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A Vehicle Routing Problem Based Scenario Analysis for Optimum Siting of Municipal Solid Waste Transfer Stations

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by

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This is to certify that we have read the thesis **A Vehicle Routing Problem Based Scenario Analysis for Optimum Siting of Municipal Solid Waste Transfer Stations** submitted by **Milas Ceren Höke**, and it has been judged to be successful, in scope and in quality, at the defense exam and accepted by our jury as a MASTER'S THESIS.

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Declaration of Authorship

I, **Milas Ceren Höke**, declare that this thesis titled **A Vehicle Routing Problem Based Scenario Analysis for Optimum Siting of Municipal Solid Waste Transfer Stations** and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for the Master's degree at this university.
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A Vehicle Routing Problem Based Scenario Analysis for Optimum Siting of Municipal Solid Waste Transfer Stations

Abstract

The management of public services requires an in-depth decision-making method to provide the intended functionality and service life. Municipal solid waste management is indeed one of the most challenging tasks of local municipalities and currently occupies a substantial portion of the overall municipal expenses.

In this study, an entirely geographic information system (GIS) based facility siting method is developed to aid governmental bodies in the decision-making process to site such facilities. The proposed method is applied to site a transfer station (TS) in the southeastern region of İzmir, Turkey where the current landfill has completed its service life, and a new landfill is to be built. In the proposed method GIS is used in both land suitability and optimization processes different from most of the previous studies; which allows a more convenient and easy means of use for the user. The applied vehicle routing problem (VRP) algorithm is already present in the Network Analyst Extension of GIS software and thus economically and computationally less costly to carry out. First, a land suitability analysis was conducted to identify suitable areas followed by a scenario analysis to determine optimum TS sites and waste collection routes for various collection vehicle capacities through VRP analysis.

Economic analysis of the potential TS sites showed that the addition of a TS reduces the collection time and number of shifts by 9%. Similarly, collection with large vehicles decreased the collection time and number of shifts by 25% and 17%, respectively. However, the unit cost of the system increased from 17.52 to 18.60 US$ metric tonnes^{-1} waste with the TS addition because of the additional costs (capital, labor, operation, and management). The results indicated that TS addition is currently not economically feasible in the study area because of the small collection vehicle fleet (eight collection vehicles), the proximity of the landfill to areas with high waste density, and district-level collection. On the other hand, TS addition resulted in lower fuel consumption which may help reduce fuel-induced air pollution.

Keywords: Municipal solid waste management, solid waste collection, waste transfer station, optimum facility siting, geographic information system (GIS), vehicle routing problem (VRP), decision support system

Belediye Katı Atık Aktarma İstasyonlarının Optimum Yerleşimi için Araç Rotalama Problemine Dayalı Senaryo Analizi

Öz

Kamu hizmetlerinin yönetimi, amaçlanan işlevselliği ve hizmet ömrünü sağlamak için derinlemesine bir karar verme yöntemini gerektirir. Belediye katı atık yönetimi yerel belediyelerin en zorlu görevlerinden biridir ve genel belediye giderlerinin önemli bir bölümünü oluşturmaktadır.

Bu çalışmada, devlet kurumlarına bu tür tesislerin yerleştirilmesine karar verme sürecinde yardımcı olmak için coğrafi bilgi sistemi (CBS) tabanlı bir tesis yerleştirme yöntemi geliştirilmiştir. Önerilen yöntem, mevcut depolama sahasının hizmet ömrünü tamamladığı ve yeni bir depolama sahasının inşa edileceği İzmir'in güneydoğu bölgesinde bir transfer istasyonu (Tİ) sahasına uygulanmaktadır. Önerilen yöntemde, önceki çalışmaların çoğundan farklı olarak hem arazi uygunluğu hem de optimizasyon süreçlerinde CBS kullanılmaktadır; bu da kullanıcı için daha rahat ve kolay bir kullanım olanağı sağlar. Uygulanan araç rotalama problemi (ARP) algoritması, CBS yazılımının Ağ Analisti Uzantısı'nda zaten mevcuttur ve bu nedenle ekonomik ve hesaplama açısından yürütülmesi daha az maliyetlidir. Çalışmada ilk olarak, uygun alanların belirlenmesi için bir arazi uygunluk analizi yapıldı ve ardından, çeşitli toplama aracı kapasiteleri için optimum Tİ sahaları ve ARP analizi yoluyla atık toplama rotalarının belirlenmesi için bir senaryo analizi yapıldı.

Potansiyel Tİ sahalarının ekonomik analizi, bir Tİ eklenmesinin toplama süresini ve vardiya sayısını %9 oranında azalttığını göstermiştir. Benzer şekilde, büyük araçlarla toplama, toplama süresini ve vardiya sayısını sırasıyla %25 ve %17 oranında azaltmıştır. Ancak, sistemin birim maliyeti, ek maliyetler (sermaye, işçilik, işletme ve yönetim) nedeniyle Tİ ilavesiyle 17,52 ABD Doları'ndan 18,60 ABD Doları metrik ton^{-1} atığa yükseldi. Sonuçlar, küçük toplama araç filosu (sekiz toplama aracı), düzenli depolama sahasının yüksek atık yoğunluğuna sahip alanlara yakınlığı ve ilçe düzeyinde toplama nedeniyle Tİ ilavesinin şu anda çalışma alanında ekonomik olmadığını göstermiştir. Öte yandan, Tİ ilavesi, yakıt kaynaklı hava kirliliğini azaltmaya yardımcı olabilecek daha düşük yakıt tüketimi ile sonuçlanmıştır.

Anahtar Kelimeler: Katı atık yönetimi, katı atıkların toplanması, atık transfer istasyonu, optimum tesis konumlandırma, coğrafi bilgi sistemi (CBS), araç rotalama problemi (ARP), karar destek sistemi

I’d like to dedicate this thesis to my family;
to my mother for being the most creative, resourceful, and astonishing; I will never stop admiring your perspective of viewing the world,
to my father for being the most genius, just, and courageous; keep being the opposition party because that's how I learned to make myself heard,
and to my older sister and younger brother for allowing me to experience the entirety of the sibling spectrum; being the only spoon in the drawer would be unimaginable.

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List of Abbreviations

GIS	Geographic Information System
TS	Transfer Station
VRP	Vehicle Routing Problem
CBS	Coğrafi Bilgi Sistemi
Tİ	Transfer İstasyonu
ARP	Araç Rotalama Problemi
MSW	Municipal Solid Waste
RCRA	Resource Conservation and Recovery Act
EPA	Environmental Protection Agency
NP	Non-deterministic Polynomial-time Hardness
AHP	Analytical Hierarchy Process
MILP	Mixed-Integer Linear Programming
IBM	International Business Machines Corporation
O&M	Operation and Maintenance
WGS 1984 UTM	World Geodetic System 1984 Universal Traverse Mercator
SI	Suitability Index
TSP	Traveling Salesman Problem
BS	Baseline Scenario
HP	Horsepower

List of Symbols

n	Number of preference factors
w_i	AHP weight of the i^{th} preference factor
μ_i	Fuzzy membership degree of the i^{th} preference factor
A	Price of the vehicle in US$
N	Amortization duration in terms of years (6)
α	Annuitization coefficient
T	Lifetime in years (20)
i	Interest rate (10%)

Chapter 1

Introduction

Civil engineering is a multifaceted discipline that utilizes scientific knowledge for developing new approaches to cope with the challenges of real-life situations that arise from planning, designing, budgeting, surveying, constructing, and operating infrastructural systems. The practice should regard aspects that are; safety, sustainability, environmental, economic, legal, and ethical aspects simultaneously. To deliver such a holistic perspective and create functional and satisfactory systems, a civil engineer should anticipate any issues that will diminish the efficacy of the said system and take precautions to prevent such depreciating circumstances beforehand.

Infrastructure often implies the production of public goods and structures; hence governmental bodies are typically responsible for financing and delivering said production. Per this, in Turkey: general directorate offices and district municipalities are the ones that often undertake this deed.

In this thesis, a novel spatial method is developed to aid governmental bodies in the decision-making process to site public infrastructural systems. The proposed method is entirely Geographic Information System (GIS) based, which allows a more comfortable means of use since it reduces the mathematical route optimization problem into a vehicle routing problem (VRP). The VRP algorithm is already present in the Network Analyst Toolbox of GIS software and thus economically and computationally less costly to carry out.

The proposed method is employed to site a transfer station (TS) for municipal solid waste (MSW) collection and transportation system for exemplifying the application of the developed method. Additionally, an economic assessment was performed to question whether introducing a TS is a viable improvement and, if so, to determine the most feasible TS location.

The collection and transportation of MSW is one of the most challenging tasks of local municipalities and occupies a significant portion of the municipal expenses [1]. In Turkey, MSW collection is performed by small collection vehicles traveling the neighborhoods on a schedule and collecting the wastes from bins on streets until their capacity is reached. Bins are not allocated to specific waste generators; they serve all nearby residential and commercial units. The collected waste is then transported to a TS or a landfill directly (in some cases to a biogas or recycling plant). In the case of a TS, the transported waste is put and compacted to larger transfer vehicles at the TS, and transportation to the landfill is conducted with these larger transfer vehicles allowing fewer transfers to be made to haul the total waste amount.

Transfer stations become valuable in cases where landfills are far from settlements; this is often the case due to the opposition by residents besides public health and safety concerns [2, 3]. Since the transfer vehicles make fewer travels to the landfill, the overall cost of MSW collection, transfer, and transport can considerably decrease. Along with reducing the transfer costs, planning a TS can reduce the amount of air pollutants emitted due to MSW collection, transfer, and transport activities [4].

Even though there are years of accumulated experience and knowledge about the sustainable management of MSW, there is still potential to increase the system performance and decrease the costs significantly [2], which constitutes a motivation for this and further research.

