates locating three essential facilities that are vital for every MSWM system, namely, TSs, P&T facilities, and SLs. Besides, the recent trends regarding development of regional and large-scale facilities are taken into account.
- Three dimensions of sustainability are taken into account by formulating two objective functions addressing economic and environmental aspects directly and social aspects indirectly.
- The FC of operating vehicles in the MSWM system is calculated in detail using vehicle speed, load, travel distance, and technical characteristics by utilizing CMEM, a microscopic emission model proposed by Barth et al. [7].
- The resulting CO_2 emission from transportation activities is evaluated with respect to FC of vehicles on every road segment of the MSWM logistics network.
- Driving speed of each vehicle on every road segment is decided explicitly with respect to vehicle's optimum speed, in terms of minimum FC, as well as upper and lower speed limits imposed by legislation and traffic congestion patterns.
- The proposed model is applied to a real case study, i.e., the MSWM system of Ankara, to investigate the sustainability benefits achieved by introducing TSs which have not been utilized in MSWM system of Ankara yet.

- Detailed features of the logistics network of the considered case study are assessed by implementing a GIS analysis framework providing precise spatial data inventory.
- Simulation analyses are performed to consider vehicle speed as a random variable and examine the impact of speed variations over the MSWM logistics network of Ankara on the resulting CO_2 emission and total daily system cost.
- Overall, detailed assessment of vehicular emissions and incorporation of environmental side effects of transportation activities into the strategic decision making of MSWM systems account for the foremost contributions of the present study.

1.4 The Outline of the Thesis

The remainder of this thesis is structured as follows. The following chapter reviews the literature with a main focus on strategic decision making of waste management systems, particularly facility location problems. Chapter 3 introduces the considered green network design problem of a regional MSWM system. Besides, the employed microscopic emission model and the mathematical model of the bi-objective MSWM problem are identified in Section 3.2 and 3.3, respectively. Chapter 4 corresponds to the performed computational experiments and analyses. The MSWM system of Ankara, Turkey, is selected as a case study and the features of the considered MSWM system and transportation network are depicted in Sections 4.1 and 4.2. Finally, Chapter 5 covers the conclusion and future research directions of this thesis.

CHAPTER 2

LITERATURE REVIEW

In this chapter, we review the literature on optimization problems in SWM systems with a main focus on facility location problems. In 2014, Ghiani et al. [23] review SWM studies from operations research point of view by focusing on strategic and tactical decisions. They classify location-allocation decisions as one of the main strategic decisions made in regional planning of SWM systems. Their survey distinguishes time aspects, economies of scale, multi-commodity, and uncertainty as the main shortcomings of literature in strategic SWM problems.

Recently, Farahani et al. [19] conduct a review regarding urban service facility location problems which waste management systems account for one of the popular applications. They suggest that concurrent consideration of tactical and operational decisions with strategic decisions of waste management systems should be explored more in waste management studies. Moreover, they observe lack of including environmental and societal objectives using proper quantification methods in urban service facility location problems involving waste management systems.

2.1 Economic Objectives in SWM/MSWM Systems

According to Li and Huang [36], the first study on economic optimization of SWM systems is conducted by Anderson and Nigam [2]. Subsequently, the objective of cost minimization in SWM problems become popular among researchers. Fiorucci et al. [21] develop a decision support system for integrated planning of MSWM by solving a constrained non-linear optimization problem. They consider the composition of MSW and aim to determine the optimal MSW flows that should be sent to disposal, recycling, and treatment plants, along with the optimal selection of such facilities in the system. The number and locations of TSs, however, are fixed a priori in their model. A cost minimization objective including transportation, maintenance, and recycling costs as well as potential economic benefits of the system are considered in their mathematical optimization model.

A relatively similar general purpose model concerning management of MSW is studied by Costi et al. [11] with a particular focus on environmental impacts of the overall MSWM system. The important feature of their study is the detailed analyses of chemical composition of MSW to control resulting emissions in incinerators as well as noxious chemicals appearing in refused derived fuel and stabilized organic material. They impose strict bounds on the released amount of pollutants through formalizing constraints in their decision model. However, in both of previous studies, transportation related emissions are not considered.

Sadeghian Sharif et al. [47] model inclusion of outsourcing policies for waste treatment procedures in MSWM systems. A bi-level mathematical programming model is formulated where at the first level, the municipality decides whether to outsource treatment of MSW or establish treatment and disposal facilities on its own. At the second level, the pricing decisions are made in the auction by bidders who suggest MSW treatment services. Moreover, a heuristic approach is invented to combine two levels of the model by inserting the constraints applying to the low-level model's feasible region into the high-level model.

2.2 TSs in SWM/MSWM Systems

The problem of locating TSs in MSWM systems has been studied by different researchers because of their particular importance as transshipment nodes. TSs serve as critical consolidation points in MSWM systems by linking the collection system to the treatment and disposal facilities where collection vehicles transfer collected MSW, typically in a compacted form, to large-volume vehicles available in TSs for more economic shipment to treatment and disposal facilities. This procedure results in flexibility in locating treatment and disposal facilities, increases the efficiency of collection and regional MSWM systems, and reduces the social and environmental damages resulting from transportation activities [53].

Kulcar [35] suggests a two-phase optimization problem to determine the required number of TSs in SWM system of Brussels. In the first phase, the terminal site (a TS or an incinerator) for every collection route is distinguished and the TSs are selected among the candidate ones. In the second phase, the impact of the collection procedure on the required number of depots is investigated to reduce the number of necessary depots in the system where waste collectors stay overnight. The objective of both phases is to minimize overall costs. Furthermore, the impact of implementing different modes of transportation other than vehicles, namely, canal or rail, for evacuation of solid waste from TSs is also investigated.

Antunes [3] proposes an MILP model to study the MSWM system in central Portugal at regional level by combining the elements of the p-median problem and capacitated facility location problem with transshipments. TSs and sanitary landfills are located by considering a minimum cost objective which comprises of annual costs of TSs and transportation costs.

Moreover, Mitropoulos et al. [40] develop an MILP optimization model for regional planning of an integrated SWM system in an economical manner. They investigate technology selection and siting of all SWM systems facilities including TSs where different transportation cost parameters are assigned to collection vehicles and trucks. After obtaining the minimum cost solution from their proposed location-allocation model, they also examine environmental and social criteria to have the best solution in accordance with planners' preferences. The applicability of their developed model is proved on the SWM system Achaia, Greece and an interchange heuristic is developed for solving large scale instances.

Ferri et al. [20] investigate inclusion of material recovery facilities functioning as intermediate nodes, similar to TSs, in a reverse logistics network. Two incoming MSW types, namely, general and recyclable, are collected separately from the generation sources using different vehicle types. Afterwards, the collected MSW streams undergo sorting and consolidation operations through material recovery facilities to be shipped to treatment and disposal facilities in a more economic way. Their model maximizes the benefit of the MSWM system by taking into account revenue from selling recyclable materials, transportation costs, and fixed costs of installing material recovery facilities.

In another study, Yadav et al. [60] propose a non-linear mixed integer programming (NLMIP) model to site TSs and determine their capacities in an economically efficient manner. The proposed model is applied on MSWM system of Nashik, India by implementing a GIS analysis framework which enables the authors to employ precise geo-spatial parameters in their mathematical model.

Rathore and Sarmah [44] propose an MILP model for locating TSs in an economically optimal way considering waste segregation and un-segregation scenarios and apply it on the MSWM system of Bilaspur, India. They also address the variations in land values of TSs' candidate locations and the subsequent impacts on site selection in their decision making process. Furthermore, Asefi et al. [5] investigate the problem of locating integrated SWM system components, including TSs, considering multiple waste types sorted and separated at generation sources. The compatibility of hazardous waste types with the treatment technologies is addressed in their study as well.

Akbarpour Shirazi et al. [48] propose an MILP model to optimize the current MSWM system of Tehran, Iran. Their model considers the optimal selection and combination of TSs and processing units where MSW is separated along with allocation of separated MSW to different technologies, namely, recovery, composting, and landfilling, with respect to the generated profit. The environmental side effects of the considered MSWM system are incorporated as constraints into their mathematical model by controlling the released amount of pollutants per unit of MSW processed in each facility.

There are various other studies in the literature that investigate the feasibility of locating TSs from different perspectives with cost control objectives. For example, Badran and El-Haggar [6] study the problem of locating TSs in the MSWM system of Port Said, Egypt; Kirca and Erkip [32] study a multi-stage decision problem to evaluate the optimal configuration, i.e., location, technology, and capacity, of TSs in a solid waste system; Eiselt [17] considers an un-capacitated location-allocation problem of locating TSs and landfills where a discount factor is assigned for transferring waste through TSs.

2.3 Sustainability in SWM/MSWM Systems

Increased environmental awareness, public concerns, and legislation call for a sustainable management of supply chains including SWM systems. Therefore, within the scope of SWM and MSWM systems, decision making methodologies should address the issues related to human welfare and environment in addition to economic considerations [10]. However, simultaneous optimization of three sustainability dimensions is not feasible and there would always be a trade-off between cost, social, and environmental factors. The crucial balance point that is needed should be reached by designing and operating a waste management system with the minimum environmental impacts while keeping the overall cost of the system in an acceptable level [37]. Besides, multi-objective decision making techniques can be utilized to perform a comprehensive optimization within waste management context by taking various criteria and objectives into consideration and putting in a balance between them.

In a study performed by Erkut et al. [18], a multi-objective facility location-allocation model is proposed at the regional level to locate TSs, material recovery plants, incinerators, and sanitary landfills and select their appropriate technologies. The environmental and economic dimensions are included into the objective function and a fair solution is obtained by implementation of lexicographic minimax approach. The considered environmental criterion comprises of generated GHG emissions by facilities, MSW amount that is landfilled, and energy and material recovery rates. The applicability of their proposed model is tested on the MSWM system of central Macedonia in North Greece.

Santibañez-Aguilar et al. [46] optimize the supply chain network of an MSWM system by proposing a bi-objective MILP model considering maximization of the net profit of the system as well as reused MSW. The quantity of recycled MSW, that is assumed to be inversely related to the amount of MSW landfilled, is used as an indicator for social and environmental criteria. In addition to facility location-allocation and technology selection decisions, their optimization model takes into account optimal distribution of resultant products from processing of MSW among markets.

A reasonable balance and adjustment between economic feasibility, environmental sustainability, and social justice is required in designing and operating an integrated sustainable MSWM systems. Some researches have focused holistically on all three dimensions of sustainability in MSWM systems from different perspectives. Yu and Solvang [62] propose a comprehensive multi-objective location-allocation model in order to minimize system cost, GHG emissions from transportation activities, and environmental impact of treatment facilities. The environmental impact is included to balance the adverse effects of the implemented technologies among communities and minimize health hazards to neighboring residences. The weighted sum method is implemented in their study to aggregate the objectives and obtain an efficient solution.

Mirdar Harijani et al. [38] propose a multi-objective MILP model to introduce treatment facilities into an MSWM system. They distinguish the location, typology, and capacity of treatment facilities as well as MSW streams among facilities by maximizing the profit of the MSWM system, minimizing resulting CO_2 emission from treatment facilities and transportation activities, and maximizing the social impacts of the considered MSWM network. Social impacts of the treatment facilities are assessed using the social life cycle assessment method where the fuzzy analytic hierarchy process is implemented to assign social scores to involved facilities.

Asefi and Lim [4] devise an optimization model by combining the elements of multi-objective programming and multi-criteria decision analysis for designing a sustainable integrated SWM system. The developed model incorporates three objectives, namely, minimization of facilities' establishment costs, minimization of transportation cost, and maximization of the suitability of the system's components. The suitability indicators of system's components are quantified with respect to environmental, social, and legal criteria. To mention important features of this study, we can point out consideration of MSW composition, selection of processing and treatment technologies that are compatible with the typology of MSW and residues, and inclusion of stakeholders' preferences into their mathematical model.

2.4 Dynamic Factors in SWM/MSWM Systems

MSWM systems are affected by dynamic aspects arising from population growth and subsequent increase in MSW generation rates over time. Incorporation of time-sensitive factors into decision making process is of particular importance to have an effective strategic planning of MSWM systems. Accordingly, dynamic location and relocation problems are developed to reflect dynamic changes in MSWM systems resulting from instability of economic, political, and demographic situations [41].

Besides, landfill capacity depletion over time and land shortage in urban areas for new establishments add to the complexity of MSWM systems. Such issues not only affect the number of operating landfills in MSWM systems, but also affect the optimal numbers and locations of TSs and treatment facilities along with the overall setting of MSWM systems over a long-term planning horizon [45].

Mitropoulos et al. [41] propose a dynamic MILP model for designing an integrated SWM system comprising of TSs, treatment facilities, and landfills. The dynamic pattern is included to reflect the evolution in the generation of solid waste across the planning horizon and the proposed model is applied on SWM system of Achaia, Greece. Their proposed dynamic location model enables decision makers to locate SWM facilities and select their technologies in a multi-period setting with a minimum total cost. However, this study does not include the environmental, social, and political criteria in their mathematical model and instead assumes an initial evaluation process in selection of potential sites of facilities.

Mirdar Harijani et al. [39] propose an MILP model to introduce new treatment facilities in an MSWM system in a multi-period setting. Their single-objective model maximizes the profit of the MSWM system with a budget restriction. The environmental costs arising from processing of MSW and resultant emissions from transportation activities are embedded within the objective. In addition, the social scores of treatment facilities are distinguished by using the social life cycle assessment method similar to [38] and a lower bound is assigned to overall social score of the network in a constraint.

2.5 Tactical and Operational Decisions in SWM/MSWM Systems

Some studies in the literature also consider sustainability in tactical and operational planning of MSWM systems. Edalatpour et al. [16] propose a reverse supply chain model for sustainable decision making of a waste management system at operational level. A single-objective mathematical model is formulated for assignment of waste to facilities and recovered materials to markets in order to maximize total profit of the system under stochastic waste generation rates. The social cost of carbon is embedded in the objective function, while the environmental side effects of GHG emissions resulting from transportation and treatment procedures are limited in a constraint. They claim that the ratio of interactions between facilities are mostly dependent on the nature and typology of waste and should be incorporated into the model as parameters instead of decision variables. Hence, they investigate the economic and environmental impacts of various waste separation parameters among facilities.

Yu et al. [61] formulate a non-linear mathematical programming model at operational level considering minimization of the overall cost, risk, and waste disposal value as distinct objectives in a multi-period setting. The allocation of waste between system's entities and the compatibility of waste with treatment technologies are assessed by the proposed non-linear mixed integer programming model.

Furthermore, Tan et al. [49] and Mohammadi et al. [42] develop MILP optimization models for sustainable management of MSW systems of Iskandar Malaysia, Malaysia and a region of Mexico, respectively, by incorporating the economic benefits of end-products and generated energy from treatment and processing of MSW in a multi-period setting. The main focus of these studies is centered around treatment and processing of MSW as well as the allocation of MSW to related facilities where locational planning and transportation cost assessment are not respected.

2.6 Uncertainty in SWM/MSWM Systems

The composition and generation of MSW varies substantially from city to city due to its dependency on society's consumption behaviors, education, level of development, and economic growth. As a result, the input parameters regarding MSW generation rates in optimization problems are uncertain in nature. Moreover, uncertainty is prevalent in associated costs and environmental impacts of MSWM systems [21]. Therefore, inclusion of uncertainty aspects in planning of MSWM systems would result in more informed decisions than deterministic settings. However, despite the substantial benefits of uncertainty considerations, the number of location-allocation problems dealing with such aspects are quite rare [23, 25].