1.1 Problem Definition

Delivering functional and satisfactory systems is particularly important in the modern world. In today's Turkey, poor/inadequate facility sitings and designs are often encountered, creating problems that may lead to a loss in functionality, shortened service life, and even the construction of an additional facility nearby. It is apparent that these designs often do not adequately estimate the effects of increasing population and dwindling resources and overestimate the service area that the facility will serve.

In this thesis, a method mainly dependent on spatial variations that determines the location of a public facility was developed and examined for a TS in a case study, and its results are presented.

The majority of the literature concerning TS siting consists of two separate parts: a GIS-based spatial analysis; and external mathematical optimization. GIS is used to determine land suitability and distance among nodes such as garages, waste sources, TSs, and landfills. The optimization process is generally carried out by mathematically modeling the question at hand and solving it under the determined constraints, and thus: the optimum number and sites for the facility are determined. A VRP algorithm was commonly used in optimization models to determine optimum routes that minimize the service time or, in some cases, the total distance. It is worth mentioning that, contrary to what was done in the present study, an economic assessment was mainly disregarded in previous studies. This study also differs from most of the previous studies by employing GIS not only for the land suitability analysis but for the optimization process as well.

Determination of travel times among nodes and route optimization in one single GIS-based VRP model in this approach made revisions to the model and interpretation of results simpler and avoided the construction of complex mathematical optimization models.

In brief, the purpose of this study is to develop an entirely GIS-based spatial modeling approach for investigating the optimum siting and economic impacts of MSW TSs. This study presents a holistic approach in the determination of economic feasibility, optimum siting, and operational specifications of TSs via spatial modeling and contributes to the sustainable collection, transfer, and transport of MSW. This study differs from the similar previous work by employing GIS in both analyses (spatial and optimizational) and conducting an economic assessment for the proposed optimum TS site.

A GIS-based land suitability analysis was conducted to identify potential TS sites followed by a scenario analysis to determine optimum TS sites and waste collection routes for two different collection vehicle capacities through VRP modeling. Finally, an economic analysis was performed. The approach was implemented in the southeastern region of İzmir where three district municipalities are located.

1.2 Scope

In the 1st chapter of this thesis, a brief introduction is given, and the definition of the problem is made.

In the following chapter, the individual tools/methods used in this study are explained and reasons to include them are justified. Previous works similar to this study are given and discussed by denoting the differences with the current one.

In Chapter 3, a summary of the methodology is given, the study area is described, and the steps that constitute the method are explained in detail.

In Chapter 4, the results of the previously explained steps are presented for the case study, and the computations are shown.

In the 5th Chapter, the results are debated, conclusions are made, and suggestions are given for the following studies.

In the References Chapter, the entirety of the references that are referred during the formation process of the current study is given.

Chapter 2

Literature Review

MSW management systems have been receiving a great deal of attention mainly for their economic and environmental consequences; hence many studies focus on improving these systems by coordinating various management strategies. In this section, before submitting any deliberations on MSW management, its description is given. GIS are explained and examples of its use are given. Then, previous works similar to this study are discussed in a systematized manner.

2.1 Municipal Solid Waste (MSW)

The definition is given by Resource Conservation and Recovery Act (RCRA) describes solid waste as "any garbage or discarded material generated by humans and human activities; sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility, and other discarded material, resulting from industrial, commercial, mining, and agricultural operations, and from community activities" [5]. These materials are not obliged to be in a physically solid state in order to be classified as solid waste.

Up until the 1970s, solid waste management was merely consisted of depositing the collected waste in unregulated landfills, accompanied by burning to reduce the accumulated volumes of waste. Industrial wastes were also discarded in the same manner. These unregulated activities caused environmental problems such as ground-water and soil/land contamination, toxic fume and greenhouse gas emissions, and increases in pest populations and hence, disease-spreading circumstances. It became apparent that a more diligent classification of said wastes should be made to minimize these environmental impacts. Under the broad title of solid wastes, a new class is identified as the MSW. According to Environmental Protection Agency (EPA) [6], MSW refers to a range of trash materials that are discarded as refused and/or useless; these can be everyday items that are used by the humans such as product packaging, furniture, clothing, bottles, and cans, food scraps, appliances, electronics, and batteries. This definition of MSW does not include industrial, hazardous, or construction and demolition waste. Currently, in most parts of the world, landfills are subject to federal or state requirements to restrain these adverse effects. In Turkey, responsibility of MSW collection is on district municipalities and transportation in metropolitan municipalities.

According to World Bank [7], the world generates 2.01 billion tonnes of MSW annually, with at least one-third of it is not managed in an environmentally safe manner. Worldwide, waste generated per person per day differs from 0.11 to 4.54 kilograms with an average value of 0.74 kilograms. Again, according to World Bank statistics, global waste is expected to reach 3.40 billion tonnes by 2050.

2.2 Geographical Information Systems (GIS)

A geographic information system is a computerized structure that merges geographical/spatial data (locations or coordinates) with tabular data in order to create, analyze, and manage all types of data. Its ability to assess geographically varying data is significantly appealing to researchers since a majority of real-world problems have such features. In brief, GIS connects data to maps, the thing of interest has locational information in addition to its descriptive information. Understanding patterns and relations differing by geography is easier considering it helps visualize the tabular data. GIS is used in almost every industry as well as in science. GIS is also used to recognize problems, monitor the changes, manage and respond to events that take place, and perform forecasting [8].

Mainly, there are two kinds of spatial data that GIS can make use of; raster data and vector data. Raster data is a matrix of cells that holds different information in each cell. These cells are arranged in rows and columns, and each represent a small rectangular area. Generally, raster data are used in areas that are hard to get high-resolution data; for instance, elevation data of 30m resolution in raster format implies that in each cell (every 30m by 30m square area) one elevation value (generally the average value) is available. Vector data, however, can be a point, a line or an arc (collection of points), and a polygon (collection of lines) that shows the exact location of the thing of interest. These types of data often have coordinates. More detailed information can be obtained by examining the book “Principles of Geographic Information Systems” referenced as [9].

There are many GIS software commercially available today with different potencies in different fields of analysis. In this thesis, ESRI's ArcGIS Desktop software version 10.7 is used due to its broad application fields, tools, and extensions. ArcGIS is the most widely used GIS software besides QGIS. Esri's ArcGIS is also preferred widely for its user-friendly geographical interface and geodatabase structures. It is updated and expanded much more frequently as it is preferred by the majority. In this study, the extensions Spatial Analyst and Network Analyst are largely used.

One of the key novelties of this study is that the decision support model is entirely GIS-based; Network Analyst Extention's VRP Solver is the main component that supports this idea.

2.3 Vehicle Routing Problem (VRP)

The VRP is a superset of the Travelling Salesman Problem (TSP) [10]. TSP is concerned with the determination of the shortest route which passes through each of the service points once. TSP solution established one route only. In a VRP, however, a group of service points must be assigned to a fleet of vehicles so that the overall cost is minimum. The VRP has undergone many improvements and additions since Dantzig and Ramser [10] due to its extensity. This problem has significant economic importance on transporting goods and providing services.

There is no universal definition of the VRP since there is a diverse constraint set for each problem. The majority of the studies involving VRP are standardized, called the classical VRP, to achieve adaptability to a number of real-life problems. Most of the research has concentrated on heuristics since the VRP is considerably more difficult to solve than a TSP of the same size [11].

The VRP is considered to be NP-hard; NP denotes problems verifiable in polynomial time and NP-hard denotes the problem is one of the hardest problems in the NP or as is usually said "at least as hard as the hardest problems in NP".

There are exact algorithms to solve a VRP, as well as classical heuristics and metaheuristics. The reader is encouraged to examine said approaches from the works referenced as [11, 12] since the heuristics used in the software are based on a tabu search metaheuristic [13, 14] and are not in the scope of this thesis.

2.3.1 VRP Solver in ArcGIS' Network Analyst

The routing solvers in Esri's ArcGIS -including TSP Solver, and the VRP Solver- are based on the well-known Dijkstra's algorithm for finding shortest paths [15]. Each solver implements two types of path-finding algorithms; one to find the exact shortest path, and one for a hierarchical path for faster performance.

The algorithm used for VRP Solver is a subset of the TSP algorithm therefore it should be introduced first.

The TSP Solver first generates an origin-destination cost matrix between all the order nodes given and uses a tabu search-based algorithm to find the best sequence. The TSP is a combinatorial problem, which means there's no straightforward way to find the optimum solution. As explained earlier heuristics are used widely to shorten the time needed to solve these problems [16, 17]. Hence, tabu-search is a metaheuristic search method broadly used to solve such combinatorial optimization problems. Tabu-search is a local search algorithm that explores and evaluates different solutions in the specified space by applying small local changes until reaching an optimal solution or computing a certain number of iterations. This is due to the computationally costly nature of these problems. Esri researched and developed extensive studies to improve the exact implementation of the tabu search in these toolboxes and they're proprietary.

The TSP implementation in Esri's Network Analyst also considers the time windows; that is the vehicle is expected to meet the services (the travel time and drop or collection time) in some user-specified time window.

VRP Solver of ArcGIS's Network Analyst Extension has other real-world constraints such as vehicle capacities, delivery time windows, and driver specialties [18]. It is expected to satisfy these constraints while minimizing an objective function of costs.

The VRP solver starts by generating an origin-destination matrix of shortest-path costs between all order and depot locations alongside the network. Using this cost matrix, it constructs an initial solution by inserting the orders one at a time onto the most appropriate route. The initial solution is then improved by resequencing the orders on each route, as well as moving orders from one route to another, and exchanging orders between routes.