Yadav et al. [58] propose an interval programming (Int.P) facility location problem of TSs in an MSWM system. They suggest that inclusion of interval-valued parameters in the decision making process is a reasonable solution in the case of data scarcity. Their study identifies seasonal and temporal variability as well as estimation and measurement errors as the major sources of uncertainty in parameters. Accordingly, MSW generation rates, MSW composition fractions, transportation costs, and operational costs of facilities are taken as uncertain parameters with interval values. Besides, they have applied their model on a hypothetical urban center to locate TSs in an economically efficient manner and conduct sensitivity analysis to assess uncertainty index of each uncertain parameter in their model. Also, an interval-valued facility location model is developed in a relatively similar study by Yadav et al. [59] to investigate the impact of uncertainty on economically best locations of TSs.

A tri-objective MILP problem is formulated by Habibi et al. [25] to locate facilities, allocate MSW flows, select the optimal capacities and technologies of facilities, and quantify the number of vehicles needed to transport MSW among system components which is in practice equal to the number of required trips. The objective functions aim to maximize the net profit of the MSWM system, minimize the GHG emissions resulting from transportation and processing of MSW in facilities, and minimize the side effects of facilities on residents of population centers. They take the uncertainty of MSW generation rates into consideration by implementing a robust-optimization method which evaluates different scenarios.

Besides, Heidari et al. [26] formulate a fuzzy multi-objective mixed integer non-linear mathematical programming model to introduce separation and processing units into an MSWM system. In addition, they decide on workforce assignment, technology and capacity arrangement of introduced facilities along with the allocation of MSW streams. The economic and environmental criteria are assessed considering similar factors as [25], while the social criterion is incorporated by maximizing the job opportunities as a result of the establishment of new facilities. The uncertainties regarding MSW generation and associated costs in the system are represented by fuzzy possibilistic parameters. The robust possibilistic programming method is implemented to deal with uncertainty and the problem is finally solved using the ϵ-constraint method.

Furthermore, Li and Huang [36] tackle the uncertainty of MSWM systems by implementing interval value and fuzzy set theories and develop an interval-based possibilistic programming (IBPP) model. They assume that MSW generation as well as capacities and variable costs of facilities are interval-valued parameters with known membership functions. Besides, they apply the proposed model on a hypothetical case study to decide about capacity-expansion patterns of MSW facilities under a dynamic setting. For this purpose, they introduce an MILP framework into IBPP and consider a cost minimization objective which takes into account environmental costs imposed by landfills and waste-to-energy facilities as well.

The summary of the reviewed studies regarding the strategic decision making of waste management systems along with the current study are highlighted in Table 2.1. We have reported the studies focusing on facility location problems by underlining their key features. Note that, the waste segregation denotes consideration of separated waste streams and associated operations, e.g., separated transportation schemes, in the modeling approach. The descriptions of the remaining considered features are outlined in Table 2.1.

Some of the reviewed studies, namely [16,25,26,38,39,61,62], assess the GHG emissions produced by vehicles using factor models. In these studies, the resultant GHG emissions of vehicles are calculated with respect to transported MSW flows and an emission coefficient which depends on the distance traveled. Whereas, the effects of vehicle speed and technical characteristics as well as speed limits and general congestion patterns over the logistics network on the resulting GHG emissions are left out.

In recent years, there has been a considerable increase in the number of studies that

Table 2.1: Summary of reviewed studies on strategic facility location problems in waste management systems

Study	Method	Multi-obj.[a]	WS[b]	Sustainability[c]			Decision Variables[d]	Facl.[e]			EM[f]	TA[g]	Unc.[h]	GIS	Case Study
				Ec.	En.	So.		TSs	P&T	SL					
[32]	MILP			✓			LA	✓							Istanbul,Turkey
[35]	MILP			✓			LA	✓							Brussels, Belguim
[3]	MILP			✓			LA	✓		✓					Central Portugal
[21]	NLMIP		✓	✓			LA		✓	✓					Genova, Italy
[11]	NLMIP		✓	✓	✓		LA		✓						Genova, Italy
[6]	MILP			✓			LA	✓							Port Said, Egypt
[17]	MILP			✓			LA	✓		✓					New Brunswick,Canada
[18]	MILP	✓		✓	✓		LA	✓	✓	✓					Central Macedonia, North Greece
[41]	MILP			✓			LA, Tech.	✓	✓	✓		✓		✓	Achaia, Greece
[40]	MILP			✓			LA, Tech.	✓	✓	✓				✓	Achaia, Greece
[46]	MILP	✓	✓	✓	✓	✓	LA, Tech.		✓						Central-west region of Mexico
[20]	MILP		✓	✓			LA, Cap.	✓	✓	✓					São Mateus, Brazil
[60]	NLMIP			✓			LA, Cap.	✓						✓	Nashik, India
[62]	MILP	✓		✓	✓	✓	LA	✓	✓	✓	F				—
[38]	MILP	✓	✓	✓	✓	✓	LA, Cap., Tech.		✓	✓	F				Tehran, Iran
[4]	MILP	✓	✓	✓	✓	✓	LA	✓	✓	✓				✓	Tehran, Iran
[39]	MILP		✓	✓	✓	✓	LA, Cap., Tech.		✓	✓	F				Tehran, Iran
[25]	MILP	✓	✓	✓	✓	✓	LA, Cap., Tech., Tri.	✓	✓	✓	F		✓		Tehran, Iran
[58]	Int.P		✓	✓			LA	✓					✓		—
[59]	Int.P			✓			LA	✓						✓	Nashik, India
[47]	NLMIP/NLP		✓	✓			LA, Pr., OS		✓	✓					Tehran, Iran
[44]	MILP		✓	✓			LA	✓						✓	Bilaspur, India
[5]	MILP		✓	✓			LA	✓	✓	✓				✓	Tehran, Iran
[48]	MILP		✓	✓	✓		LA	✓							Tehran, Iran
[26]	NLMIP	✓	✓	✓	✓	✓	LA, Cap., Tech., Lab.		✓	✓	F		✓	✓	Tehran, Iran
This Study	MILP	✓		✓	✓	✓	LA, Tri.	✓	✓	✓	Mic.			✓	Ankara, Turkey

[a] Multi-obj.: Multi-objective
[b] WS: Waste Segregation
[c] Ec.: Economic, En.: Environmental, So.: Social
[d] LA: Location-Allocation, Cap.: Capacity, Tech.: Technology, Lab.: Number of required labor, Tri.: Number of required trips, Pr.: Pricing, OS: Outsourcing
[e] Facl.: Facilities to be located
[f] EM: Emission Model, F: Factors, Mic.: Microscopic
[g] TA: Time Aspects
[h] Unc.: Uncertainty

aim to minimize GHG emissions in logistics networks by quantifying FC of vehicles utilizing different approaches and principals. For example, Bektaş and Laporte [8], in a pioneering study, introduce the pollution-routing problem (PRP) which is an extension of the vehicle routing problem with time-windows. The PRP incorporates the harmful effects of transportation in routing of vehicles by assessment of CO_2 emission with using a microscopic emission model. A cost function composed of fuel, emission, and labor costs is minimized in the objective of the proposed model. Afterwards, there have been several studies focusing on extensions or modifications of the PRP. For instance, Franceschetti et al. [22] consider time-dependent PRP in which the effect of traffic congestion through different time periods is included in order to assess the optimal speed of vehicles along with their departure time. Also, Demir et al. [14] introduce the bi-objective PRP where two conflicting objectives, namely, fuel consumption and driving time of vehicles, are minimized. For a detailed review of studies regarding green location and routing problems, the reader is referred to the recent survey by Dukkanci et al. [15].

Considering the key features and gaps of the studied literature, this thesis aims to focus on the green facility location problem of a regional MSWM system by investigating the interplay between economic feasibility and environmental sustainability criteria. The environmental sustainability criterion minimizes the resulting CO_2 emission from transportation activities which is calculated in a detailed manner using a microscopic emission model. Moreover, our model integrates specific features of the transportation network into the strategic decision making of regional MSWM systems. To the best of our knowledge, such detailed analyses of GHG emissions from transportation services in locational planning of MSWM systems at regional level have not yet been carried out in the literature.

CHAPTER 3

THE GREEN NETWORK DESIGN OF A REGIONAL MSWM SYSTEM

3.1 MSWM Network Description and Notation

Locational planning of MSWM systems utilizing mathematical programming tools can be enhanced by sustainability considerations. In this thesis, a bi-objective facility location-allocation problem is developed in order to determine the locations of facilities selected among candidate ones so as to minimize total daily MSWM system cost and daily CO_2 emission from transportation activities. The total daily MSWM system cost takes into account fixed and variable costs of facilities, variable transportation cost, fuel cost resulting from transportation activities, and the revenue generated by processing and treatment of MSW.

Transportation constitutes an essential part of MSWM systems as MSW flows among different levels of the system for shipment, transshipment, processing and treatment, and final disposal. In order to incorporate the impact of transportation services into strategic decision making of integrated MSWM systems at regional level, we should first have a general overview of the configuration of MSWM systems. A general framework of an integrated MSWM network respected in this thesis has four levels depicted in Figure 3.1 with the following organizations.

- First level of the considered MSWM network corresponds to MSW generation sources, denoted by set I, where source $i \in I$ has a deterministic generation rate of G_i (tonne/day). In this thesis, MSW collection activities are not taken into account explicitly and it is assumed that the relative activities are performed by the collection system of each municipality operating separate from regional sector which is responsible for overall treatment and disposal of col-

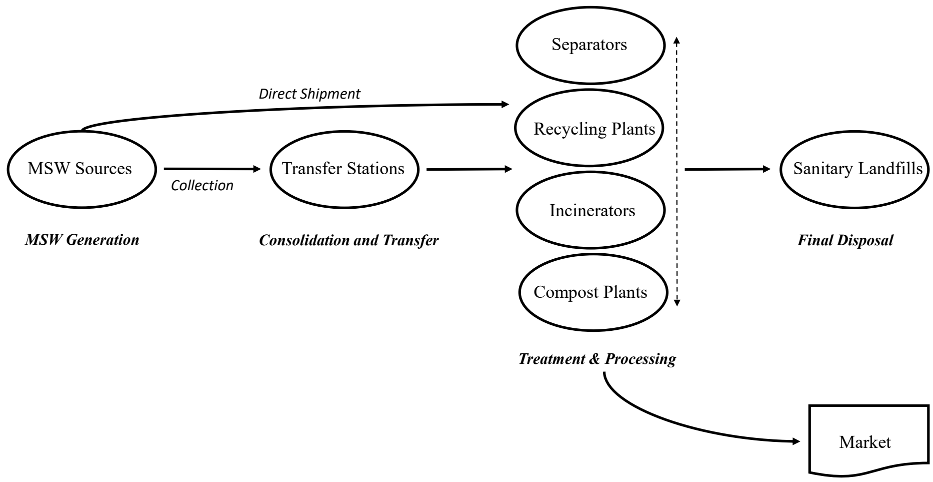


Figure 3.1: The general MSWM network under study

lected MSW. Hence, we assume single or multiple MSW generation points for every municipal district, an approach which is the most common method in the literature.

It should be noted that separated MSW flows are not considered in this study since segregated MSWM systems lack the advantages of economies of scale and interactions between different processing and treatment options, resulting in economical and environmental inefficiencies [37].

- Second level accounts for TSs functioning as intermediate facilities to link MSW collection system to processing, treatment, and disposal facilities. TSs serve as critical consolidation and transshipment points for cost effective shipment of MSW through large-volume vehicles to distant regional facilities.

  The primary reason for implementation of TSs in MSWM systems is to cut the associated transferring costs and provide transportation efficiency. Additionally, presence of TSs would result in time efficiency of refuse collectors for collection activities; reduced maintenance costs and driver wages; lower fuel consumption and atmospheric pollutants; and less traffic congestion, noise, and road wear.

  We denote the set of TSs by J. The set J can be partitioned into two subsets;

J_1 corresponding to candidate TSs and J_2 corresponding to existing TSs. We assume that transfer station $j \in J$ has a daily capacity of CT_j tonnes, daily fixed cost of FCT_j €, and daily variable cost of VCT_j € per tonne of MSW transferred.

- Third level composes of a set K of MSW P&T facilities. MSW is transferred from TSs by large-volume vehicles to these facilities. Separators, recycling plants, refused derived fuel facilities, composting plants, incinerators, and waste to energy plants are some examples of third level facilities where MSW is processed and treated while producing residues.

  The index set K is divided into two subsets; K_1 corresponding to candidate P&T facilities and K_2 corresponding to existing P&T facilities. We assume that P&T facility $k \in K$ has a daily capacity of CP_k tonnes, daily fixed cost of FCP_k €, and daily variable cost of VCP_k € per tonne of MSW processed and treated. Besides, the average monetary benefits obtained by selling the processed and treated MSW to market is considered as C_k € per tonne of MSW entering facility $k \in K$. The constant C_k depends on the type of P&T facility and implemented technologies there.

  It has been assumed that various types of P&T technologies operate together in regional P&T mega-facilities. As pointed out by USEPA [53], existence of such mega-facilities is beneficial as considerable construction and maintenance costs would be compensated by handling a high volume of MSW. Likewise, associated processing and tipping expenses per unit of MSW would be cut off.

  Moreover, the noxious materials and emissions stemming from P&T facilities are not regarded in our analyses. Since, such consideration might lead to unreliable solutions which allocate excessive MSW flows to P&T facilities producing low associated noxious materials and emissions, though having serious environmental impacts [62].

- Fourth and final level corresponds to a set L of SLs which are the final destination of MSW that could not be processed or treated. The residues from third-level facilities are sent to SLs for final disposal. We assume that a fraction σ_k of MSW entering P&T facility $k \in K$ is sent to SLs. The fraction σ_k called the residual coefficient of P&T facility k depends on the implemented technologies and therefore may change from facility to facility. In a similar manner, the set L can be partitioned into L_1 and L_2 which are the sets of candidate and existing SLs in the system, respectively. Also, it is assumed that SL $l \in L$ has a daily capacity of CL_l tonnes, daily fixed cost of FCL_l €, and daily variable cost of VCL_l € per tonne of MSW landfilled.

MSW sources and facilities represent nodes of the considered MSWM network. A single path is defined to connect each pair of nodes in successive levels of the network. Preliminary selection of the paths and potential locations of facilities should incorporate variety of factors relative to environmental and social impacts in addition to economic suitability factors such as land price, reachability, and vicinity to urban centers. Reasonable distance from residential, recreational, and institutional centers; risk of accident and pollution; natural resources contamination; and population exposure are examples of environmental and social factors which can be taken into account by utilizing GIS analytic tools or life cycle assessment methods accurately. However, such preliminary analyses are not considered in this study and we assume that vehicles of type $1, 2$, and 3 perform transportation activities on the shortest paths connecting MSW sources to TSs, TSs to P&T facilities, and P&T facilities to SLs, respectively.

Moreover, each shortest path on the network is divided into a number of road segments with respect to different speed limits imposed by local or governmental authorities directly and by traffic congestion indirectly. Note that, temporal issues arising from traffic congestions in different time periods and the subsequent impacts on scheduling of vehicles are not addressed and the average traffic congestion on each road segment is taken into account in determining the travel speeds of vehicles.

We denote the sets of road segments on the shortest paths connecting MSW source i to TS j, TS j to P&T facility k, and P&T facility k to SL l by T_{ij}, P_{jk}, and L_{kl}, respectively. The travel speed of a vehicle on a road segment is evaluated explicitly considering its FC, quantified by CMEM model, and segment-wise speed limits. We present details of the implemented emission model in Section 3.2.

3.2 Calculation of FC and CO_2 Emission

Transportation is an essential and prevalent element in every MSWM network producing a considerable amount of GHG emissions with serious contributions to the greenhouse effect and acid rains [50]. The adverse atmospheric impacts of transportation services in locational planning of an integrated MSWM system is addressed in this thesis by controlling the resulting CO_2 emission.

As the amount of emitted CO_2 from a vehicle is directly proportional to its FC [22], we utilize the CMEM developed by Barth et al. [7] for heavy-duty vehicles to calculate the FC rates of vehicles. We employed the procedure analogous to [8, 14, 22] to calculate FC and emitted CO_2. According to CMEM, the FC of a heavy-duty vehicle can be calculated as

$$F = \lambda\Big(eNV\frac{z}{v} + \gamma\alpha z\ell + \gamma\alpha\mu z + \beta\gamma v^2 z\Big), \tag{3.2.1}$$

where F is the amount of fuel consumed in liter (L) by a heavy-duty vehicle traversing a distance of z meters (m) with a constant speed of v meters/second (m/s) carrying a load of ℓ kilograms (kg) [14]. Remaining parameters are vehicle and road specific parameters with the descriptions and notations as follows

> e is the engine friction factor $(kJ/rev/l)$, N is the engine speed (rev/s), V is engine displacement (L), μ is the vehicle curb weight (kg);
>
> $\lambda = \xi/\kappa\psi$, where ξ is fuel-to-air mass ratio, κ is the heating value of a typical diesel fuel (kJ/g), ψ is a conversion factor from grams to liters;
>
> $\gamma = 1/1000\epsilon\pi$, where ϵ is the vehicle drive train efficiency, and π is an efficiency parameter for diesel engines;
>
> $\beta = 0.5C_dA\rho$, where C_d is the coefficient of aerodynamic drag, A is the frontal surface area (m^2), and ρ is the air density (kg/m^3);
>
> $\alpha = g\sin(\Phi) + gC_r\cos(\Phi)$, where g is gravitational acceleration (equal to 9.81 m/s^2), Φ is the road angel, and C_r is the coefficient of rolling resistance.

As can be seen, λ, γ, β are vehicle-specific parameters while α is vehicle-road-specific parameter which is dependent on the road angel as well. Note that we do not specify road angels and consider $\Phi = 0$, similar to [14, 22, 27, 31], which turns $\alpha = gC_r$ to a vehicle-specific parameter.

Defining $\omega_1 = \lambda e N V$, $\omega_2 = \lambda\gamma\alpha$, $\omega_3 = \lambda\gamma\alpha\mu$, and $\omega_4 = \lambda\beta\gamma$, Equation 3.2.1 can be rewritten as

$$F = \omega_1 \frac{z}{v} + \omega_2 z\ell + \omega_3 z + \omega_4 v^2 z. \tag{3.2.2}$$

The set of parameters required by CMEM are also reported in Table 3.1. For detailed study of the parameters used in CMEM and comparison of different vehicular emission models the reader is referred to [13].

Table 3.1: FC function parameters

Notation	Description
ξ	Fuel-to-air mass ratio
κ	Heating value of a typical diesel fuel (kJ/g)
ψ	Conversion factor $(g/s$ to $L/s)$
ϵ	Vehicle drive train efficiency
π	Efficiency parameter for diesel engines
ρ	Air density (kg/m^3)
e	Engine friction factor $(kJ/rev/L)$
g	Gravitational constant (m/s^2)
Φ	Road angel
C_r	Coefficient of rolling resistance
C_d	Coefficient of aerodynamic drag
N	Engine Speed (rev/s)
V	Engine displacement (L)
A	Frontal surface area (m^2)
μ	Curb weight (kg)

3.3 Mathematical Model

The MSWM problem with cost minimization and emission control objectives is formulated as an MILP model in this section. This bi-objective facility location problem locates facilities at candidate locations in each level, quantifies MSW flows between the nodes of the network in different levels, and determines the required number of vehicle trips at the same time. Additionally, by selecting facilities among sets of candidate locations and determining the MSW flows, we explicitly determine the travel speeds of vehicles.

In order to determine where to locate facilities, a binary variable is introduced for each candidate facility location. We denote binary variables using notations XT_j, XP_k, and XL_l which take the value 1 if and only if TS $j \in J_1$, P&T facility $k \in K_1$, and SL $l \in L_1$ are opened, respectively. For the already existing facilities, the same notation is used and it is assumed that $XT_j = 1, XP_k = 1$, and $XL_l = 1$ for each $j \in J_2$, $k \in K_2$, and $l \in L_2$. The sets and parameters as well as decision variables of the proposed MILP model are reported in Tables 3.2 and 3.3, respectively.

Table 3.2: Sets and parameters

Notation	Description
i, j, k, l	Indices of MSW generation sources, TSs, P&T facilities, and SLs
I	Set of MSW generation sources
J_1, K_1, L_1	Sets of candidate TSs, P&T facilities, and SLs
J_2, K_2, L_2	Sets of existing TSs, P&T facilities, and SLs
J, K, L	Sets of TSs, P&T facilities, and SLs, i.e., $J = J_1 \cup J_2$, $K = K_1 \cup K_2$, and $L = L_1 \cup L_2$
t	Index of vehicle types, i.e., $t \in \{1, 2, 3\}$
T_{ij}, P_{jk}, L_{kl}	Sets of road segments on the shortest paths connecting i to j, j to k, and k to l
r	Index of road segments
G_i	MSW generation rate of source i $(tonne/day)$
CT_j, CP_k, CL_l	Capacities of facilities i, j, and k $(tonne/day)$
FCT_j, FCP_k, FCL_l	Fixed costs of facilities j, k, and l (€$/day$)
VCT_j, VCP_k, VCL_l	Unit variable costs of facilities j, k, and l (€$/tonne/day$)
TT, TP, TL	Maximum number of TSs, P&T facilities, and SLs to be built in the MSWM system
σ_k	Residual coefficient of P&T facility k
C_k	Unit monetary benefit coefficient of P&T facility k (€$/tonne$)
$DMT_{ij}, DTP_{jk}, DPL_{kl}$	Distances of the shortest paths between i and j, j and k, k and l (km)
$LT_{ij}^r, LP_{jk}^r, LL_{kl}^r$	Lengths of the r^{th} segment of the shortest path from i to j, j to k, and k to l (km)
c	CO_2 emission coefficient: the amount of CO_2 emission in kg per liter of fuel consumed (kg/L)
f	Unit fuel (diesel) cost (€$/L$)
w_t	Unit variable transportation cost for a vehicle of type t (€$/km$)
cap_t	Capacity of vehicle of type t $(tonne)$
$LSLT_{ij}^r, LSLP_{jk}^r, LSLL_{kl}^r$	Lower speed limits of the $r^{\text{th}}(r \in T_{ij}, P_{jk}, L_{kl})$ segment of the shortest paths connecting i to j, j to k, and k to l (km/h)
$USLT_{ij}^r, USLP_{jk}^r, USLL_{kl}^r$	Upper speed limits of the $r^{\text{th}}(r \in T_{ij}, P_{jk}, L_{kl})$ segment of the shortest paths connecting i to j, j to k, and k to l (km/h)
V_{opt}^t	Optimal speed of vehicle of type t (km/h)
VT_{ij}^r,	Travel speed of vehicle of type 1 on the $r^{\text{th}}(r \in T_{ij})$ segment of the shortest path from i to j (km/h)
VP_{jk}^r,	Travel speed of vehicle of type 2 on the $r^{\text{th}}(r \in P_{ij})$ segment of the shortest path from j to k (km/h)
VL_{kl}^r,	Travel speed of vehicle of type 3 on the $r^{\text{th}}(r \in L_{ij})$ segment of the shortest path from k to l (km/h)
$\omega_1^t\omega_2^t, \omega_3^t, \omega_4^t$	Vehicle-specific parameters for vehicles of type t

The first set of constraints restricts the number of facilities that are going to be opened at candidate locations. If no such restrictions exist, then these constraints can be

Table 3.3: Decision variables

Notation	Description
$QMT_{ij}, QTP_{jk}, QPL_{kl}$	Quantity of MSW to be transfered from i to j, j to k, and k to l $(tonne/day)$
$NMT_{ij}, NTP_{jk}, NPL_{kl}$	Number of required trips to transfer quantified daily MSW from i to j, j to k, and k to l
XT_j	Binary variable determining presence/absence of a TS at candidate location j
XP_k	Binary variable determining presence/absence of a P&T facility at candidate location k
XL_l	Binary variable determining presence/absence of a SL at candidate location l
$fcMT_{ij}, fcTP_{jk}, fcPL_{kl}$	FC on the shortest paths from i to j, j to k, and k to l (L)

discarded.

$$\sum_{j \in J_1} XT_j \leq TT \tag{3.3.1}$$

$$\sum_{k \in K_1} XP_k \leq TP \tag{3.3.2}$$

$$\sum_{l \in L_1} XL_l \leq TL \tag{3.3.3}$$

The second set of constraints are mass balance constraints presented as follows.

$$\sum_{j \in J} QMT_{ij} = G_i, \ \forall i \in I \tag{3.3.4}$$

$$\sum_{k \in K} QTP_{jk} = \sum_{i \in I} QMT_{ij}, \ \forall j \in J \tag{3.3.5}$$

$$\sum_{l \in L} QPL_{kl} = \sigma_k \sum_{j \in J} QTP_{jk}, \ \forall k \in K \tag{3.3.6}$$

Equation 3.3.4 implies that the generated MSW at every source should be entirely served and transported to TSs. The MSW flows from source i to TS j, TS j to P&T facility k, and P&T facility k to SL l are denoted by QMT_{ij}, QTP_{jk}, and QPL_{kl}, respectively. Equation 3.3.5 balances the input and output MSW flows at every TS, and Equation 3.3.6 specifies that the sum of the input MSW quantities of a P&T facility multiplied by its residual coefficient is equal to the sum of the output MSW quantities from that facility.

The third set of constraints makes sure that MSW can only be transported to open facilities and also restricts the amount of entering MSW to each open facility by its capacity.

$$\sum_{i \in I} QMT_{ij} \leq CT_j XT_j, \; \forall j \in J \tag{3.3.7}$$

$$\sum_{j \in J} QTP_{jk} \leq CP_k XP_k, \; \forall k \in K \tag{3.3.8}$$

$$\sum_{k \in K} QPL_{kl} \leq CL_l XL_l, \; \forall l \in L \tag{3.3.9}$$

Equations 3.3.7, 3.3.8, and 3.3.9 correspond to capacity constraints of TSs, P&T facilities, and SLs, respectively.

The forth set of constraints identifies the required number of trips to transport MSW on the shortest paths from MSW sources to TSs, TSs to P&T facilities, and P&T facilities to SLs, respectively, as follows.

$$NMT_{ij} \geq \frac{QMT_{ij}}{cap_1}, \; \forall i \in I, \; \forall j \in J \tag{3.3.10}$$

$$NTP_{jk} \geq \frac{QTP_{jk}}{cap_2}, \; \forall j \in J, \; \forall k \in K \tag{3.3.11}$$

$$NPL_{kl} \geq \frac{QPL_{kl}}{cap_3}, \; \forall k \in K, \; \forall l \in L \tag{3.3.12}$$

The number of required trips between MSW source i and TS j, TS j and P&T facility k, and P&T facility k and SL l are denoted by NMT_{ij}, NTP_{jk}, and NPL_{kl}, respectively. Equations 3.3.10, 3.3.11, and 3.3.12 assess the number of required trips considering the capacity of the vehicles performing the transportation services on the shortest paths connecting these facilities and the MSW quantity transfered. The objective function of the MILP model will make sure that NMT_{ij}, NTP_{jk}, and NPL_{kl} are equal to the ceiling of the right hand sides of Equations 3.3.10, 3.3.11, and 3.3.12, respectively.

Next, we present constraints related to the calculation of FC of vehicles traversing a path joining two nodes of the MSWM network. First, we consider vehicles of type 1 which transfer MSW on the shortest paths connecting MSW sources to TSs. We assume that in all but one trip, vehicles travel with full capacity and all vehicles come back to source i from TS j following the same path with no load. Therefore, the total amount of FC by vehicles of type 1 over path $i-j$ can be calculated as

$$fcMT_{ij} = \theta^1_{ij} + \theta^2_{ij} + \theta^3_{ij}, \tag{3.3.13}$$

where θ^1_{ij} corresponds to FC of vehicles traversing path $i-j$ with full capacity, θ^2_{ij} accounts for FC of a vehicle transferring $QMT_{ij} - (NMT_{ij} - 1)cap_1$ amount of remaining MSW on path $i-j$, and θ^3_{ij} amounts to FC of the vehicles coming back with no load through the same path $i-j$. $\theta^1_{ij}, \theta^2_{ij}$, and θ^3_{ij} are calculated using the following Equation:

$$\theta^1_{ij} = (NMT_{ij} - 1)\left(\omega^1_1\left(\sum_{r\in T_{ij}} \frac{LT^r_{ij}}{VT^r_{ij}}\right) + \omega^1_2 cap_1 DMT_{ij} + \omega^1_3 DMT_{ij} + \omega^1_4 \sum_{r\in T_{ij}} (VT^r_{ij})^2 LT^r_{ij}\right), \tag{3.3.14}$$

$$\theta^2_{ij} = \left(\omega^1_1\left(\sum_{r\in T_{ij}} \frac{LT^r_{ij}}{VT^r_{ij}}\right) + \omega^1_2\left(QMT_{ij} - (NMT_{ij}-1)cap_1\right) DMT_{ij} + \omega^1_3 DMT_{ij} + \omega^1_4 \sum_{r\in T_{ij}} (VT^r_{ij})^2 LT^r_{ij}\right), \tag{3.3.15}$$

$$\theta^3_{ij} = NMT_{ij}\left(\omega^1_1\left(\sum_{r\in T_{ij}} \frac{LT^r_{ij}}{VT^r_{ij}}\right) + \omega^1_3 DMT_{ij} + \omega^1_4 \sum_{r\in T_{ij}} (VT^r_{ij})^2 LT^r_{ij}\right), \tag{3.3.16}$$

where $\omega^1_1, \omega^1_2, \omega^1_3$, and ω^1_4 are vehicle-specific parameters in Equation 3.2.2 for vehicles of type 1. To obtain Equations 3.3.14, 3.3.15, and 3.3.16, the first and last terms of Equation 3.2.2 are computed for each road segment of path $i-j$ and summed up as the travel speed of vehicles may not be constant over the segments of the path.

In these equations, LT^r_{ij} is the length of the r^{th} $(r \in T_{ij})$ segment of path $i-j$ and VT^r_{ij} is the feasible travel speed (i.e., satisfying the speed limits) of vehicle of type 1 corresponding to the lowest FC amount on the r^{th} segment of path $i-j$. If path $i-j$ is not used by the vehicles, i.e., $NMT_{ij} = 0$ and $QMT_{ij} = 0$, then one can see that $\theta^1_{ij}, \theta^2_{ij}$, and θ^3_{ij} add up to zero. Note that, $\sum_{r\in T_{ij}} LT^r_{ij} = DMT_{ij}$, which DMT_{ij} accounts for the distance of the shortest path connecting source i to TS j, and $\theta^1_{ij}, \theta^2_{ij}$, and θ_{ij}^3 are introduced to make the exposition simpler and they are indeed not part of the MILP model.

The total FC of vehicles of type 2 transferring MSW between TS j and P&T facility k and total FC of vehicles of type 3 transferring MSW between P&T facility k and SL l are denoted by $fcTP_{jk}$ and $fcPL_{kl}$, respectively. The calculations of $fcTP_{jk}$ and $fcPL_{kl}$ are similar to that of $fcMT_{ij}$ and outlined in Appendix A.