The VRP Solver comes up with an itinerary for each driver (or route) for a fleet of vehicles to sequence and schedule their visits so that the orders are efficiently serviced and in the meantime restrictions/constraints such as time windows, driver breaks, and vehicle capacities are respected. The VRP Solver enables the user to input features; the orders, depots, routes, breaks, route zones (hard zone or soft zone), route renewals, time window factor, restrictions, and vehicle capacity. These are the network analysis objects that are used to solve the vehicle routing problem. The output features of the analysis are; depot visits, pick-up, and delivery quantities, total travel time, and distances, renewal counts and sequences, start-arrive-depart-end times, violations, and step by step summary of the route to be followed with directions. The reader is encouraged to browse the reference [19] to get a better understanding of the inputs and outputs of the analysis.

The main objective of this analysis is to obtain a high service level with satisfied constraints while keeping the overall operating and investment costs minimum.

2.4 Analytical Hierarchy Process (AHP)

Making sensible decisions is critical in every part of our lives. Choosing which car to buy, choosing a subject to focus on in high school, or moving to another city or state for occupation purposes: we are faced with comparing numerous choices throughout our lives. Moreover, there are a vast number of factors to be considered to make these decisions.

When these decisions concern more than one person or a community -for example, whether to build a dam or not- they become more complex problems of choice. Local or governmental issues like the above-mentioned dam construction proposal necessitate a logical decision-making process.

Saaty [20] states that the human mind is not capable of considering all the factors and their impacts in a simultaneous fashion to arrive at a logical decision. Individuals make choices on a reactive and unplanned basis with little anticipation of how the decisions are linked.

The Analytic Hierarchy Process (AHP) by Saaty [21] is a decision-making model that assists decision-makers in said complex circumstances. The AHP is of particular value when subjective, abstract, or nonquantifiable criteria are involved in the decision.

The AHP is a tool that has found uses in a wide range of problem areas from simple personal to complex and capital intensive decisions. Economic/management problems (auditing, database selection, design, finance, macro-economic forecasting, marketing, strategy, planning, and so on), political problems (arms control, conflicts and negotiation, political candidacy, security assessment, and so on), social problems (education, environmental, health, law, medicine, population dynamics and so on), and technological problems can be given as examples [22].

Lozano et al. [23] combined the AHP with GIS to determine the optimal placement of photovoltaic solar power plants in Spain. In the GIS part of the study, the areas that prevent the implementation of a power plant according to the legislation (planning regulations, protected areas, road networks, railways, waterways, mountains, etc) are eliminated. According to the objective to be reached, the rest of the areas are weighted with the AHP. The considered criteria, in this case, were location, geomorphological, environmental and climatic criteria.

Bosompem et al. [24] again integrated the AHP with GIS to obtain suitable areas to construct TSs in Kumasi, Ghana but ecological or economic restraints were left out in this evaluation. A total of 11 areas were found suitable for this area according to the criteria; proximity to highways, residential areas, rivers/streams, geology, slope, distance to fault lines, and distance to waste generation centers.

In another study by Güler and Yomralıoğlu [25] suitable areas to build a landfill site in İstanbul are investigated. In this evaluation, a total of 11 criteria are considered in two main groups of criteria: economic and environmental. The study showed that 80% of the study area were unauthorized to build such a plant and only 2% were very suitable.

It should be noted that the available data has significant importance in these studies for consideration of criteria. The resolution of the data also carries a significant role. Unless there is a great amount of data, the researchers should make sensible decisions while selecting the criteria for the evaluation for the AHP wights to be reasonable.

2.5 Mathematical Optimization and Land Suitability

Municipal solid waste management systems have been receiving a great deal of attention mainly for their economic and environmental consequences; hence many studies focus on improving these systems by coordinating various management strategies.

The most notorious and recent approach is integrating a TS into the system because of its ability to significantly reduce the cost of transporting the collected waste to the landfill facility.

The majority of the studies in the literature decomposes the problem at hand into two levels for determining the optimum TS location. These levels are briefly;

- Spatial Analysis: where a series of analyses are carried out to determine the areas that are not preoccupied or suitable (technically or legally) to contain the idealized facility (in this case; a TS),
- Optimization Analysis: where different algorithms are examined to specify the most economical (in terms of time and/or monetary cost) candidate between the locations determined in the 1st step.

For instance, in an early study by Chang and Lin [26], the TS siting problem was addressed by proposing a methodology that incorporates GIS with a mixed-integer programming model. Spatial analysis via GIS was performed to exclude unsuitable areas and identify candidate sites. The outputs of spatial analysis were used as inputs in the optimization model. They demonstrated their model's success with a case study and concluded that the optimal siting strategies of TSs are essential to reduce system cost and generate relatively reasonable operational programs. Accomplishing the above-mentioned objectives necessitated a mass of tools to be involved in the analysis; Foxpro is used to store the information, statistical analyses are performed with Excell, Statistica is used to construct the decision-support function, ArcView is used as the GIS component, and LINDO is used for the optimization analysis.

In another study, Chatzouridis, and Komilis [27] developed a methodology that combines GIS with binary programming to site TSs in an MSW system. They first performed a spatial analysis to establish potential TS locations and compute the optimal routes among all nodes in the system. Later, as per the second level, optimization was implemented to determine the number and the location of the TSs needed in the system. The study area (Region of Eastern Macedonia – Thrace in North Greece, a total of 53 municipalities) considered by the authors is almost eight times larger than the study area considered in this thesis. The input data that is necessary for the model is, therefore, less precise than the current study. For instance, collection vehicles were assumed to start and terminate their collection routes at the centers of the municipalities. Collection costs through the municipalities are estimated with an approximative approach. Also, the mentioned study by Chatzouridis and Komilis examined the total area as a whole (soft-zone) rather than a district-level collection system approach (hard-zone), much like in Turkey.

Mantzaras and Voudrias [28] extended the work by Chatzouridis and Komilis [27] and developed an optimization model for the collection of infectious medical wastes that includes the collection, transfer, transport, treatment, and disposal stages for the determination of several kinds of treatment facilities and TSs in the system. Two different optimization models were implemented in addition to a preliminary GIS analysis to determine the location, number, and capacity of the TSs and treatment facilities required in the system. Economic assessment of the system was conducted for various collection frequencies. MapInfo Software was selected as the GIS component; Evolver (based on the use of genetic algorithms) and Crystal Ball (based on Monte Carlo simulation) are used for the optimization solvers.

Rathore and Sarmah [29] also incorporated GIS with a mixed-integer linear programming (MILP) model to determine potential TSs under different scenarios. The novelty of this study is specified as the consideration of the wastes with different segregation levels. A total of 6 assumptions are made to cope with the substantial study area (30.42 km2 and 55 wards). The economic impact of having multiple TSs was investigated in the case study.

Kůdela et al. [30] proposed a method that addresses the problem as a multi-objective two-stage mixed-integer stochastic programming problem to determine the number, the location, and the capacity of the TSs for the entire Czech Republic. This multi-objective optimization model was successfully applied to investigate the trade-off between economic and environmental objectives. However, no land suitability analysis has been performed for the proposed TS locations.

Mohsenizadeh et al. [31] constructed a bi-objective facility location-allocation problem that aims to minimize the costs and emissions due to transport operations. This paper's novelty is that it has given equal importance to the environmental cost of the MSW collection and transport system as the economical one. The constructed MILP models were applied to locate candidate TSs in Ankara, Turkey. The MILP models in this study are solved using ILOG CPLEX Optimization Studio Software by International Business Machines Corporation (IBM).

Various studies have also adopted route optimization through mathematical modeling for other purposes such as emission reduction [32, 33], optimal routing [34], and waste bin reallocation [35]. Son and Louati [36] proposed a vehicle routing model with multiple nodes and inhomogeneous vehicles for MSW collection optimization. Hannan et al. [37] constructed a capacitated vehicle routing problem (VRP) model incorporating a particle swarm optimization algorithm to solve the routing optimization problem.

Some recent studies performed GIS-based land suitability analysis to identify suitable sites for TSs, but no further analyses have been made to determine the optimum number and locations of TSs. These studies provide a methodology for systematically ranking land in the study areas for potential TS sites. Ağaçsapan and Çabuk [38] performed a GIS-based land suitability analysis to determine technically suitable sites for TSs in Eskişehir, Turkey.

Chapter 3

Materials and Methods

3.1 Introduction

In this chapter of the thesis, the whereabouts of the study area and the reasons why it is deemed appropriate for the analysis are discussed first. Features such as its geographical location, population, and waste production per capita statistics are given.

Following the study area, the methodology is explained. The developed method consists of four sequential steps;

1- Data acquisition from the district and metropolitan municipalities, state agencies, and ministries, and followed by integrating the various types of data to create a consistent and accurate geodatabase
2- Land suitability analysis where a sequence of analyses was performed to determine the potential TS locations
3- Scenario analysis was implemented. VRP models were constructed and solved so as to calculate optimum routes and collection times for various combinations of TSs and collection vehicle capacities.
4- Economic assessment was performed to question whether introducing a TS is a viable improvement and if so, to determine the most feasible TS location.

The flowchart of the methodology is presented in Figure 3.1.