The final set of constraints characterizes the non-negativity, integrality, and binary characteristics of decision variables, along with specifying the presence of the existing facilities.

$$QMT_{ij} \geq 0, QTP_{jk} \geq 0, QPL_{kl} \geq 0, \ \forall i \in I, \ \forall j \in J, \ \forall k \in K, \ \forall l \in L \quad (3.3.17)$$

$$fcMT_{ij} \geq 0, fcTP_{jk} \geq 0, fcPL_{kl} \geq 0, \ \forall i \in I, \ \forall j \in J, \ \forall k \in K, \ \forall l \in L \quad (3.3.18)$$

$$NMT_{ij}, NTP_{jk}, NPL_{kl} \in \mathbb{Z}_+, \ \forall i \in I, \ \forall j \in J, \ \forall k \in K, \ \forall l \in L \quad (3.3.19)$$

$$XT_j, XP_k, XL_l \in \{0, 1\}, \ \forall j \in J_1, \ \forall k \in K_1, \ \forall l \in L_1 \quad (3.3.20)$$

$$XT_j, XP_k, XL_l = 1, \ \forall j \in J_2, \ \forall k \in K_2, \ \forall l \in L_2 \quad (3.3.21)$$

Equations 3.3.17 and 3.3.18 specify that MSW flows and FC values are non-negative. Equation 3.3.19 indicates that the variables identifying the number of required trips have to be non-negative integers. Equation 3.3.20 assigns 0 or 1 values to decision variables corresponding to selection of candidate locations for facilities. Finally, Equation 3.3.21 specifies the presence of existing facilities in the system.

Lastly, two objective functions of the considered MILP model are presented in Equations 3.3.22 and 3.3.23, corresponding to total daily system cost and resulting CO_2

emission from transportation activities, respectively.

$$Z_{cost} = \sum_{j \in J} XT_j FCT_j + \sum_{k \in K} XP_k FCP_k + \sum_{l \in L} XL_l FCL_l + \tag{3.3.22a}$$

$$\sum_{j \in J} VCT_j \sum_{i \in I} QMT_{ij} + \sum_{k \in K} VCP_k \sum_{j \in J} QTP_{jk} + \sum_{l \in L} VCL_l \sum_{k \in K} QPL_{kl} + \tag{3.3.22b}$$

$$f\Big(\sum_{i \in I} \sum_{j \in J} fcMT_{ij} + \sum_{j \in J} \sum_{k \in K} fcTP_{jk} + \sum_{k \in K} \sum_{l \in L} fcPL_{kl}\Big) + \tag{3.3.22c}$$

$$2\left(w_1 \sum_{i \in I} \sum_{j \in J} DMT_{ij} NMT_{ij} + w_2 \sum_{j \in J} \sum_{k \in K} DTP_{jk} NTP_{jk} + w_3 \sum_{k \in K} \sum_{l \in L} DPL_{kl} NPL_{kl}\right) - \tag{3.3.22d}$$

$$\sum_{k \in K} C_k \sum_{j \in J} QTP_{jk} \tag{3.3.22e}$$

$$Z_{emission} = c\Big(\sum_{i \in I} \sum_{j \in J} fcMT_{ij} + \sum_{j \in J} \sum_{k \in K} fcTP_{jk} + \sum_{k \in K} \sum_{l \in L} fcPL_{kl}\Big) \tag{3.3.23}$$

Equation 3.3.22 refers to the total cost of the system on a daily basis. Daily fixed costs of open facilities are calculated by Equation 3.3.22a. Equation 3.3.22b corresponds to variable costs of facilities calculated with respect to allocated MSW quantities to TSs, P&T facilities, and SLs, respectively. Equation 3.3.22c assesses fuel cost which is calculated by multiplying total FC of vehicles of types $1, 2$, and 3 in L by the unit fuel cost per liter, f. Equation 3.3.22d amounts to variable transportation cost calculated by multiplying the total travel distance of vehicles of type t by the unit transportation cost w_t. Equation 3.3.22e calculates possible monetary benefits gained by processing and treatment of MSW in P&T facilities. Equation 3.3.23 refers to the total amount of emitted CO_2 from transportation activities which is calculated by multiplying the amount of FC in L by the CO_2 emissions coefficient, c, in kg/L [22].

In conclusion, the objective function of the proposed MILP model is as follows:

$$\text{Minimize}(Z_{cost}, Z_{emission}) \tag{3.3.24}$$

The conceptual framework of the MSWM network under study is shown in Figure 3.2 where different levels of the network, existing and candidate facilities, MSW flows among facilities, path distances, and road segments are depicted using related notations.

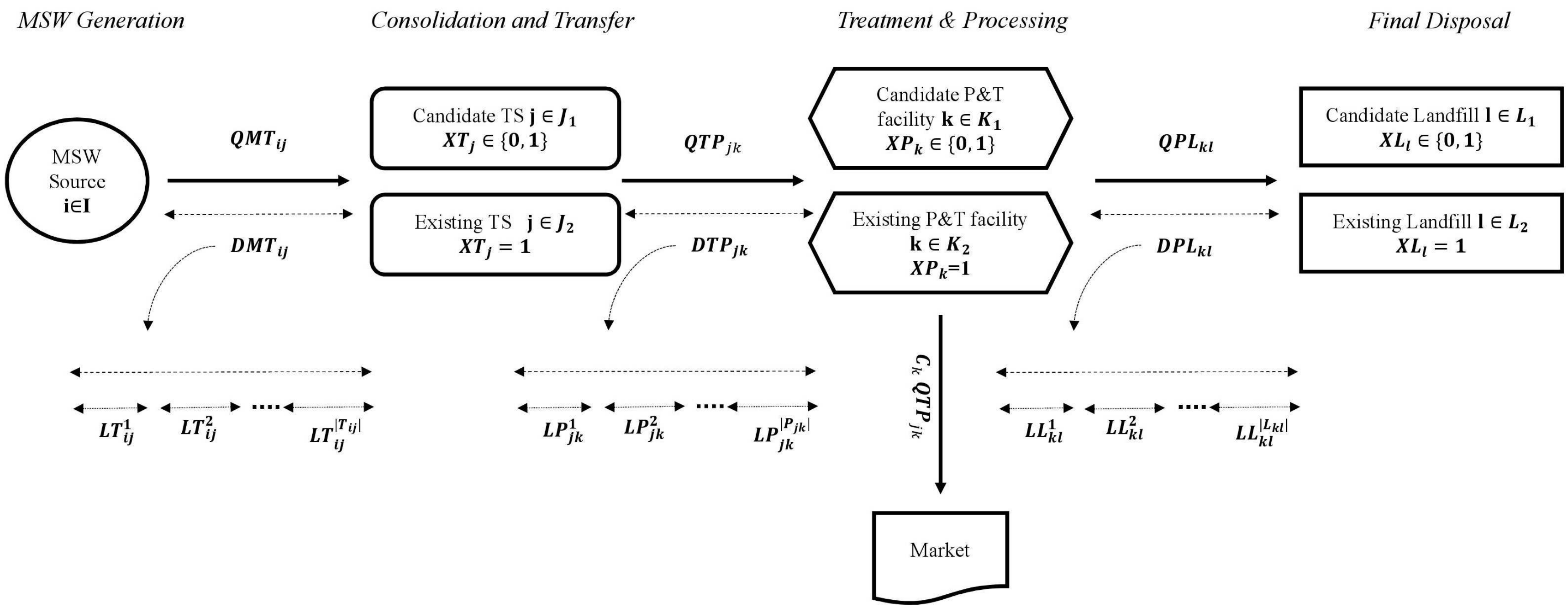


Figure 3.2: The conceptual framework of the considered MSWM network

CHAPTER 4

COMPUTATIONAL EXPERIMENTS AND ANALYSES

4.1 Municipal Solid Waste Management System at Ankara

We apply the proposed model on the MSWM system operating in Ankara to investigate resulting sustainability benefits. Ankara is the capital and the second most populated city of Turkey with a total population of 5,346,518 in 2016 [52]. According to municipal waste statistics released by the Turkish statistical institute (TurkStat) [52], in November 2017 ; of the 31.6 million tonnes of MSW collected in Turkey in 2016, Ankara has a share of 2.2 million tonnes. Furthermore, 26 municipal districts in Ankara received waste services producing an average of 1.14 kg municipal waste per capita per day in 2016 [52].

In order to apply our proposed model on the MSWM system of Ankara, we conduct an extensive investigation towards the system and its related components. ITC (Invest, Trading, & Consulting AG) is the company that is in charge of providing disposal and treatment services in Ankara and a number of cities in Turkey [30]. We had an interview on September 28, 2017 with a consultant of this company, Mr. Erdoğan Bayin, to get information regarding detailed services and operations of MSWM system of Ankara and its relative parameters. The employed parameters in this case study partially attribute to the actual operating system such as capacities of treatment and landfill facilities and MSW generation rates per capita per day, and are partially selected with respect to the literature such as fixed and variable costs of facilities [51] and vehicle related parameters.

Ankara's MSWM system composes of two plants located in Sincan and Mamak municipal districts where they serve collected MSW from Ankara's municipalities on a

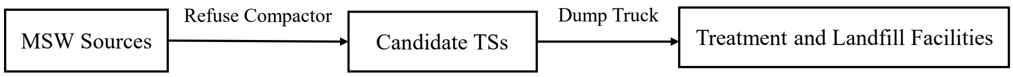


Figure 4.1: The schematic diagram of the extended MSWM system under study

daily basis. There are no hard rules regarding the assignment of collected MSW of certain municipalities to one of these facilities. A significant feature of this case study is that TSs do not operate in this system and the system comprises of MSW generation sources as well as Mamak and Sincan facilities. As a result, MSW is directly transfered from the generation sources to these two facilities for handling. It should be noted that various technologies such as separators, anaerobic digestors, compost plants, along with sanitary landfills operate in a single integrated mega-facility both in Mamak and Sincan. Thus, the third and forth levels of the considered MSWM network should be combined to formulate the underlying MILP model of Ankara's MSWM system.

In this case study, our aim is to locate the TSs in Ankara to investigate the economic feasibility and environmental benefits of the resulting system in comparison with the current one. Subsequently, the problem under study would have a network structured as in Figure 4.1 which locates TSs to minimize total daily system cost and daily CO_2 emission from transportation activities.

4.2 Network Construction

Geographical Information Systems have enabled decision makers to handle, analyze, and demonstrate spatial data in a more exact and easy manner. In this study, the physical distances between MSW sources, existing facilities, and candidate ones are measured by utilizing the *Network Analyst* extension of *ESRI's ArcGIS 10* software by introducing the road network of Ankara as a shapefile, created by OpenStreetMap [43], to *ArcGIS*. The daily MSW generation rates are calculated with respect to the population of the municipal districts of Ankara in 2016, released by TurkStat [52], multiplied by respective 2016's MSW generation rate per capita per day.

Additionally, for each municipal district having a daily MSW generation rate less than 250 tonnes, the centroid of the district obtained by *ArcGIS* is used as the MSW generation source. Districts with more than 250 tonnes of daily MSW generation rates are divided into a number of sub-districts possessing equal MSW generation rates that are less than the specified threshold. For each sub-district, its centroid is again taken as the MSW generation source. There are usually more than one MSW generation source in highly populated municipal districts and by dividing such districts into a number of sub-districts, we aim to obtain a relatively realistic MSWM network for Ankara.

60 candidate locations for TSs are introduced as a shapefile in *ArcGIS* for the MSWM system of Ankara, see Figure 4.2. We generate the daily fixed and variable costs (€) of each candidate TS uniformly at random from $[250, 400]$ and $[1, 5]$ intervals, respectively. Note that, we incorporate depreciation cost of facilities, which is linked to construction costs and expected life span, in evaluation of the fixed cost interval. Besides, the variable cost is considered as the operating cost of facilities which is directly proportional to the processed MSW in each facility.

Figures 4.3 and 4.4 represent the considered MSW transportation network. In Figure 4.3 one can observe the spatial distribution of MSW sources and candidate TSs along with the shortest paths connecting them. Besides, Figure 4.4 depicts the second level of the MSWM network comprising of candidate TSs, treatment and landfill facilities, and the connecting shortest paths.

Furthermore, two vehicle types are considered, namely, a refuse compactor with $18\,m^3$ capacity and a dump truck with 40 tonne capacity functioning as collection vehicles and high-volume transfer vehicles, respectively [28]. There are a number of parameters with common values for both vehicle types [13, 34], see Table 4.1, and a few parameters with different values for each vehicle type taken from [28], see Table 4.2.

Typically, the FC rate per unit distance as a function of vehicle speed as estimated by CMEM is a convex U-shaped curve [8]. The optimal speed, V_{opt}, of a vehicle minimizing the FC rate is independent of the load carried and is equal to $(\omega_1/2\omega_4)^{1/3}$ [31]. Figure 4.5 displays the FC rate as a function of speed plotted for each vehicle

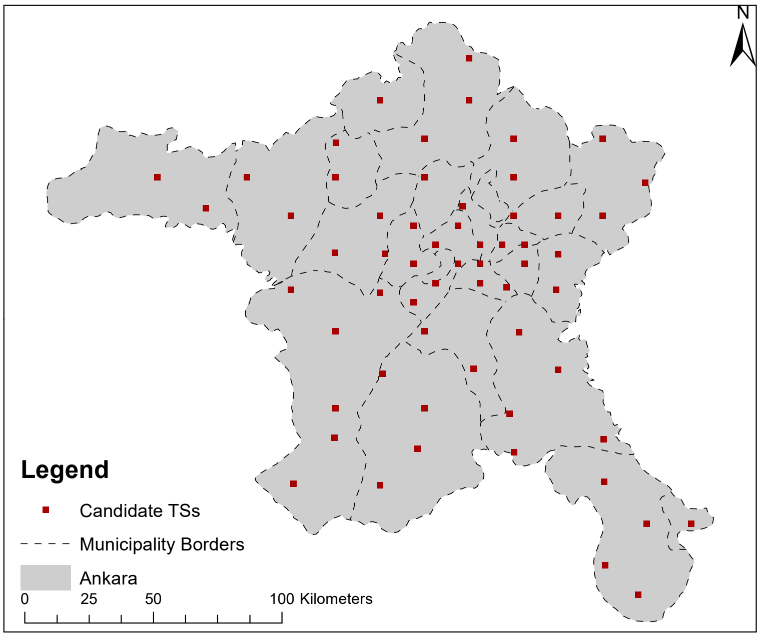


Figure 4.2: Spatial distribution candidate TSs.

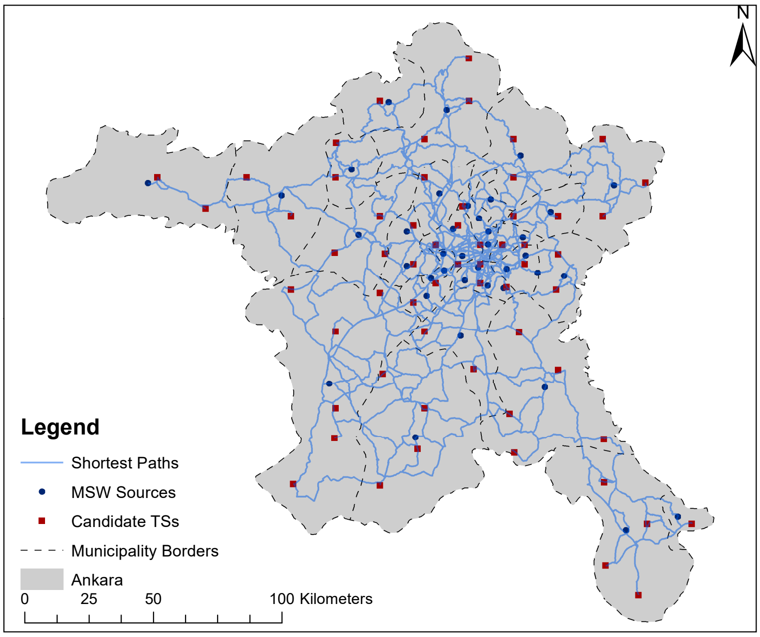


Figure 4.3: Spatial distribution of MSW sources and candidate TSs along with the shortest paths connecting them.

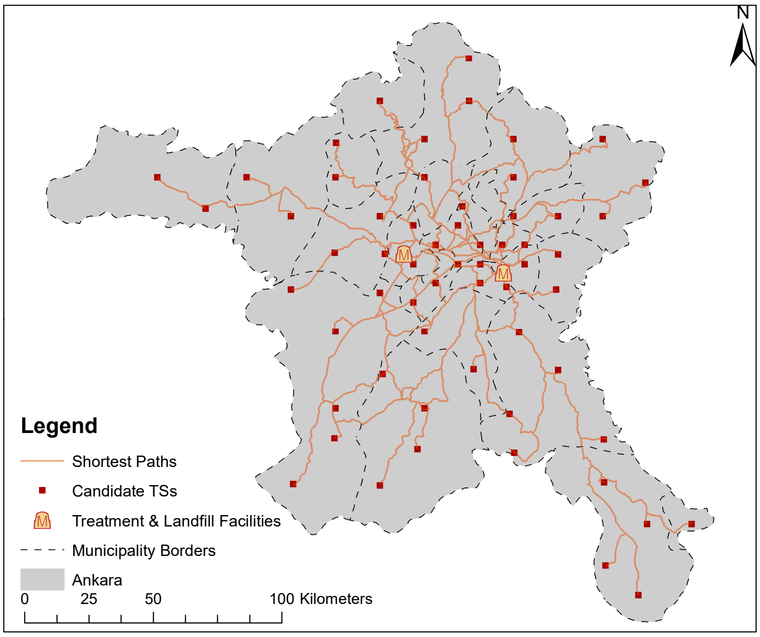


Figure 4.4: Spatial distribution of candidate TSs and treatment and landfill facilities along with the shortest paths connecting them.

type carrying no load with respect to the parameters specified in Tables 4.1 and 4.2. Increasing the load of the vehicles shifts the FC rate curve upwards which can be observed in Figure 4.6 for the refuse compactor.

We assume that angel of every road segment is equal to zero ($\Phi = 0$). As can be noticed from Figure 4.5, transporting a specific amount of MSW through the same distance with the same speed using refuse compactors results in a slightly higher FC than dump trucks. The difference in FC of refuse compactors and dump trucks would be more noticeable when a single dump truck carries a certain amount of MSW that can be alternatively carried by multiple refuse compactors.

For instance, in order to transport 24 tonnes of MSW for $100\,km$ with a speed of $60\,km/h$, 3 refuse compactors are needed consuming around $177\,L$ of diesel fuel in total. However, a single dump truck can transport the same amount of MSW over the same distance with the same speed by consuming $79\,L$ of diesel fuel. Hence, utilizing large volume dump trucks could be beneficial for the MSWM system in terms of cost and emission savings.

Table 4.1: Parameters common to all vehicle types

Notation	Description	Value
ξ	Fuel-to-air mass ratio	1
κ	Heating value of a typical diesel fuel (kJ/g)	44
ψ	Conversion factor $(g/s$ to $L/s)$	737
ϵ	Vehicle drive train efficiency	0.45
π	Efficiency parameter for diesel engines	0.45
ρ	Air density (kg/m^3)	1.2041
e	Engine friction factor $(kJ/rev/L)$	0.2
g	Gravitational constant (m/s^2)	9.81
Φ	Road angel	0
C_r	Coefficient of rolling resistance	0.01
C_d	Coefficient of aerodynamic drag	0.7

Table 4.2: Vehicle-specific parameters

Notation	Description	Refuse Compactor	Dump Truck
N	Engine Speed (rev/s)	41.6	36.6
V	Engine displacement (L)	6.7	8.9
A	Frontal surface area (m^2)	7.35	7.53
μ	Curb weight (kg)	15880	12005

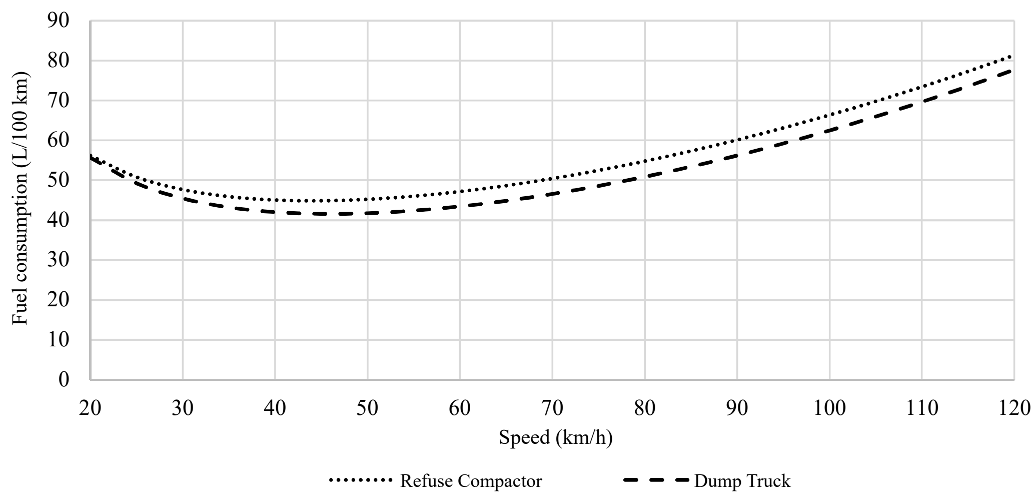


Figure 4.5: Fuel consumption per 100 km as a function of vehicle speed with empty load

An input of our model is the speed limits for each road segment. These speed limits should be specified not only based on legal speed limits imposed by legislative bodies, but also considering the impact of average traffic congestion over each road segment. For instance, in a highly congested road segment with a legal upper limit of $100\,km/h$, the traffic cannot flow with the specified upper speed limit. We assume in our model that the speed limits, given as input, are determined with respect to the average congestion in addition to the legal speed limits and any speed value between the given speed limits is achievable by the vehicles.

In our case study, as we do not have any information regarding congestion over the road network of Ankara, we define the speed limits as a function of population density of each municipal district. For this purpose, we divide Ankara into three zones with respect to the population density of its municipal districts defined as sparsely, medium, and densely populated zones. Correspondingly, lower and upper speed limits are assigned to each zone where they increase from densely to sparsely populated districts.

In Figure 4.7, categorization of the speed zones is provided. Lower and upper speed limits are assumed to be $20, 30, 40\,km/h$ and $30, 55, 70\,km/h$ for densely, medium, and sparsely populated zones, respectively. As locating TSs is a strategic level de-

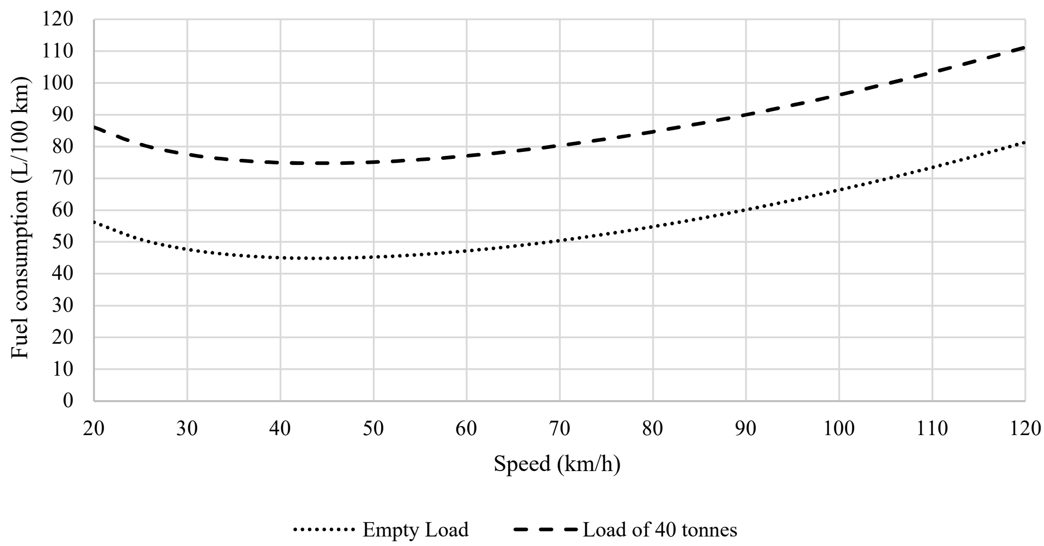


Figure 4.6: Fuel consumption of refuse compactor per 100 km as a function of vehicle speed with respect to different loads

cision, we ignore the impact of traffic congestion over different time periods on the speed limits. Once the locations of TSs are determined by implementing the proposed bi-objective MILP model, one can consider the scheduling problem in the MSWM system by taking the congestion in different time periods into account as a post hoc analysis.

4.3 Computational Experiments and Analyses

In the current MSWM system of Ankara, MSW collection is performed by municipalities using a specific type of refuse compactors and MSW is then sent directly to the treatment and landfill facilities by these vehicles. Presence of TSs as consolidation points proved to be cost-effective and environmentally beneficial for MSWM systems, as multiple MSW collection vehicles with limited capacities replace with large-volume transfer vehicles to transport MSW to distant facilities [53]. Therefore, we investigate the impact of introducing TSs into Ankara's MSWM system by applying the proposed bi-objective MILP model. We further investigate the influence of speed variations on the resulting CO_2 emission by conducting simulation analyses.

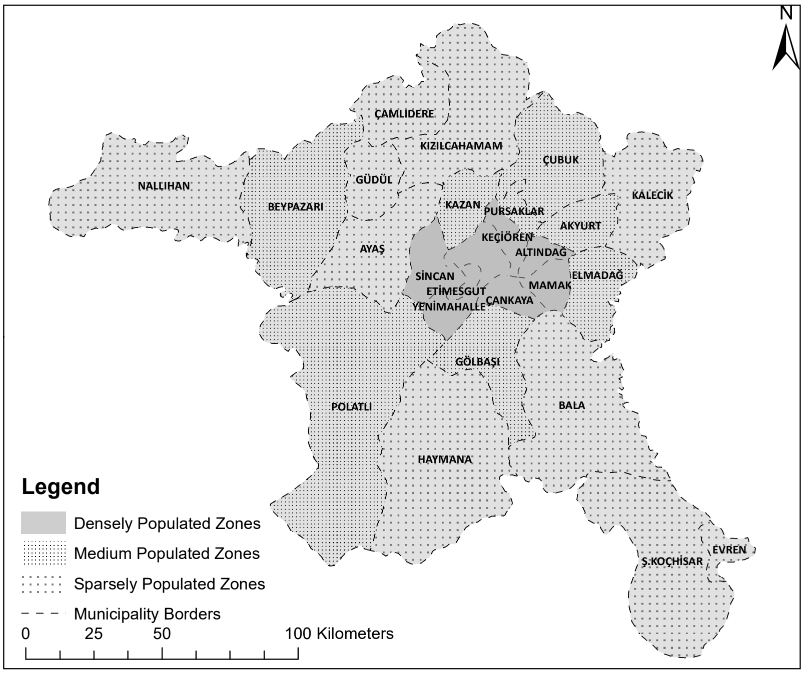


Figure 4.7: Speed zones

The MILP models in this section are solved using IBM ILOG CPLEX Optimization Studio (12.8.0) [29] on a server with Intel(R) Core(TM) i7-4770S CPU 3.10 GHz (8 CPUs) and 16384 MB RAM with operating system Windows 10. The simulation analyses are carried out using Matlab 2018RA on the same server.

The FC of vehicles and the emitted CO_2 are calculated by considering the best travel speed configuration of the vehicles resulting in the lowest emission on each road segment. For the refuse compactors and dump trucks considered in this study, the optimal speed values minimizing the FC rate are found as $V_{opt}^1 \approx 44\ (km/h)$ and $V_{opt}^2 \approx 46\ (km/h)$, respectively, which can be observed in Figure 4.5 as well.

Travel speeds of vehicles are determined by considering the U-shaped FC function along with the lower and upper speed limits of each zone. If the optimal speed of a vehicle V_{opt} satisfies the speed limits, then the travel speed of a vehicle would be V_{opt}. Otherwise, the travel speed of a vehicle is taken as the feasible speed (i.e., speed value satisfying the speed limits) that is closest to V_{opt}. Thus, the travel speeds of refuse compactors and dump trucks are chosen according to Table 4.3.

Table 4.3: Travel speeds of vehicles on each road segment

Road segment	Lower-Upper speed limits (km/h)	Travel speed (km/h)	
		Refuse Compactor ($V_{opt}^1 \approx 44\, km/h$)	Dump Truck ($V_{opt}^2 \approx 46\, km/h$)
in densely populated zones	20-30	30	30
in medium populated zones	30-55	44	46
in sparsely populated zones	40-70	44	46

In our computational experiments, emission values are calculated considering CO_2 emission coefficient c as $2.67\, kg$ per liter of diesel consumed by vehicles [54]. The unit fuel cost f is set to $1.01\,€/L$ according to [24] and unit variable transportation cost coefficient w_t is assumed to be $2\,€$ per kilometer for each vehicle type t.

The existing MSWM system in Ankara (operating without TSs) has been formulated with respect to the proposed MILP model, and optimized in terms of CO_2 emission minimization objective which is solved within 0.08 seconds. The minimum amount of CO_2 emitted by refuse compactors in this system is calculated as $65,048\, kg/day$ which is the result of direct shipment of MSW from sources to treatment and landfill facilities. Corresponding to this solution, the total daily cost of the current system is $63,942\,€$. This cost comprises of fuel cost which is $24,606\,€$, fixed and variables costs of the facilities which is $37,029\,€$, and variable transportation cost which is $2,307\,€$. Optimizing the current system in terms of the cost minimization objective results in almost the same amounts of total daily system cost, $63,937\,€$, and CO_2 emission, $65,052\, kg/day$, as no decision is made regarding establishment of new facilities.

First, we aim to extend the current system by introducing TSs to minimize the total daily system cost. We use the model developed in Section 3.3 for this purpose. In this case, the model locates 9 TSs out of 60 candidate locations (see Figure 4.11a) with a total daily system cost of $65,131\,€$. $17,445\,€$ of this value amounts to fuel cost, $46,192\,€$ to fixed and variable costs of the facilities, and $1,494\,€$ to variable transportation cost. Introducing these 9 TSs increases the total daily cost of the current system by 1.86%, and results in a 29.10% reduction in the amount of emitted CO_2 in the extended system. Thus, a relatively small increase in the total daily system cost results in a considerable reduction in the daily CO_2 emission from transportation activities. Note that, in this case, the MILP model is solved within 4.59 seconds.

The two objectives, namely, total daily MSWM system cost and daily CO_2 emission from transportation of MSW, of the proposed MILP model are in conflict with each other as increasing the system cost results in locating more TSs bringing more flexibility in transportation services and less CO_2 emission. As a matter of fact, it is not possible to find a solution which optimizes these two objectives simultaneously and Pareto efficient solutions are needed to be generated instead. The ϵ-constraint method is employed to generate the Pareto front [57]. This method solves a sequence of single-objective optimization problems by transforming the other objective into a constraint and changing its upper bound progressively. For more details on the ϵ-constraint method in bi-objective optimization problems, the reader is referred to [9].

We transform cost minimization objective into a constraint and change its upper bound, considered as a budget, progressively to achieve the Pareto front. Algorithm 1 describes the implemented ϵ-constraint method for generating the Pareto front of the the proposed bi-objective MILP Model. Let f be a solution belonging to F, the set of feasible solutions generated by the entire set of constraints of the proposed MILP model in Section 3.3. Figure 4.8 represents the set of Pareto efficient solutions as points on the Pareto front which are obtained by implementing the ϵ-constraint method for the extended system operating with TSs.

As can be seen from Figure 4.8, increasing the budget (total daily system cost), upon the request from the responsible organization, from the budget of the minimum cost solution by a relatively small amount results in a considerable reduction in the daily CO_2 emission. As a result, we investigate the impact of increasing the budget from its minimum value step by step to investigate the gained environmental benefits in terms of CO_2 emission reduction.