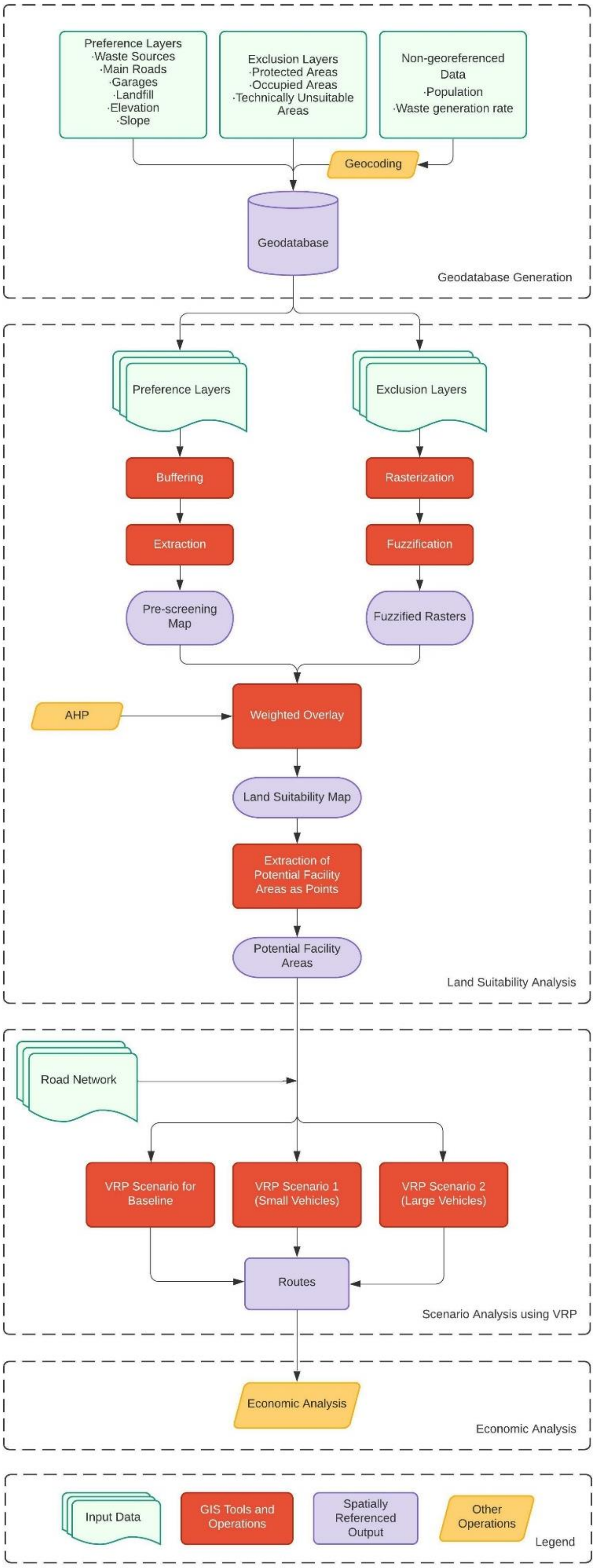

Figure 3.1: Flowchart of the methodology

3.2 Study Area

The study area encompasses three district municipalities located in the southeast of İzmir/Turkey with an area of 1,782 km^2. İzmir is located west of Turkey on the Aegean Coast. It is the third most populous city in Turkey, with a population of 4,367,251 by 2019 [39]. The city's daily waste generation rate was estimated to be 1.36 kg per capita in 2018 [40]. The location of the study area is presented in Figure 3.2.

According to the İzmir Metropolitan Municipality Solid Waste Management Master Plan, solid waste is planned to be managed by dividing the city into zones in the upcoming years. One of these zones, titled Ödemiş Zone in this study, is selected as the study area and includes Ödemiş, Kiraz, and Beydağ Districts. The total population of Ödemiş Zone was 188,491 in 2017 [41]. The population survey indicates that 70% of the population lives in Ödemiş, 23% in Kiraz, and 7% in Beydağ. There are a total of 180 neighborhoods in the Ödemiş Zone [42]. The data used to determine the total waste amount are given in Table 3.1.

Table 3.1: Population, estimated waste generation, and number of neighborhoods per district in the study area

District	Population	Estimated waste generation (kg/day)	Number of neighborhoods
Ödemiş	132,241	179,848	99
Kiraz	43,859	59,648	56
Beydağ	12,391	16,852	25

An unregulated waste disposal site in Kiraz has been receiving wastes from Kiraz, Ödemiş, and Beydağ districts for years. According to the master plan, this unregulated landfill will be shut down, and a new sanitary landfill will be built in Ödemiş to serve all three district municipalities in the Ödemiş Zone [43]. The new plan is expected to end the long-run disputes between the İzmir Metropolitan Municipality and residents in Kiraz and provide environmentally sustainable solid waste management in the study area.

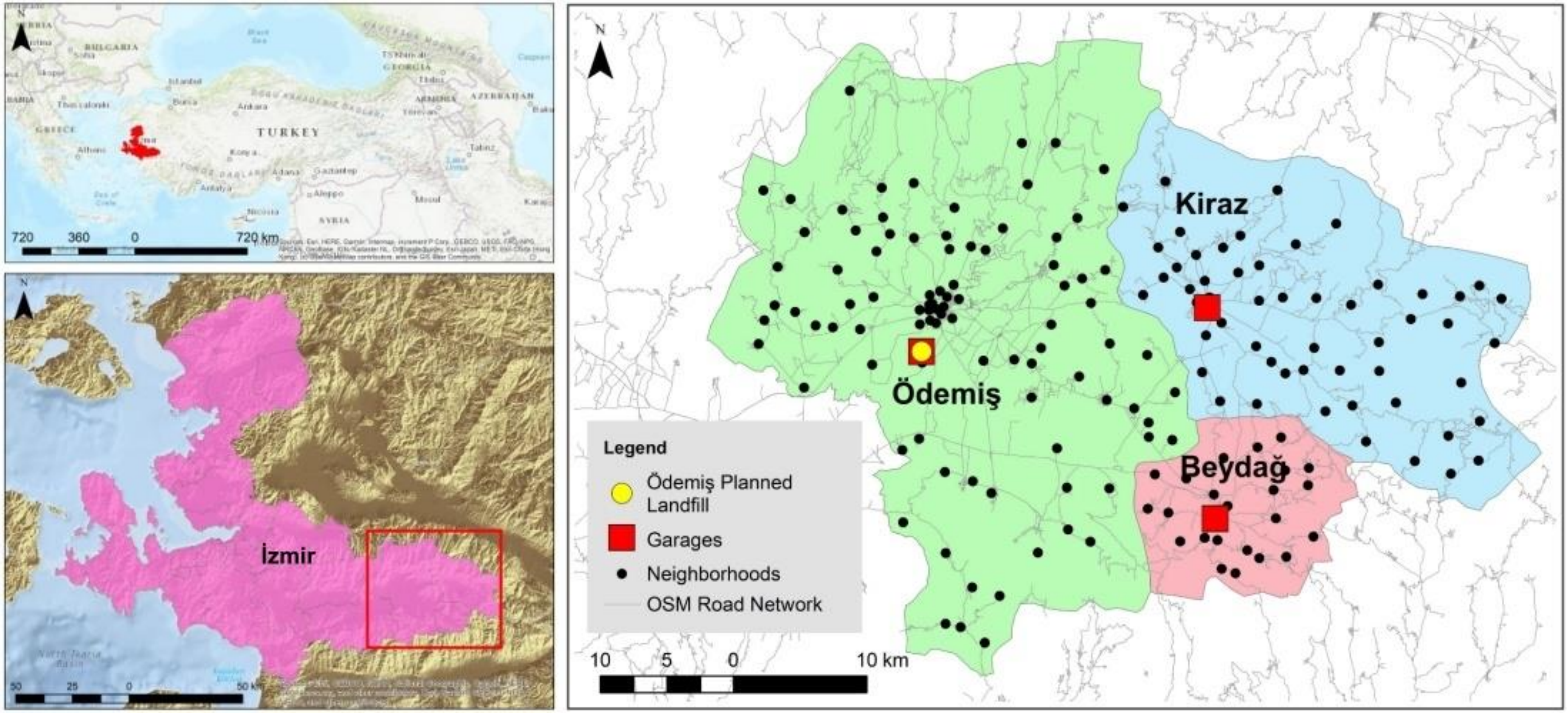

Figure 3.2: Map of the study area

3.3 Analyses

3.3.1 Geodatabase Generation

The development of an appropriate geodatabase was achieved by generating, collecting, and integrating various geospatial and statistical data in a GIS environment. To achieve this task ArcGIS Software version 10.7 is used.

ArcGIS Software nearly has everything to view, edit, and analyze GIS data. Its interface is user-friendly; it allows the user to benefit from its various tools, and even create a new toolbox if necessary. It also includes many visualization tools for mapping and workflows. Primarily ArcGIS's Spatial Analyst and Network Analyst extensions were used in this study for analysis and computations.

The essential georeferenced data in the created geodatabase includes various points such as; neighborhood centers as the waste generation points, garage points for the MSW collection vehicles' start points, and the point data of the planned landfill facility. These data were obtained from the İzmir Metropolitan Municipality Waste Management Department. The official land-use dataset mainly for exclusion and preference analyses was obtained from the Ministry of Environment and Urbanization. The land-use dataset contains 58 land-use categories (see “Exclusion” in [44, 45]). 30m resolution Shuttle Radar Topography Mission digital elevation models were used to produce elevation and slope maps of the study area [46] A thorough road network based on OpenStreetMap data is generated for the study area by the authors [47]. Statistical data, i.e. population and waste generation rate in İzmir per day, are obtained from the Turkish Statistical Institute [39-42].

All of the vectorial spatial data were transformed into the World Geodetic System 1984 Universal Traverse Mercator (WGS 1984 UTM) Zone 35 projected coordinate system to preserve the integrity of the raster analyses.

3.3.2 Land Suitability Analysis

The methodology implemented in land suitability analysis was adopted from [44].

Before any attempt for determination of the potential areas for a TS, a pre-screening analysis was performed. Following this step, a preference analysis was conducted on the remaining areas.

3.3.2.1 Pre-screening Analysis

There are certain restrictions to follow in order to prevent inappropriate siting of TSs and to increase the facility’s effectiveness while relieving their adverse effects on society and the environment. Hence, a prescreening analysis was carried out to satisfy these regulations and technical requirements.

The land-use data were used as the primary identifier of whether a site is suitable or not. Occupied sites, i.e. residential areas, lakes and rivers, military zones, archaeological or cultural heritage sites, protected zones, and agricultural lands were directly eliminated from the study area.