Table 4.4 compares different budget values and the resulting CO_2 emission amounts, along with respective percent changes from two settings, namely, the current system operating without TSs (1$^{\text{st}}$ setting) and the extended system optimized with respect to

Algorithm 1 The implemented ϵ-constraint algorithm

Determine f^0 as the optimal solution of $\min_{f \in F}\{Z_{emission}\}$

Record Z_{cost} corresponding to solution f^0 as Z^0_{cost}

$P \leftarrow \{f^0\}$

Determine f^1 as the optimal solution of $\min_{f \in F}\{Z_{emission} + \epsilon_1 * Z_{cost} | Z_{cost} \leq Z^0_{cost}\}$

Record Z_{cost} corresponding to solution f^1 as Z^1_{cost}

$P \leftarrow P \cup \{f^1\}$

$i \leftarrow 2$

while $\min_{f \in F}\{Z_{emission} + \epsilon_1 * Z_{cost} | Z_{cost} \leq Z^{(i-1)}_{cost} - \epsilon_2\}$ is feasible **do**

  $f^i \leftarrow \min_{f \in F}\{Z_{emission} + \epsilon_1 * Z_{cost} | Z_{cost} \leq Z^{(i-1)}_{cost} - \epsilon_2\}$

  Record Z_{cost} corresponding to solution f^i as Z^i_{cost}

  $P \leftarrow P \cup \{f^i\}$

  $i \leftarrow i + 1$

end while

Remove dominated solutions from P

cost minimization objective (2nd setting).

If the budget of the current system is increased by 4.78%, then with this budget 14 TSs are located out of 60 candidate locations in the extended system when the daily CO_2 emission objective is minimized. This results in a 38.39% reduction in daily CO_2 emission from transportation activities. In the extended system, when we compare the solution obtained by the minimization of the total daily system cost objective and the solution corresponding to the $67,000$ € budget, a 2.87% increase in the budget leads to a 13.10% decrease in CO_2 emission from transportation activities. This reduction in CO_2 emission is achieved by opening 5 more TSs (see Figure 4.11b).

As mentioned before, in the current MSWM system, there are no TSs and the MSW is directly sent from MSW sources to treatment and landfill facilities. We have so far investigated the effect of using TSs as transshipment facilities. We now consider a hybrid system in which there are candidate TSs to be located while MSW is also allowed to be sent directly from MSW sources to treatment and landfill facilities via a new set of shortest paths introduced between them. The schematic diagram of the hybrid MSWM network of Ankara is depicted in Figure 4.9 where dashed line

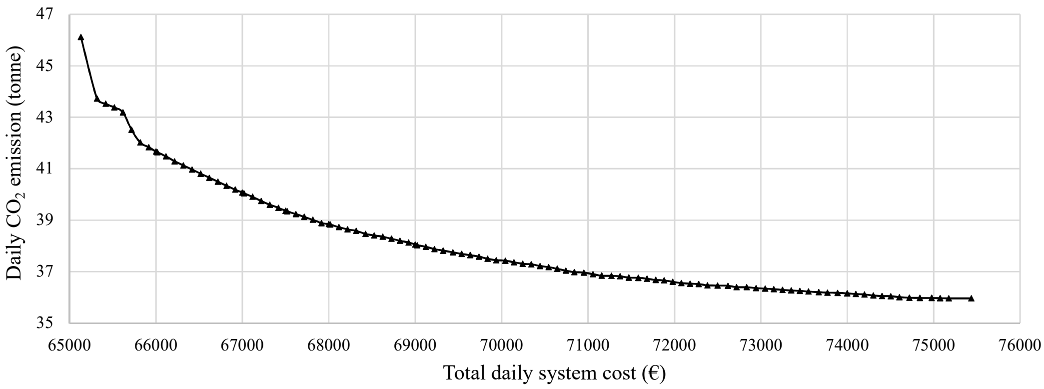


Figure 4.8: Pareto front of the extended system operating with TSs

represents the newly introduced set of paths.

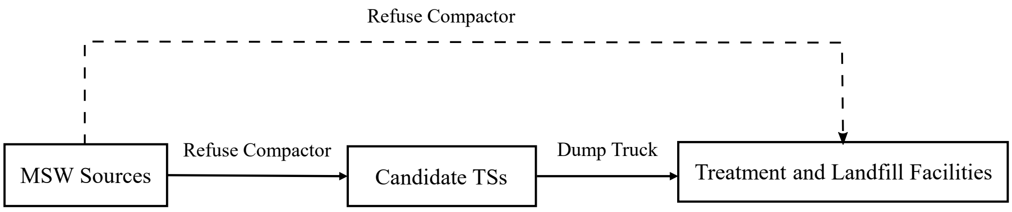


Figure 4.9: The schematic diagram of the hybrid MSWM system under study

It is expected that, inclusion of these new set of paths would result in lower CO_2 emission from transportation of MSW as it brings more flexibility in path selection for refuse compactors. As a result, the generated MSW at some sources that are comparatively closer to treatment and landfill facilities can be partially or totally transfered directly to the treatment and landfill facilities via the newly introduced shortest paths.

In order to formulate the underlying MILP model of this hybrid MSWM system, we need to introduce new sets of parameters and decision variables, perform some modifications in the objective functions, add new sets of constraints, and modify the MSW generation balance constraints in the MILP formulation of Section 3.3. The details regarding new MILP formulation is omitted here as it is analogous to the one given in Section 3.3. We provide the MILP formulation of the hybrid system for the general network configuration with four levels, MSW generation sources; TSs; P&T facilities; and SLs, in Appendix B. Note that, no direct shipment is allowed

Table 4.4: Comparison of different settings in terms of both objectives

Setting	Objective		% change from the 1st setting		% change from the 2nd setting	
	$Z_{cost}(€)$	$Z_{emission}(kg)$	$\Delta Z_{cost}(€)$	$\Delta Z_{emission}(kg)$	$\Delta Z_{cost}(€)$	$\Delta Z_{emission}(kg)$
1st setting [a]	63,942	65,048	-	-	-	-
2nd setting [b]	65,131	46,117	1.86	-29.10	-	-
3rd setting [c]	66,000	41,666	3.22	-35.95	1.33	-9.65
4th setting [d]	67,000	40,075	4.78	-38.39	2.87	-13.10
5th setting [e]	68,000	38,850	6.35	-40.27	4.41	-15.76
6th setting [f]	69,000	38,056	7.91	-41.49	5.94	-17.48

[a]Current system

[b]Extended system with minimum Z_{cost}

[c]Extended system with minimum $Z_{emission}$ and budget $\leq$ 66,000

[d]Extended system with minimum $Z_{emission}$ and budget $\leq$ 67,000

[e]Extended system with minimum $Z_{emission}$ and budget $\leq$ 68,000

[f]Extended system with minimum $Z_{emission}$ and budget $\leq$ 69,000

between MSW generation sources and SLs as MSW should go through precessing and treatment operations before final disposal. Hence, we introduce new set of paths $i - k$ along with the required parameters and decision variables between MSW generation sources and P&T facilities to the mathematical model reported in Section 3.3.

In order to compare the results for the extended and hybrid systems, Pareto front of the hybrid model is generated. The set of Pareto efficient solutions on the Pareto front of the hybrid model is shown in Figure 4.10 along with the Pareto front of the extended model. As can be seen, the hybrid model's Pareto front falls below the extended one which supports the claim that for every fixed budget value, the hybrid system results in lower daily CO_2 emission from transportation activities.

Fixing the budget to $67,000$ €, the resulting daily CO_2 emission is $40,075$ and $36,132$ kg in the extended and hybrid models, respectively. This 9.84% decrease in CO_2 emission is due to locating 22 TSs in the hybrid model in comparison to locating 14 TSs in the extended one. In the extended model, $15,160$ € is allocated to fuel cost, $50,570$ € to fixed and variable costs of the facilities, and $1,270$ € to variable transportation cost. On the other hand, in the hybrid system, the fuel cost accounts for

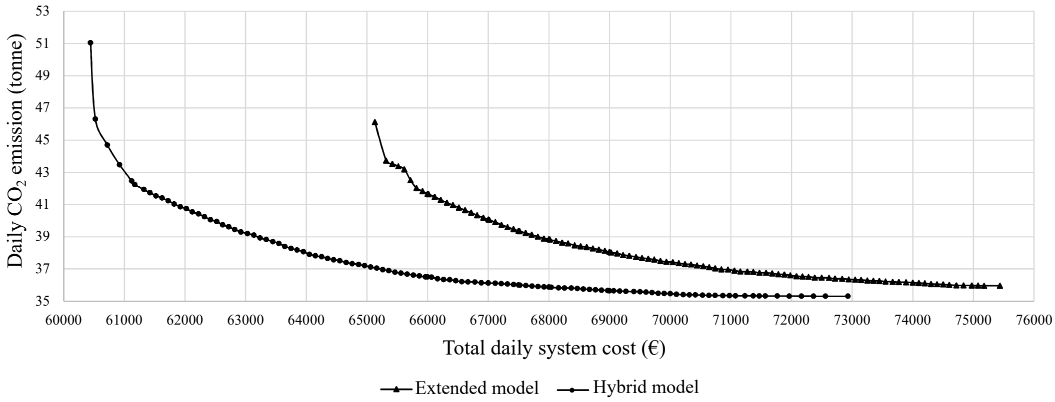


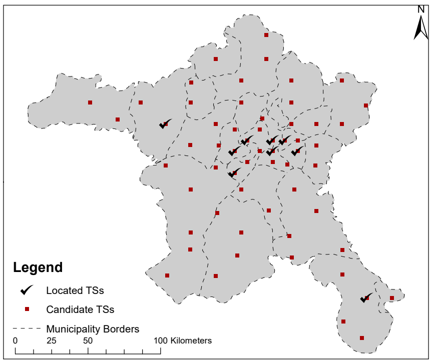
Figure 4.10: The extended vs hybrid models' Pareto fronts

$13,668$ €, fixed and variable costs of the facilities account for $52,205$ €, and variable transportation cost amounts to $1,127$ €. In the hybrid model, 17.56% of the MSW is transported directly from sources to treatment and landfill facilities.

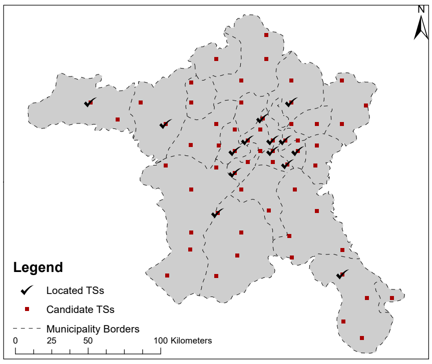
In Figure 4.11, one can see all candidate TSs and compare the locations of the selected ones in the extended setting with minimum total daily system cost (Figure 4.11a), in the extended setting with minimum daily CO_2 and $67,000$ € budget (Figure 4.11b), in the hybrid setting with minimum total daily system cost (Figure 4.11c), and in the hybrid setting with with minimum daily CO_2 and $67,000$ € budget (Figure 4.11d).

In summary, if we consider the current system, extended system with minimum total daily system cost, extended system with minimum emission and $67,000$ € budget, hybrid system with minimum total daily system cost, and hybrid system with with minimum emission and $67,000$ € budget, the respective allocation of total daily system cost into fuel cost (Z_{fuel}), fixed and variable costs of the facilities (Z_{fac}), and variable transportation cost (Z_{trans}) are reported in Table 4.5. Note that $Z_{emission} = \dfrac{c}{f} Z_{fuel}$. Additionally, the percent changes of the reported cost values from the values of the current system are included in Table 4.5.

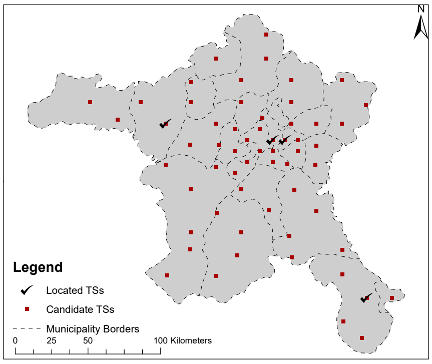
It is worth mentioning that the hybrid system with minimum total daily system cost (7th setting) improves the current system (1st setting) in terms of both total daily system cost and CO_2 emission objectives. In this setting, the cost saving in transportation activities, resulted by inclusion of TSs, is large enough to be allocated for opening TSs without imposing any additional costs into the system.



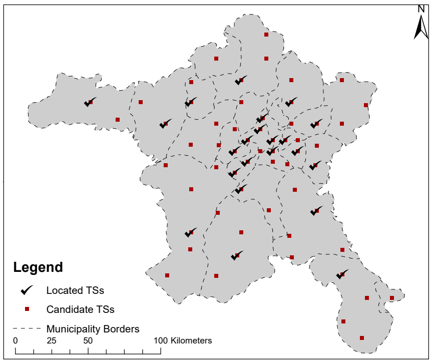
(a) Selected TSs by extended model with the minimum total daily system cost.



(b) Selected TSs by extended model with with an $67,000$ € budget.



(c) Selected TSs by hybrid model with with the minimum total daily system cost.



(d) Selected TSs by hybrid model with with an $67,000$ € budget.

Figure 4.11: Selected TSs

4.4 Simulation Analyses

As was mentioned before, vehicle speed is one of the factors affecting the FC of a particular vehicle. The CO_2 emission in previous analyses was calculated with respect to optimal speed of vehicles in terms of FC as well as lower and upper speed limits of the zones according to Table 4.3.

The travel speed of a vehicle depends on numerous factors such as drivers' behavior, road and weather conditions. In this section, we want to investigate the sensitivity of the resulting CO_2 emission from transportation activities and the total daily system cost in MSWM system of Ankara to speed variations.

Table 4.5: Comparison of different settings in terms of cost categories

Setting	Daily system cost categories (€)					% changes from the 1st setting (€)			
	$Z_{emission}$	Z_{cost}	Z_{fuel}	Z_{fac}	Z_{trans}	ΔZ_{cost}	ΔZ_{fuel} *	ΔZ_{fac}	ΔZ_{trans}
1st setting	65,048	63,942	24,606	37,029	2,307	-	-	-	-
2nd setting	46,117	65,131	17,445	46,192	1,494	1.86	-29.10	24.75	-35.25
4th setting	40,075	67,000	15,160	50,570	1,270	4.78	-38.39	36.57	-44.94
7th setting[a]	51,052	60,442	19,312	39,400	1,730	**-5.47**	**-21.52**	6.40	-24.99
8th setting[b]	36,132	67,000	13,668	52,205	1,127	4.78	-44.45	40.98	-51.13

$^*\Delta Z_{fuel} = \Delta Z_{emission}$

[a]Hybrid system with minimum Z_{cost}

[b]Hybrid system with minimum $Z_{emission}$ and budget $\leq$ 67,000

For this purpose, we consider the current system along with four network configurations designed by the optimization model proposed in this paper, where locations of the MSWM facilities, including the TSs, MSW flows, and number of trips between them are fixed. Monte Carlo simulation experiments are carried out considering vehicle speed on each road segment as a random variable following a particular probability distribution. Based on the realized vehicle speed values, we assess the total daily system cost and CO_2 emission.

The four network configurations considered in the simulation analyses are the following settings;

- 1st setting: Current system (Operating without TSs),
- 2nd setting: Extended system with minimum total daily system cost,
- 4th setting: Extended system with minimum daily CO_2 and $67,000$ € budget,
- 7th setting: Hybrid system with minimum total daily system cost,
- 8th setting: Hybrid system with with minimum daily CO_2 and $67,000$ € budget.

We consider two types of probability distributions, namely, the uniform and triangular distributions, for vehicle speeds on each road segment. In the first set of simulation experiments, we assume that the travel speed of each vehicle traversing through

Table 4.6: The realized minimum, average, and maximum total daily system cost and CO_2 emission values in 1000 replications along with the margin of errors.

Setting	Distribution	Total daily system cost (€)				CO_2 emission (kg)			
		Minimum	Average	Maximum	MOE**	Minimum	Average	Maximum	MOE***
1st setting	Triangular	65,175	65,239	65,312	1.25	68,308	68,476	68,670	3.31
	Uniform	65,235	65,335	65,423	1.83	68,466	68,731	68,964	4.83
2nd setting	Triangular	65,938	65,977	66,024	0.82	48,251	48,353*	48,478	2.18
	Uniform	65,985	66,042	66,113	1.21	48,376	48,526*	48,714	3.19
4th setting	Triangular	67,700	67,736	67,780	0.76	41,927	42,021*	42,138	2.01
	Uniform	67,732	67,792	67,841	1.09	42,012	42,170*	42,298	2.89
7th setting	Triangular	61,362	61,415*	61,476	0.90	53,484	53,624*	53,784	2.38
	Uniform	61,408	61,488*	61,553	1.33	53,606	53,815*	53,990	3.51
8th setting	Triangular	67,623	67,660	67,700	0.74	37,779	37,876*	37,983	1.95
	Uniform	67,666	67,709	67,762	1.03	37,893	38,007*	38,147	2.71

*Mean values are significantly smaller than the corresponding values in the current system under the best speed pattern at the 5% significance level.

**MOE: margin of error for a 95% confidence interval for the mean total daily system cost.

***MOE: margin of error for a 95% confidence interval for the mean CO_2 emission.

densely, medium, and sparsely populated zones follows $U(20, 30)$, $U(30, 55)$, and $U(40, 70)$, respectively, where $U(a, b)$ represents the continuous uniform distribution with parameters a and b. For the second set of experiments, it is assumed that the travel speed of each vehicle traversing through densely, medium, and sparsely populated zones follows $T(20, 25, 30)$, $T(30, 40, 55)$, and $T(40, 55, 70)$, respectively, where $T(a, b, c)$ represents the triangular distribution with parameters a, b, and c.

For each of the network configurations and for each of the probability distributions, 1000 replications are done and the realized minimum, average, and the maximum total daily system cost and CO_2 emission values along with the margin of error for a 95% confidence interval for the mean total daily system cost and the mean CO_2 emission are reported in Table 4.6.

Moreover, for each setting, the respective percent changes from the values reported in Table 4.5 (i.e., the values obtained by the best speed patterns) are displayed in Table 4.7.

Looking at Table 4.6, we can see that the mean CO_2 emission values for the consid-

Table 4.7: Percent changes of minimum, maximum, and average total daily system cost and CO_2 emission values obtained in Monte Carlo simulation from total daily system cost and CO_2 emission of best-speed schemes.

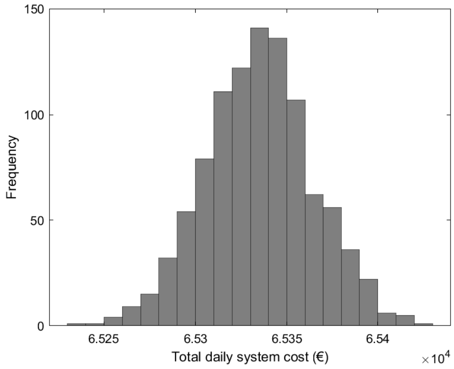
setting	Distribution	% change of total daily system cost (€)			% change of CO_2 emission (kg)		
		Minimum	Average	Maximum	Minimum	Average	Maximum
1st setting	Triangular	1.93	2.03	2.14	5.01	5.27	5.57
	Uniform	2.02	2.18	2.32	5.26	5.66	6.02
2nd setting	Triangular	1.24	1.30	1.37	4.63	4.85	5.12
	Uniform	1.31	1.40	1.51	4.90	5.22	5.63
4th setting	Triangular	1.05	1.10	1.16	4.62	4.85	5.15
	Uniform	1.09	1.18	1.26	4.83	5.23	5.55
7th setting	Triangular	1.52	1.61	1.71	4.76	5.04	5.35
	Uniform	1.60	1.73	1.84	5.00	5.41	5.75
8th setting	Triangular	0.93	0.98	1.05	4.56	4.83	5.12
	Uniform	0.99	1.06	1.14	4.88	5.19	5.58

ered four network configurations (2nd, 4th, 7th, and 8th settings) with random speeds are significantly smaller than the CO_2 emission amount in the current system under the best speed patterns ($65,048\,kg$) at the 5% significance level. Moreover, the mean total daily system cost for the 7th setting with random speeds is significantly smaller than the total daily system cost of the current system under the best speed patterns (63,942 €) at the 5% significance level. Therefore, it can be concluded that the 7th setting improves the current system even when the vehicles do not travel according to the best speed patterns.

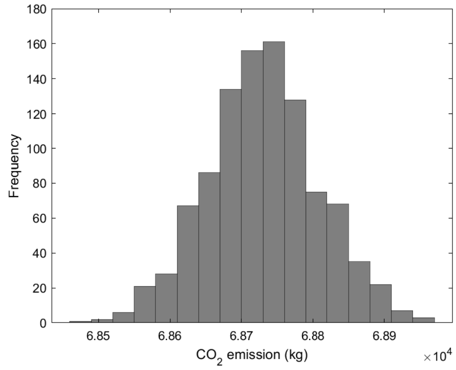
As can be seen from Table 4.7, if the vehicles do not follow the best speed patterns, but instead drive with speeds following the considered distributions, there will be less than 2.4% increase in total daily system cost and less than 6.1% increase in the emitted CO_2 amount for all five settings considered.

Even though the CO_2 emission amount increases when vehicles travel with random speeds, the resulting mean CO_2 emission amounts in all settings except the current one are still significantly less than the amount emitted in the current system under both best and random speed patterns.

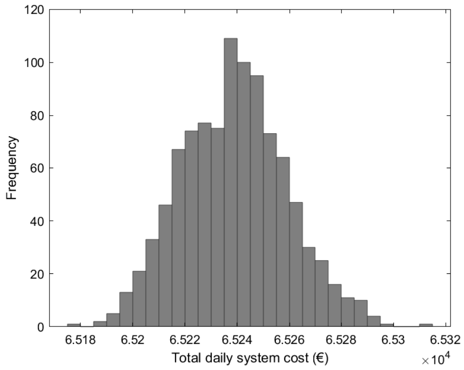
Finally, the histograms corresponding to the total daily system cost and CO_2 emission values for the considered network configurations are plotted and represented in Figures 4.12,4.13, 4.14, 4.15, and 4.16. As can be observed, all of the histograms have bell-shaped curves which is expected because of the large number of replications.



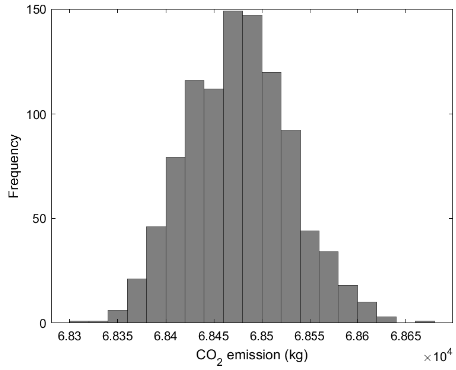
(a) Histogram of the total daily system cost values generated by the Uniform distribution.



(b) Histogram of the CO_2 emission values generated by the Uniform distribution.

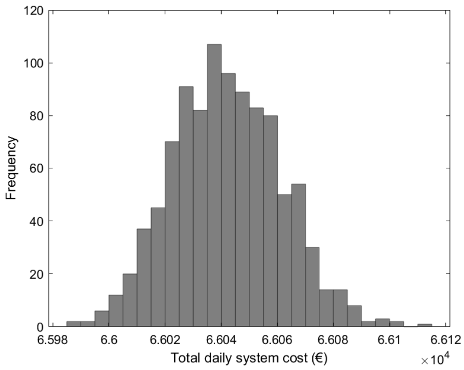


(c) Histogram of the total daily system cost values generated by the Triangular distribution.

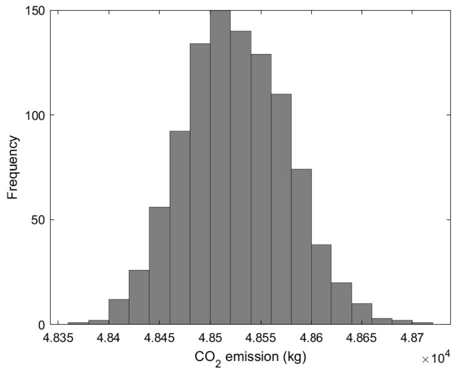


(d) Histogram of the CO_2 emission values generated by the Triangular distribution.

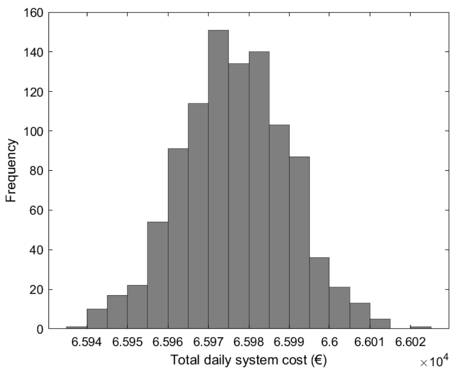
Figure 4.12: Histograms of the 1st setting generated by 1000 replications



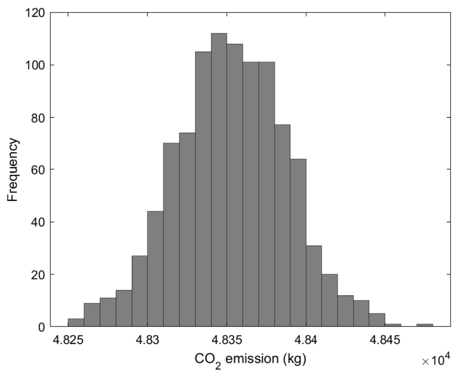
(a) Histogram of the total daily system cost values generated by the Uniform distribution.



(b) Histogram of the CO_2 emission values generated by the Uniform distribution.

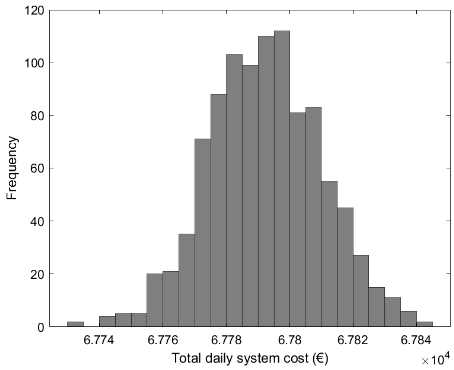


(c) Histogram of the total daily system cost values generated by the Triangular distribution.

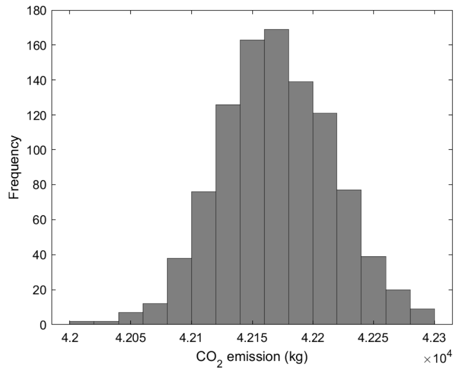


(d) Histogram of the CO_2 emission values generated by the Triangular distribution.

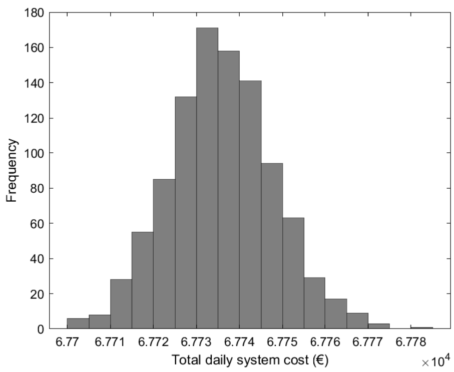
Figure 4.13: Histograms of the 2nd setting generated by 1000 replications



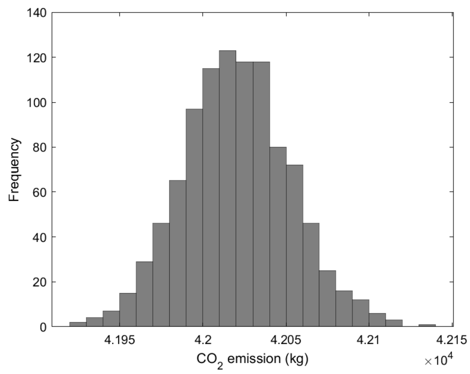
(a) Histogram of the total daily system cost values generated by the Uniform distribution.



(b) Histogram of the CO_2 emission values generated by the Uniform distribution.

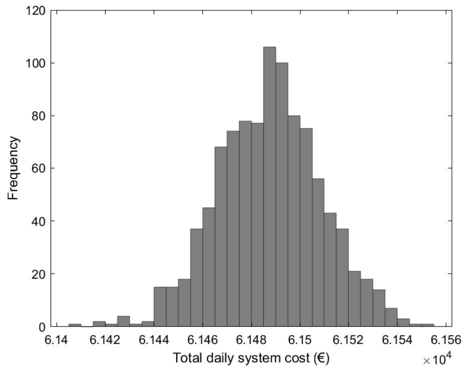


(c) Histogram of the total daily system cost values generated by the Triangular distribution.

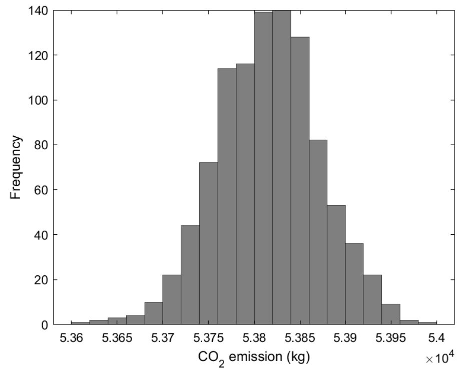


(d) Histogram of the CO_2 emission values generated by the Triangular distribution.

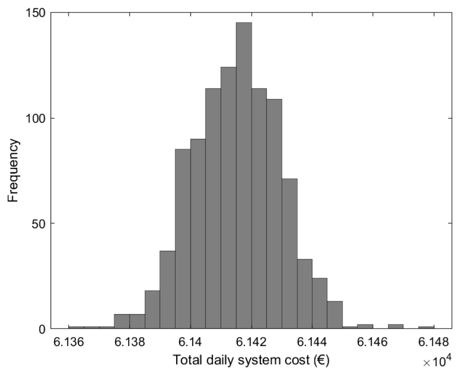
Figure 4.14: Histograms of the 4^{th} setting generated by 1000 replications



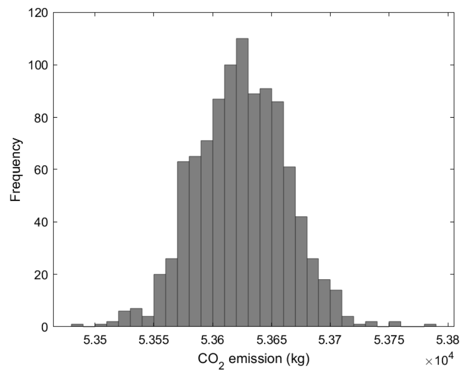
(a) Histogram of the total daily system cost values generated by the Uniform distribution.



(b) Histogram of the CO_2 emission values generated by the Uniform distribution.