Grasslands and meadows were selected as suitable lands in addition to solid waste, wastewater, and hazardous waste treatment and storage plants, since public infrastructures are allowed to be built in these areas. Obligatory buffer distances were implemented on such areas prior to exclusion. 250 m and 200 m buffer distances were applied to residential sites and rivers, respectively [44].

Transmission lines and railways were also eliminated in addition to the road network, with buffers of 100, 30, and 30 m, respectively [44, 49, 50].

Furthermore, to be closer to city centers and avoid an increase in exhaust emissions, areas that are loftier than 500m and has a higher slope than 15% were excluded from the remaining sites [44, 50]. The remaining areas were cleaned from slivers and small land portions.

3.3.2.2 Preference Analysis

In preference analysis, the primary objective is to create a form of a scale for classifying the remaining areas from most suitable to least suitable. To achieve this, the essential factors of preference should be determined.

A lot of factors are found to be significant in selecting the most suitable area; either being technical, environmental, legal, political, or even psychological [3]. In this study, however, the number of factors considered for analysis is limited, to make the case study inclusive and free of biased or irregular angles. Also taking every factor into account is nearly impossible with the available data.

Determination of the preference factors was conducted by considering the aforementioned matters, the available data, structure of the problem, and previous studies [3, 24, 38].

Proximity to waste sources was ranked as the most significant factor since the main objective is collecting MSW most economically, or simply, shorter distances and shorter periods are preferred. The next most significant factor is being close to the main roads and being readily accessible.

Distances between waste generation points and garages or landfills will not be driven as extensively, thus their proximity to a TS is said to have relatively lower significance than the previously explained factors. The land area to build a facility is also significant since a greater area indicates a higher expansion potential.

Elevation and slope are decided to be two of the significant factors but selected as the least significant ones among all factors. In a previous study [51], it is reported that road grade does have substantial effects on the fuel economy of heavy-duty vehicles, therefore, building a facility on areas with steep slopes and high elevation is not desired.

Analytic Hierarchy Process analysis is employed to assess the relative significance of the factors on the problem.

AHP analysis developed by Saaty [20-22, 52] is a robust multi-criteria decision-making technique that simplifies the problem into a set of pairwise comparisons. AHP delivers a rational framework for a demanded decision by quantifying its criteria and relating those to the objective at hand. In this analysis, factors are compared to each other in pairs, by attaining numbers that define the relative significance by its magnitude, and they're all assigned to a calculated significance weight at the end. The factors and their calculated AHP weights are given in Table 3.2.

After determining the AHP weights, spatial membership degree maps for each preference factor are produced using the ArcGIS' linear fuzzy membership function of the Spatial Analyst Toolbox. This function reclassifies the input data to a scale of 0 to 1 based on the possibility of being a member of a user-specified set. Value 0 is assigned to the non-member areas (definitely unsuitable) and value 1 is assigned to those that are definitely a member (definitely suitable) of the set. Possibilities between 0 and 1 are assigned linearly depending on the specified parameters [53].

There are various fuzzy membership functions in the mentioned toolbox. Since in this case, the majority of the factors are based on one parameter only (distance, values of slope, and elevation), the relationship is best captured with the linear function.

The fuzzy linear membership function applies a linear function between the user-specified minimum and maximum values. Anything below the minimum will be assigned a 0 and anything above the maximum a 1.

Maximum and minimum parameters were defined as minimum distances and maximum distances for proximity to waste sources and proximity to garages, respectively. On the contrary, maximum and minimum parameters for proximity to landfills were defined as maximum distances and minimum distances, respectively, because it is not optimal for a TS to be in close range of a landfill. This implies being close to waste sources and garages will result in high spatial membership degrees while being close to the landfill will yield low spatial membership degrees.

Flat areas (Values of 1), and areas that have grades lower than 15% are considered suitable to place a TS while areas with grades 15% and higher are unsuitable (Values of 0) [50].

The minimum parameter for elevation was set as 500 m considering the elevations of three district centers, while the maximum parameter was set as the minimum elevation value of the entire study area.

The minimum and maximum values for the land area are determined by investigating the currently existing 15 TSs in the city. The maximum and minimum parameters for each factor are provided in Table 3.2.

Table 3.2: Preference factors, analytic hierarchy process (AHP) weights and maximum and minimum parameters for linear fuzzy membership functions

Factors	AHP weights	Maximum	Minimum
Proximity to waste sources	0.2570	Min. distance	Max. distance
Proximity to main roads	0.2570	10 m	1 km
Proximity to garages	0.1953	Min. distance	Max. distance
Proximity to landfill	0.1199	Max. distance	Min. distance
Land area	0.0689	10 ha	2 ha
Slope	0.0629	0%	15%
Elevation	0.0390	71 m	500 m

The AHP weights and created fuzzy membership maps are combined by weighted overlay analysis and normalized to create an ultimate suitability index (SI) map with maximum suitability of 1 and a minimum of 0. Calculation of the SI was adopted from [44]. The SI equation is as follows:

$$SI = \sum_{i=1}^{n} w_i \times \mu_i \tag{3.1}$$

where n is the number of factors, w_i and μ_i is the AHP weight and fuzzy membership degree of the i^{th} preference factor, respectively.

Areas with an SI of 0.79 and higher were selected as potential areas while the rest were eliminated [44, 45]. The remaining areas were transformed into point vector data to be used as potential TS sites in the following routing analyses.

Potential sites were further narrowed down by selecting only the point with the highest SI if more than one point was located within a distance of 2 km.

3.3.3 Scenario Analysis Using VRP Algorithm

A scenario analysis using the Network Analysis Toolbox's VRP is conducted to compare the performance of different TS locations. Furthermore, since the majority of the study area seems to be more rural rather than urban, the performances of two different collection vehicle capacities are investigated.

VRP is one of the well-known combinatorial optimization problems. VRP is a superset of the traveling salesman problem (TSP) [10-12]. In a TSP there is one traveler that travels each city and returns to the origin city by using the shortest possible route; whereas in a VRP there is a fleet of vehicles with real-world constraints such as vehicle capacities, and delivery time windows and the objective function is to determine optimal routes while ensuring the minimum overall cost. Consequently, the VRP algorithm is selected as the best candidate to exhibit the problem at hand.

Esri's VRP solution begins with the generation of an origin-destination matrix of shortest-path costs between all orders and depot locations on the network. It later constructs a temporary solution by assigning each order to the most appropriate route individually. The temporary solution is then adjusted by resequencing and replacing the orders on each route [16-19].

The VRP models were constructed and solved for each scenario by reducing route number one by one until the minimum number of routes to collect the entire waste in the system was found. The number of routes, TS visits, total times, travel times, TS service areas, and amount of waste off-loaded at TSs were the outcomes of each VRP model. The waste collection, transfer, and transport system for each scenario is depicted in Figure 3.3.

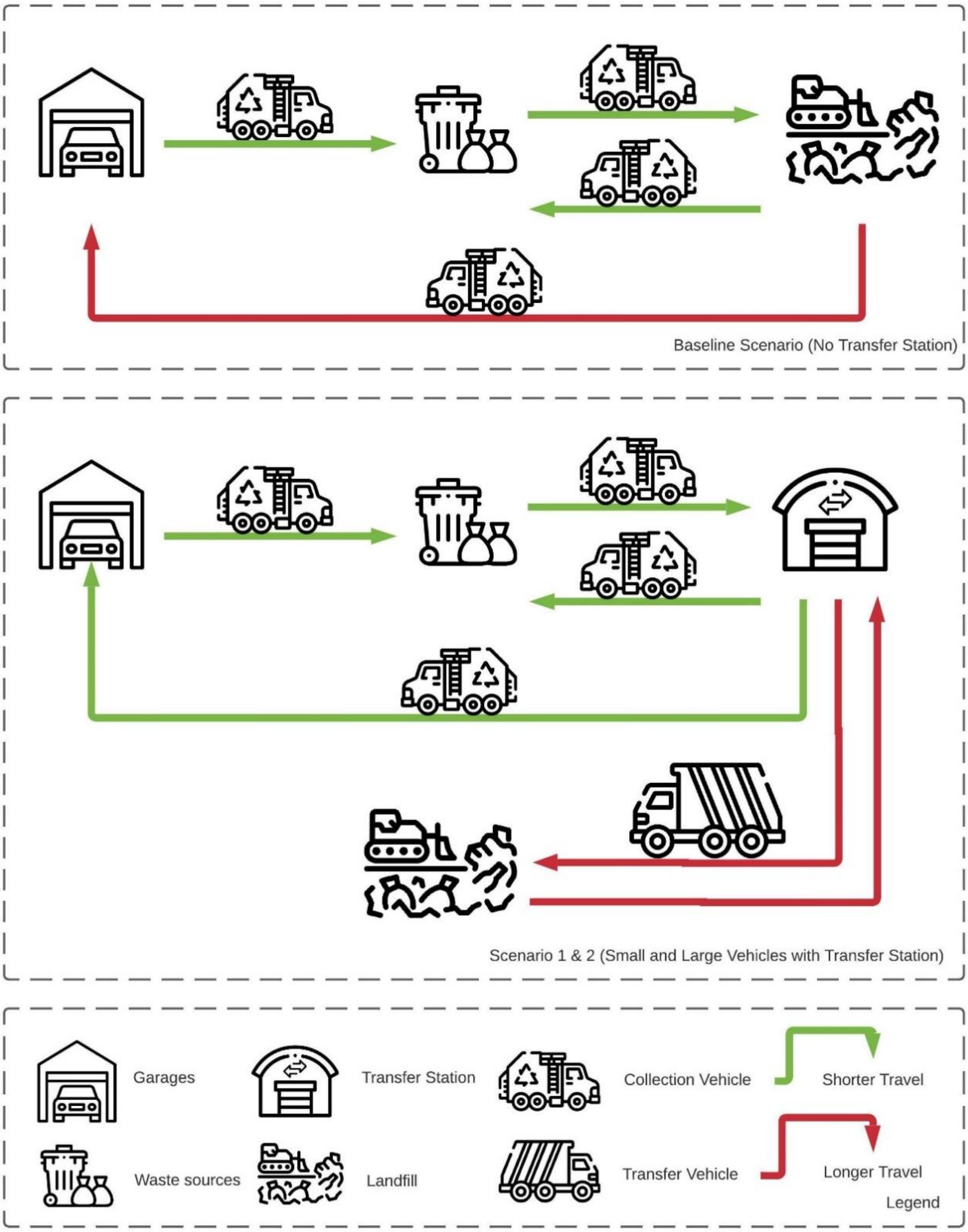

Figure 3.3: Waste collection and transport in baseline scenario (no transfer station), and scenarios 1 and 2 (with transfer station)

3.3.3.1 VRP Model Setup

The VRP model construction begins with defining orders, routes, depots, route zones, and route renewal points. Then, the road network is selected with desired restrictions, and analysis settings are assigned. VRP solver is set to minimize the total time in this study.

Center points of neighborhoods were assumed to be the location of waste sources (therefore the orders for the analysis) since trash bins are not allocated to specific waste generators; they serve all nearby residential and commercial units, and currently, there isn't any data that shows every bin location in the district or city. Due to this lack of information, neighborhood centers are accepted as the order locations.

The number of bins required for the daily collection of each neighborhood is calculated by multiplying the neighborhood population and waste generation rate, then dividing by the bin capacity (770 L, 340 kg). According to the examinations of the currently available bins in İzmir, the selected bin capacity is the most widely used.

The numbers of bins were calculated as 532, 176, and 50 respectively for Ödemiş, Kiraz, and Beydağ.

Since a statistical approach is adopted due to the lack of precise data, the amount of waste in bins is assumed to be equally distributed for each neighborhood.

To compensate for the approximation errors, even though the bins are assumed to be in the same location, the time for emptying a bin and traveling from one to another was taken as 5 minutes [30]. Also during the analysis, it is ensured that each bin is collected by one vehicle only and not divided for insufficient capacity reasons.

Depots are all locations where the routes start, end, or are renewed. The landfill, vehicle garages in each district (three in total), and potential TS sites are defined as depots in the model.

Route renewals represent the intermediate depots/locations where collection vehicles can unload their waste. Any number of route renewal depots can be defined for a route. For instance, the landfill and a TS can both be route renewal depots.

The amount of time spent at a depot is specified as start and end depot service times for each route. The start and end depot service times are set as 30 minutes for each, while renewal depot service time is set as 20 minutes [30].

Routes represent the overall movement (from orders to depots) of a collection vehicle in a specified time window (in an 8-hour shift since the daily collection performance is investigated).

The routes are limited to their respective districts due to the given hard zones. In other words, a route belonging to Ödemiş district could not pick up an order located in Beydağ.

Since the operation of TSs and transport of solid waste from TS to the landfill is conducted by the Metropolitan Municipality; collection vehicle properties, such as capacity, model, and the number of workers, were obtained from the district municipalities, while transport vehicle properties were obtained from the İzmir Metropolitan Municipality Department of Solid Waste Management.

Loading capacity of 5,000 kg and 11,000 kg were defined for small and large capacity collection vehicles, respectively, including approximately 20% safety factors. The maximum loading capacity of a vehicle must not be exceeded. Transfer vehicles, on the other hand, have a capacity of 27,000 kg.

Wastes were assumed to be collected daily. It was also assumed that there are three shifts per day, that take up 8 hours each [30]. Every three routes in a district correspond to one vehicle since there are three shifts per day. For instance, if there are 13 routes in a district, that district needs at least five vehicles that end up with 2 vacant shifts.

Collection vehicle capacities and TSs were set specifically for each combination of TS and collection vehicle capacity in each scenario. The rest of the settings were not variable between scenarios.

3.3.3.2 Baseline Scenario (BS)

The existing waste management system with the addition of the planned landfill in Ödemiş, and the subtraction of the TS in Kiraz, is modeled as the baseline scenario

(BS). There is no TS in this model; the collection vehicles are the ones that transport the waste to the landfill.

Collection vehicles (of either capacity) start their routes from the corresponding district garages, collect waste from neighborhoods by traveling, unload the collection at the Ödemiş Landfill, and return to their garages at the end of their shifts.

Two VRP models for this scenario were solved: one for small (5,000 kg) and one for large (11,000 kg) capacity collection vehicles.

3.3.3.3 Scenario 1 & 2

Considering land suitability analysis yields a handful of potential sites to place a TS, another prescreening is performed by constructing and solving VRP models for all potential TS sites. In this case, however, each potential TS is introduced as a route renewal point. The potential TS is then considered to have the ultimate suitability if at least two routes visit the location. The performance of these individual TS sites was also simulated by analyzing the individual VRP models.

Collection with small (5,000 kg) and large (11,000 kg) vehicles were analyzed in scenario 1 and scenario 2, respectively.

Same with the BS, collection vehicles start their routes from the corresponding district garages, collect waste from neighborhoods by traveling, unload the collection at the Ödemiş Landfill or the potential TS site, and return to their garages at the end of their shifts.

Seven VRP models for each scenario were examined; one for each one of the selected TS sites. Transport of waste from the potential TS site to the landfill was not included in the VRP model but was calculated separately by external analyses.

3.3.4 Economic Analysis

Economic analyses are conducted to make a conclusion based on the monetary performances of each scenario. These analyses include fuel consumption, labor, TS capital, and O&M costs. The total amount of waste dropped by the TS, number of total routes, and travel times are used to estimate the total cost of the system. Equation (3.2), given by the Ministry of Environment and Urbanization is used to calculate the fuel consumption [56];

$$Fuel\ Consumption = ((0.0853 + 0.0171) \times HP) \tag{3.2}$$

where the fuel consumption is in kg h^{-1}, 0.0853 is the fuel consumption coefficient in kg HP^{-1}, 0.0171 is the diesel equivalent of engine oil in kg HP^{-1}, and HP is the vehicle horsepower. The fuel (diesel) price of 83 Cents kg^{-1} is used to calculate fuel costs [56].

The vehicle capacities, HP, vehicle costs, and calculated unit fuel costs of collection and transport vehicles are presented in Table 3.3.

Table 3.3: The capacities, horsepower (HP), vehicle costs and calculated unit fuel costs of collection and transport vehicles

Vehicle type	Capacity (kg)	Horsepower (HP)	Price (US$)	Fuel cost (US$/h)
Small collection vehicle	5,000	206	46,323	17.47
Large collection vehicle	11,000	316	84,886	26.82
Transport Vehicle	27,000	415	136,774	35.21

The vehicle cost includes amortization, repair, and maintenance, spare parts, capital interest and insurance, and transport and assembling. Equations (3.3-3.8), given by the Ministry of Environment and Urbanization is used to calculate the vehicle cost per year (US$ y^{-1}) [56]:

$$\begin{aligned} Vehicle\ Cost = {} & Amortization + Spare\ Parts \\ & + Repair\ and\ Maintenance \\ & + Capital\ Interest\ and\ Insurance \\ & + Transportation\ and\ Assembling \end{aligned} \tag{3.3}$$

$$Amortization = \frac{A}{N} \tag{3.4}$$

$$Spare\ Parts = 0.53 \times \frac{A}{N} \tag{3.5}$$

$$Repair\ and\ Maintenance = 0.13 \times \frac{A}{N} \tag{3.6}$$

$$Capital\ Interest\ and\ Insurance = 0.08 \times (N+1) \times \frac{A}{2 \times N} \tag{3.7}$$

$$Transportation\ and\ Assembling = 0.02 \times \frac{A}{N} \tag{3.8}$$

where A is the price of the vehicle (US$), N is the amortization duration in terms of years. Amortization duration of 6 years is common in public procurements for solid waste collection service [57].

The labor cost is calculated based on 2020 values given by the Public Procurement Institution [58]. The labor cost is taken as 1013 US$ per month for a driver and 856 US$ per month for a worker. Typically, one driver is in command in each collection and transport vehicle; but collection vehicles require additional two workers per vehicle to haul the bins.

Capital and O&M costs of Selçuk Transfer Station in İzmir are used as a reference in TS cost calculation [59] (registration number: 2017/159516). The capital cost of 604,412 US$ includes the construction of a TS with an area of 5,900 m^2. The O&M cost of a TS, including the labor cost, was taken as 49,553 US$ per year. The Annuitization coefficient (α) is calculated assuming a 20-year lifetime (T) and 10% interest rate (i) for estimating the annual cost of a TS [45, 60]. The total annual cost of a TS was calculated using the equations below:

$$Annual\ TS\ Cost = Capital\ Cost\ \times \alpha + O\&M\ Cost \tag{3.9}$$

$$\alpha = \frac{i(1+i)^T}{((1+i)^T - 1)} \tag{3.10}$$

The monetary values are indicated in US$. The US dollar to Turkish lira exchange rate was used as 6.8. A complete list of variables used in the economic analysis is presented in Table 3.4.