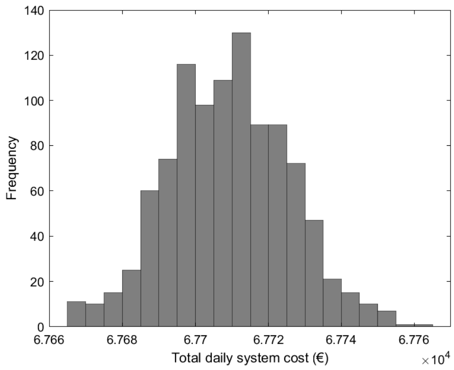


(c) Histogram of the total daily system cost values generated by the Triangular distribution.

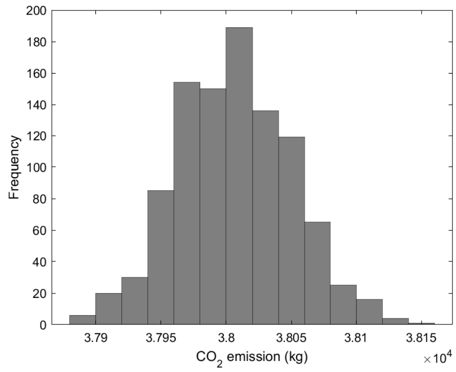


(d) Histogram of the CO_2 emission values generated by the Triangular distribution.

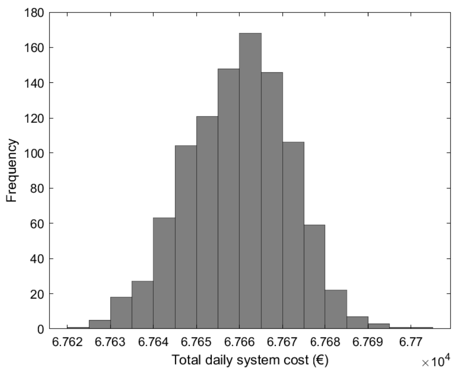
Figure 4.15: Histograms of the 7th setting generated by 1000 replications



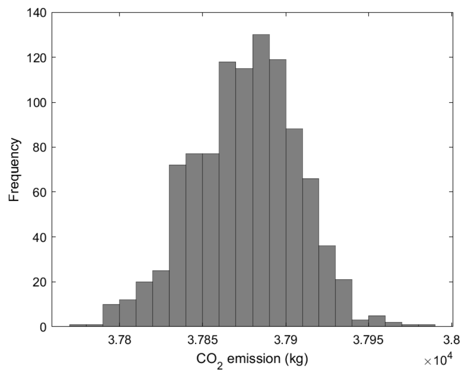
(a) Histogram of the total daily system cost values generated by the Uniform distribution.



(b) Histogram of the CO_2 emission values generated by the Uniform distribution.



(c) Histogram of the total daily system cost values generated by the Triangular distribution.



(d) Histogram of the CO_2 emission values generated by the Triangular distribution.

Figure 4.16: Histograms of the 8^{th} setting generated by 1000 replications

CHAPTER 5

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The objective of this study was to investigate the impact of CO_2 emission from transportation activities in locational planning of MSWM systems. A bi-objective MILP optimization model is developed to manage the system economically and environmentally by minimizing the total daily system cost and CO_2 emission of vehicles, respectively. The ϵ-constraint method was implemented to generate the Pareto efficient solutions of the proposed model.

This model was applied on MSWM system of Ankara to investigate the economic and environmental benefits obtained by introducing TSs into the current system. Two extensions of the current MSWM system have been considered, namely, the extended system in which no direct shipment from MSW sources to treatment and landfill facilities is allowed and the hybrid system where direct shipments are allowed in addition to indirect shipments through TSs. As the hybrid system brings more flexibility into the current system in terms of transportation services, the solutions found in the hybrid system dominate those found in the extended one. However, even for the extended system, little increase in the budget results in a considerable reduction in the CO_2 emission.

The results of the simulation analyses indicate that for both extensions of the current system, once the locations of the facilities and the allocations of MSW flows are fixed, the resulting CO_2 emission from transportation activities and the total daily system cost values are not subject to a considerable change due to speed variations. Moreover, it is observed that the 7^{th} setting improves the current one in terms of both objective functions even when the vehicles do not follow the best speed patterns. The proposed MSWM model can be utilized as a decision support tool by regional authorities and city logistics planners to have effective and efficient management of MSW services. This model enables decision makers to investigate MSWM system throughly by selecting the locations of MSW facilities, assessing the performances of different types of vehicles in the system, managing travel speeds of vehicles, and investigating the impact of imposed speed limits throughout the transportation network.

As a possible future research direction, one can consider stochastic MSW generation rates, their variations through time, and their subsequent impact on capacity allocation decisions of MSWM facilities. Moreover, it is assumed that the refuse compactors start their trips from the centroids of the considered municipal districts and sub-districts. Consideration of MSW collection operations, associated costs and emissions, and the integration of the collection system with the regional planning of MSWM system could be an interesting research direction for future.

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Appendix A

FC FORMULATIONS OF VEHICLES OF TYPE 2 & 3

FC by vehicles of type 2 over path $j-k$ can be calculated as

$$fcTP_{jk} = \upsilon_{jk}^{1} + \upsilon_{jk}^{2} + \upsilon_{jk}^{3}, \tag{A.0.1}$$

where

$$\upsilon_{jk}^{1} = (NTP_{jk}-1)\left(\omega_1^2\left(\sum_{r\in P_{jk}} \frac{LP_{jk}^r}{VP_{jk}^r}\right) + \omega_2^2 cap_2 DTP_{jk} + \omega_3^2 DTP_{jk} + \omega_4^2 \sum_{r\in P_{jk}} (VP_{jk}^r)^2 LP_{jk}^r\right), \tag{A.0.2}$$

$$\upsilon_{jk}^{2} = \left(\omega_1^2\left(\sum_{r\in P_{jk}} \frac{LP_{jk}^r}{VP_{jk}^r}\right) + \omega_2^2\left(QTP_{jk} - (NTP_{jk}-1)cap_2\right)DTP_{jk} + \omega_3^2 DTP_{jk} + \omega_4^2 \sum_{r\in P_{jk}} (VP_{jk}^r)^2 LP_{jk}^r\right), \tag{A.0.3}$$

$$\upsilon_{jk}^{3} = NTP_{jk}\left(\omega_1^2\left(\sum_{r\in P_{jk}} \frac{LP_{jk}^r}{VP_{jk}^r}\right) + \omega_3^2 DTP_{jk} + \omega_4^2 \sum_{r\in P_{jk}} (VP_{jk}^r)^2 LP_{jk}^r\right). \tag{A.0.4}$$

FC by vehicles of type 3 over path $k-l$ can be calculated as

$$fcPL_{kl} = \tau_{kl}^{1} + \tau_{kl}^{2} + \tau_{kl}^{3}, \tag{A.0.5}$$

where

$$\tau_{kl}^{1} = (NPL_{kl}-1)\left(\omega_1^3\left(\sum_{r\in L_{kl}} \frac{LL_{kl}^r}{VL_{kl}^r}\right) + \omega_2^3 cap_3 DPL_{kl} + \omega_3^3 DPL_{kl} + \omega_4^3 \sum_{r\in L_{kl}} (VL_{kl}^r)^2 LL_{kl}^r\right), \tag{A.0.6}$$

$$\tau_{kl}^{2} = \left(\omega_1^3\left(\sum_{r\in L_{kl}} \frac{LL_{kl}^r}{VL_{kl}^r}\right) + \omega_2^3\left(QPL_{kl} - (NPL_{kl}-1)cap_3\right)DPL_{kl} + \omega_3^3 DPL_{kl} + \omega_4^3 \sum_{r\in L_{kl}} (VL_{kl}^r)^2 LL_{kl}^r\right), \tag{A.0.7}$$

$$\tau_{kl}^3 = NPL_{kl}\left(\omega_1^3\left(\sum_{r\in L_{kl}} \frac{LL_{kl}^r}{VL_{kl}^r}\right) + \omega_3^3 DPL_{kl} + \omega_4^3 \sum_{r\in L_{kl}} (VL_{kl}^r)^2 LL_{kl}^r\right). \quad \text{(A.0.8)}$$

Appendix B

THE MILP MODEL OF THE PROPOSED HYBRID SYSTEM

Table B.1: The introduced set of parameters and decision variables for the MILP model of the hybrid system.

Notation	Description
D_{ik}	Sets of road segments on the shortest paths connecting i to k
DMP_{ik}	Distances of the shortest paths between i and k (km)
LD^r_{ik}	Lengths of the r^{th} segment of the shortest path from i to k (km)
$LSLD^r_{ik}$	Lower speed limits of the $r^{\text{th}}(r \in D_{ik})$ segment of the shortest paths connecting i to k (km/h)
$USLD^r_{ik}$	Upper speed limits of the $r^{\text{th}}(r \in D_{ik})$ segment of the shortest paths connecting i to k (km/h)
VD^r_{ik}	Travel speed of vehicle of type 1 on the $r^{\text{th}}(r \in D_{ik})$ segment of the shortest path from i to k (km/h)
QMP_{ik}	Quantity of MSW to be transfered from i to k $(tonne/day)$
NMP_{ik}	Number of required trips to transfer quantified daily MSW from i to k
$fcMP_{ik}$	FC on the shortest paths from i to k (L)

Two objectives of the MILP model of hybrid system are

$$Z_{cost} = \sum_{j \in J} XT_j FCT_j + \sum_{k \in K} XP_k FCP_k + \sum_{l \in L} XL_l FCL_l + \tag{B.0.1a}$$

$$\sum_{j \in J} VCT_j \sum_{i \in I} QMT_{ij} + \sum_{k \in K} VCP_k \Big(\sum_{i \in I} QMP_{ik} + \sum_{j \in J} QTP_{jk} \Big) + \sum_{l \in L} VCL_l \sum_{k \in K} QPL_{kl} + \tag{B.0.1b}$$

$$f \Big(\sum_{i \in I} \sum_{j \in J} fcMT_{ij} + \sum_{i \in I} \sum_{k \in K} fcMP_{ik} + \sum_{j \in J} \sum_{k \in K} fcTP_{jk} + \sum_{k \in K} \sum_{l \in L} fcPL_{kl} \Big) + \tag{B.0.1c}$$

$$2 \Big(w_1 \sum_{i \in I} \sum_{j \in J} DMT_{ij} NMT_{ij} + \mathrm{w}_1 \sum_{i \in I} \sum_{k \in K} DMP_{ik} NMP_{ik} + w_2 \sum_{j \in J} \sum_{k \in K} DTP_{jk} NTP_{jk} + w_3 \sum_{k \in K} \sum_{l \in L} DPL_{kl} NPL_{kl} \Big) - \tag{B.0.1d}$$

$$\sum_{k \in K} C_k \sum_{j \in J} QTP_{jk}, \tag{B.0.1e}$$

and

$$Z_{emission} = c\Big(\sum_{i \in I}\sum_{j \in J} fcMT_{ij} + \sum_{i \in I}\sum_{k \in K} fcMP_{ik} + \sum_{j \in J}\sum_{k \in K} fcTP_{jk} + \sum_{k \in K}\sum_{l \in L} fcPL_{kl}\Big). \tag{B.0.2}$$

Overall, the bi-objective MILP model of hybrid system minimizes $(Z_{cost}, Z_{emission})$ subject to the following sets of constraints.

$$\sum_{j \in J_1} XT_j \leq TT \tag{B.0.3}$$

$$\sum_{k \in K_1} XP_k \leq TP \tag{B.0.4}$$

$$\sum_{l \in L_1} XL_l \leq TL \tag{B.0.5}$$

$$\sum_{j \in J} QMT_{ij} + \sum_{k \in K} QMP_{ik} = G_i, \ \forall i \in I \tag{B.0.6}$$

$$\sum_{k \in K} QTP_{jk} = \sum_{i \in I} QMT_{ij}, \ \forall j \in J \tag{B.0.7}$$

$$\sum_{l \in L} QPL_{kl} = \sigma_k(\sum_{j \in J} QTP_{jk} + \sum_{i \in I} QMP_{ik}), \ \forall k \in K \tag{B.0.8}$$

$$\sum_{i \in I} QMT_{ij} \leq CT_j XT_j, \ \forall j \in J \tag{B.0.9}$$

$$\sum_{i \in I} QMP_{ik} + \sum_{j \in J} QTP_{jk} \leq CP_k XP_k, \ \forall k \in K \tag{B.0.10}$$

$$\sum_{k \in K} QPL_{kl} \leq CL_l XL_l, \ \forall l \in L \tag{B.0.11}$$

$$NMT_{ij} \geq \frac{QMT_{ij}}{cap_1}, \ \forall i \in I, \ \forall j \in J \tag{B.0.12}$$

$$NMP_{ik} \geq \frac{QMP_{ik}}{cap_1},\ \forall i \in I,\ \forall k \in K \tag{B.0.13}$$

$$NTP_{jk} \geq \frac{QTP_{jk}}{cap_2},\ \forall j \in J,\ \forall k \in K \tag{B.0.14}$$

$$NPL_{kl} \geq \frac{QPL_{kl}}{cap_3},\ \forall k \in K,\ \forall l \in L \tag{B.0.15}$$

$$QMT_{ij} \geq 0, QMP_{ik} \geq 0, QTP_{jk} \geq 0, QPL_{kl} \geq 0,\ \forall i \in I,\ \forall j \in J,\ \forall k \in K,\ \forall l \in L \tag{B.0.16}$$

$$fcMT_{ij} \geq 0, fcMP_{ik} \geq 0, fcTP_{jk} \geq 0, fcPL_{kl} \geq 0,\ \forall i \in I,\ \forall j \in J,\ \forall k \in K,\ \forall l \in L \tag{B.0.17}$$

$$NMT_{ij}, NMP_{ik}, NTP_{jk}, NPL_{kl} \in \mathbb{Z}_+,\ \forall i \in I,\ \forall j \in J,\ \forall k \in K,\ \forall l \in L \tag{B.0.18}$$

$$XT_j, XP_k, XL_l \in \{0, 1\},\ \forall j \in J_1,\ \forall k \in K_1,\ \forall l \in L_1 \tag{B.0.19}$$

$$XT_j, XP_k, XL_l = 1,\ \forall j \in J_2,\ \forall k \in K_2,\ \forall l \in L_2 \tag{B.0.20}$$

Similarly, FC by vehicles of type 1 over path $i - k$ is calculated as

$$fcMP_{ik} = \upsilon_{ik}^1 + \upsilon_{ik}^2 + \upsilon_{ik}^3, \tag{B.0.21}$$

where

$$\upsilon_{jk}^1 = (NMP_{ik} - 1) \left(\omega_1^1 \left(\sum_{r \in D_{ik}} \frac{LD_{ik}^r}{VD_{ik}^r} \right) + \omega_2^1 cap_1 DMP_{ik} + \omega_3^1 DMP_{ik} + \omega_4^1 \sum_{r \in D_{ik}} (VD_{ik}^r)^2 LD_{ik}^r \right), \tag{B.0.22}$$

$$\upsilon_{jk}^2 = \left(\omega_1^1 \left(\sum_{r \in D_{ik}} \frac{LD_{ik}^r}{VD_{ik}^r} \right) + \omega_2^1 \left(QMP_{ik} - (NMP_{ik} - 1) cap_1 \right) DMP_{ik} + \omega_3^1 DMP_{ik} + \omega_4^1 \sum_{r \in D_{ik}} (VD_{ik}^r)^2 LD_{ik}^r \right), \tag{B.0.23}$$

$$\upsilon_{jk}^{3} = NMP_{ik}\left(\omega_1^1\left(\sum_{r\in D_{jk}} \frac{LD_{ik}^r}{VD_{ik}^r}\right) + \omega_3^1 DMP_{ik} + \omega_4^1 \sum_{r\in D_{ik}} (VD_{ik}^r)^2 LD_{ik}^r\right). \tag{B.0.24}$$