Table 3.4: Notations, names, values and references of variables used in the economic analysis

Notation	Variable Name	Value	Reference
	FC is the fuel consumption in liters per hour	Equation 3.2	[56]
	Horsepower for small collection vehicle (Model: MLC 100 E 19-Euro 6_C)	206	[61]
HP	Horsepower for large collection vehicle (Model: 2020 AROCS 2032 K 4x2)	316	[62]
	Horsepower for transport vehicle (Model: 2020 AROCS 3342 K 6x4)	415	[62]
	Fuel price in cents per kilogram	83	[56]
	Price of small collection vehicle in US$ (single payment)	46,323.00	[61]
A	Price of large collection vehicle in US$ (single payment)	84,886.00	[62]
	Price of transport vehicle in US$ (single payment)	136,774.00	[62]
N	Amortization duration in years	6	[57]
	Driver cost in US$ per month	1,013.00	[58]
	Worker cost in US$ per month	856.00	[58]
	Transfer station capital cost in US$ (single payment)	604,412.00	[59]
	Transfer station operation and maintenance cost in US$ per month	49,553.00	[59]
α	Annuization coefficient	Equation 3.10	[45,60]
i	Interest rate in percents	10	[45,60]
T	Lifetime in years	20	[45,60]

Chapter 4

Results and Discussion

4.1 Land Suitability and Potential TS Sites

The ultimate land suitability map after pre-screening and preference analyses is shown in Figure 4.1. Blank areas on the map represent excluded areas: while suitable areas are shown with a color gradient based on their SI values.

The pre-screening analysis yielded only 2.7% of the total study area as suitable. Most suitable areas were found to be located between three district centers and close to major roads, as their significance weights are greater (Table 3.2).

Since the landfill is planned near Ödemiş district center, the areas near Ödemiş district center were received a relatively low SI or excluded. The northern parts of the study area also resulted in low SI values or were excluded, as they have high elevations and lower amounts of generated waste due to low population.

Land suitability analysis resulted in 26 potential TS sites that acquired an SI value equal to or greater than 0.79 (purple dots in Figure 4.1).

One potential TS site received three visits (TS-06), and six potential TS sites received two visits from the routes after the preliminary VRP screening. The remaining potential TS sites were received only one visit or never visited by any of the routes. The aforementioned seven potential TS sites that received two or more visits were examined in the scenario analysis (red dots in Figure 4.1). Potential and selected TS sites are illustrated in Figure 4.1.

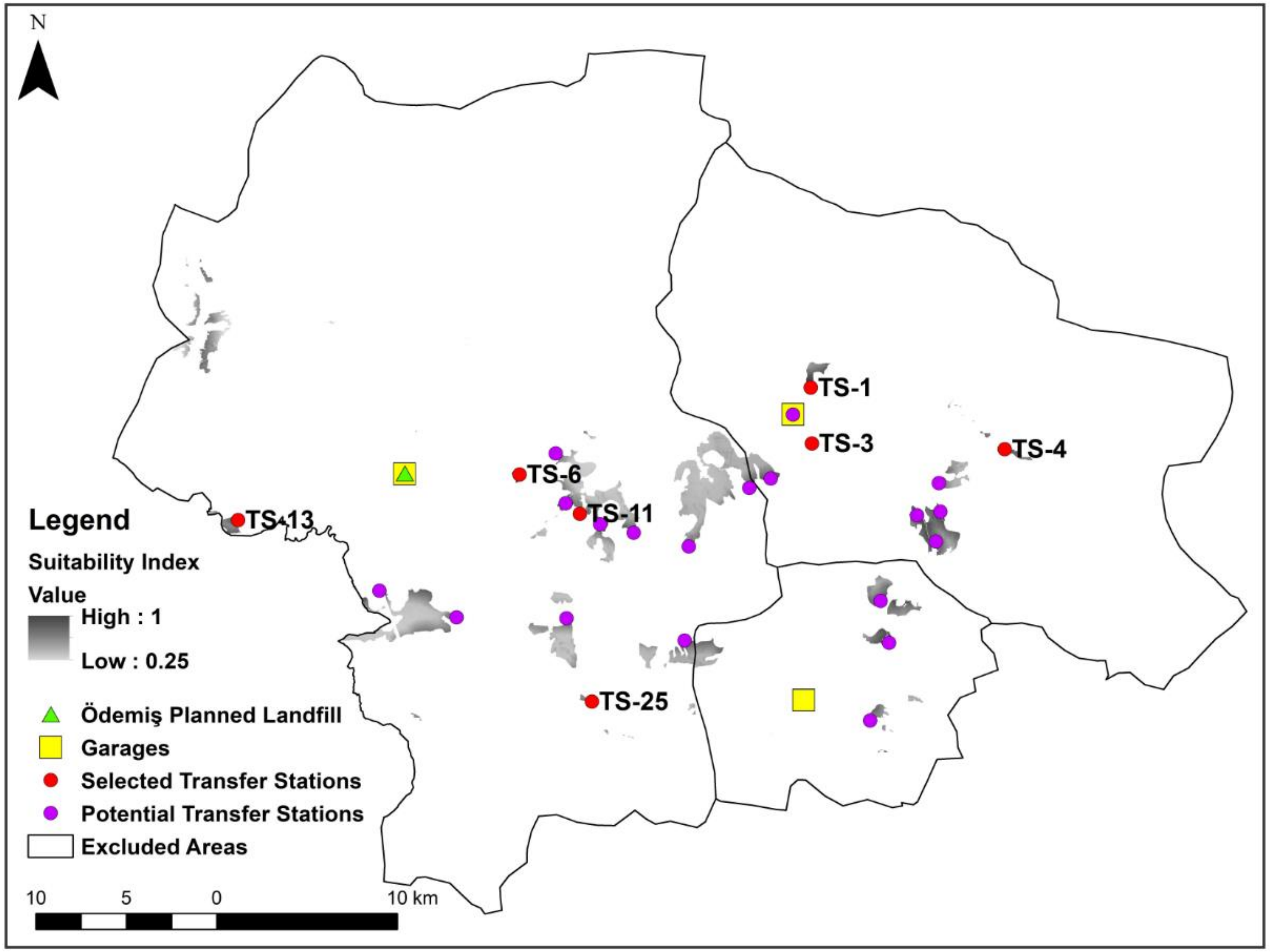

Figure 4.1: Land suitability map with potential and selected transfer station sites

4.2 Scenario Analysis and VRP Results

The BS represents the no TS scenario or the current system with small (5,000 kg) and large (11,000 kg) collection vehicles. Since there isn't any TS in this scenario the collection vehicles are the ones that transfer the collected waste to the landfill.

In this scenario, the number of routes, each corresponding to an 8-hour shift, decreased from 23 to 19 when the vehicle capacity increased from 5,000 kg to 11,000 kg; this yields approximately 2000 minutes (25%) decrease in total travel time and one vehicle reduction in the collection vehicle fleet. Although the vehicle capacity was doubled, the number of vehicles did not considerably reduce because of the small collection vehicle fleet (eight collection vehicles) and district level collection (hard zones).

A comparison of the VRP model results for each scenario is presented in Table 4.1.

Scenarios 1 and 2 represent the TS addition scenarios with small and large collection vehicles, respectively.

In scenario 1, TS addition decreased the total travel times and the number of routes in general. The maximum reductions in total travel time and routes were achieved for TS-03 and TS-04. Distance to the landfill and amount of waste unloaded is also reasonable for TS-03 and TS-04. Therefore, TS-03 and TS-04 were selected as the best options in scenario 1. The number of collection vehicles did not decrease in scenario 1, on the contrary, an additional transport vehicle was added to the system.

Similar trends to scenario 1 were also observed in scenario 2. However, the reduction in total travel time was not significant compared to the BS with a large collection vehicle. TS-01 was selected as the best option in scenario 2 considering the total travel time, the number of routes, distance to the landfill, and amount of waste unloaded.

Optimum routes for the BS – small collection vehicle and scenario 1 – are shown in Figure 4.2, while for the BS – large collection vehicle and scenario 2 – are shown in Figure 4.3.

Waste densities are represented by gradual red dots and each route was drawn with a different color. The routes are shown with straight lines in order to prevent the overlapping of the routes that use the same road and to show the visited neighborhoods more clearly.

TS-04 and the landfill received respectively 18 and 44 visits (including four visits by transport vehicles) per day in scenario 1, while the landfill received 57 visits in the BS with small collection vehicles.

On the other hand, TS-01 and the landfill received 9 and 24 visits (including three visits by transport vehicles) per day in scenario 2, respectively, while the landfill received 29 total visits in the BS with large collection vehicles. Increasing the collection vehicle capacity decreased the number of trips to the TS and the landfill.

Table 4.1: Comparison of vehicle routing problem model results for baseline scenario (BS), scenario 1 (S1) and 2 (S2)

Scenario	TS ID	Number of Routes	Number of Vehicles				Total Travel Time (minutes)	Time from TS to landfill (minutes)	Waste unloaded at TS (kg d^{-1})
			Ödemiş	Kiraz	Beydağ	Transport			
BS-small	-	23	5	2	1	-	8720	-	-
S1	06	22	5	3	1	2	8255	13	118,558
S1	11	21	5	2	1	2	8064	16	108,965
S1	04	21	5	2	1	1	8012	48	69,261
S1	01	21	5	2	1	2	8096	40	82,728
S1	03	21	5	2	1	1	7925	40	77,446
S1	25	23	5	3	1	2	8409	28	81,742
S1	13	23	5	3	1	1	8611	21	9,986
BS-large	-	19	4	2	1	-	6767	-	-
S2	06	18	4	2	1	2	6671	13	119,644
S2	11	18	4	2	1	2	6628	16	130,189
S2	04	17	4	2	1	1	6601	48	74,250
S2	01	17	4	2	1	1	6588	40	74,250
S2	03	18	4	2	1	1	6599	40	74,250
S2	25	18	4	2	1	2	6845	28	84,040
S2	13	19	4	2	1	1	6742	21	10,992

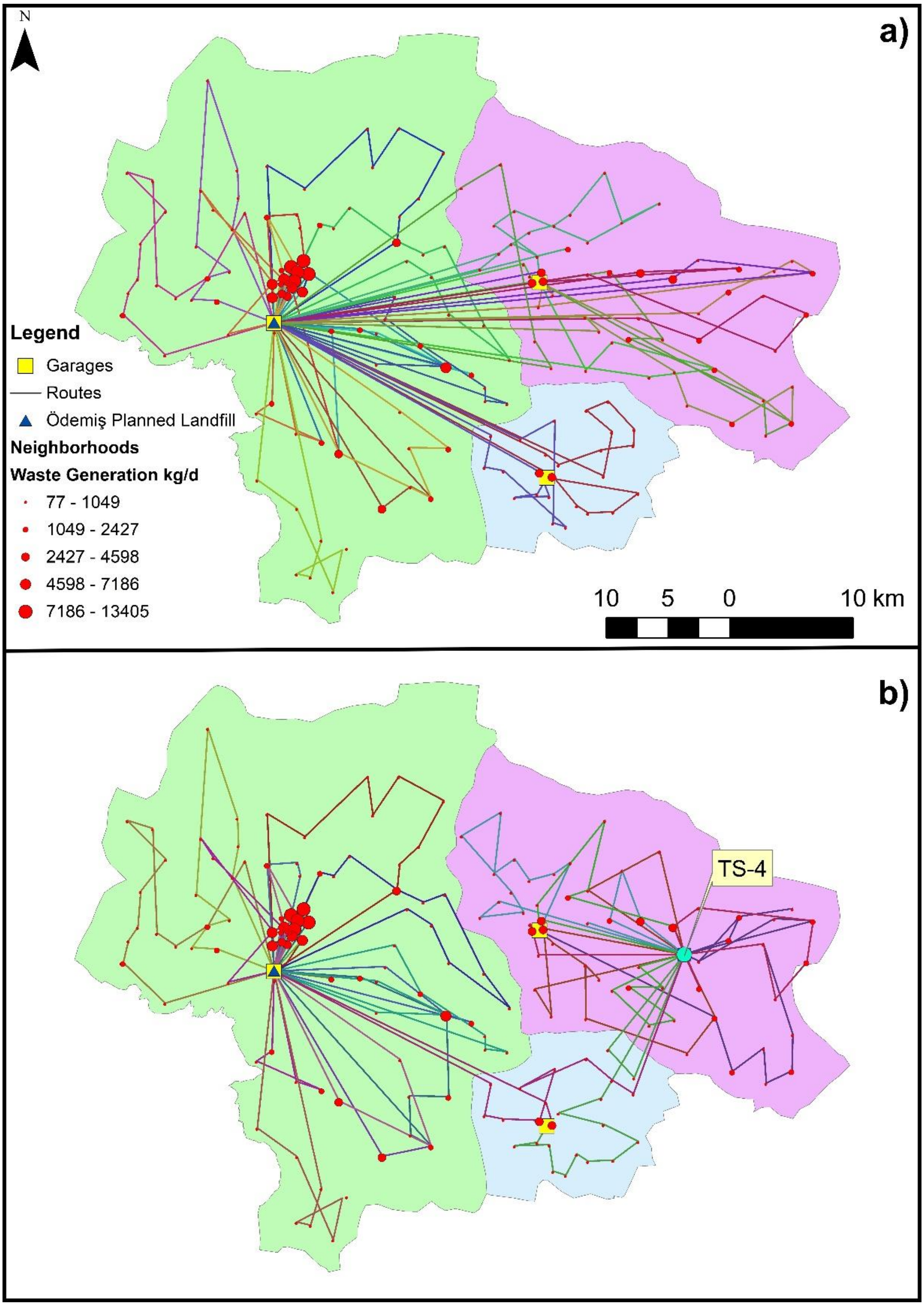

Figure 4.2: Optimum routes for: (a) baseline scenario (BS) – small collection vehicle; and (b) scenario 1 for the TS-4

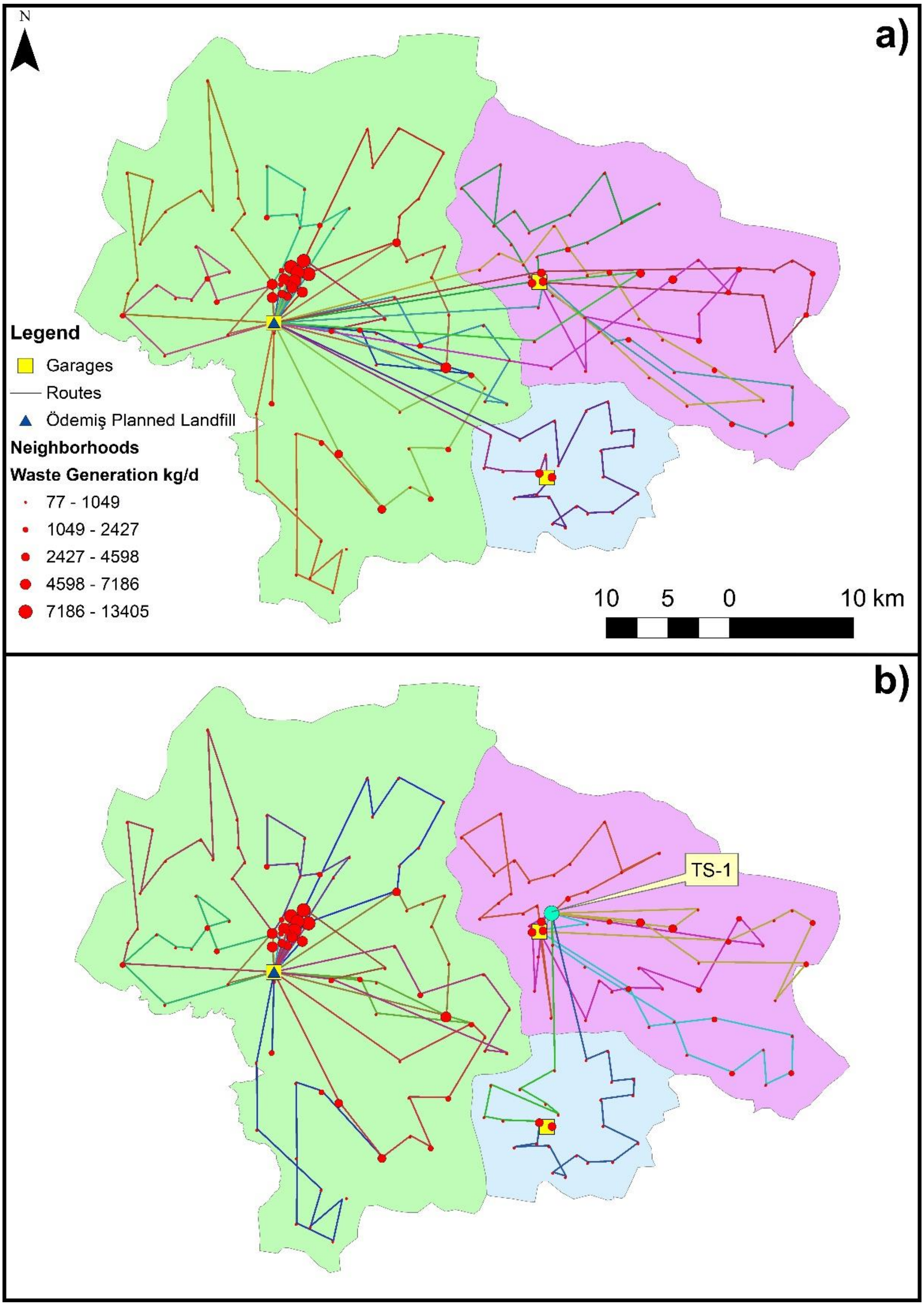

Figure 4.3: Optimum routes for: (a) baseline scenario (BS) – large collection vehicle; and (b) scenario 2 for the TS-1

4.3 Economic Assessment

Economic analysis includes fuel, vehicle, labor costs for all scenarios. In addition to these, scenarios 1 and 2 also incorporate the TS-related fuel, vehicle, capital, and O&M costs. Collection, transfer, and transportation costs for each scenario are presented in Table 4.2.

Although large collection vehicles reduced the collection time by approximately 25%, increasing the collection vehicle capacity raised the fuel costs by 4% for the BS. Because large collection vehicles have greater magnitudes of horsepower that yield more fuel consumption, a TS addition resulted in a reduction in fuel consumption due to the decrease of the traveled distance. This argument is true for all except for scenario 1 with TS-25. This may force decision-makers to decide between cost-induced and fuel-induced air pollution.

Although TS addition reduced the fuel consumption, it brought in additional costs that increased the overall cost. The most economical option with TS, scenario 1 with TS-04, has an overall cost of 1,689,489 US$ per year (18.60 US$ metric tonnes $(Mt)^{-1}$ waste): while the BS (no TS scenario) with small collection vehicles already has a lower overall cost of 1,591,445 US$ per year (17.52 US$ $(Mt)^{-1}$ waste). Even the most attractive scenario with a TS yielded an increase of 6.2% in the overall cost. Therefore, collection of MSW with small vehicles and transporting directly to the landfill without a TS presents the most economical option for the study area under the current conditions.

The TS addition is currently not economically feasible in the study area because of three major reasons;

- First of all, the study area is rural and lowly populated. Waste collection is conducted with a small vehicle collection fleet, i.e. eight in total. Savings in collection time are overcome by the capital and M&O cost of the TS.
- The second reason is the proximity of the landfill to the areas with high waste density. Ödemiş district has more than half of the collection trucks, and trucks haul wastes directly to the landfill. That significantly reduces the benefits of TS addition.

- District level collection (hard zones) is the third reason. A waste collection planning regardless of the district boundaries can make TS addition economically more feasible.

4.4 Sensitivity Analysis

A sensitivity analysis is conducted to analyze the effects of fuel cost, vehicle cost, labor cost, capital and O&M costs, and interest rate on the economic impacts of TS in the solid waste collection, transfer, and transport system. These parameters are selected as the most fitting because they have the highest possibility of changing the solution.

The change in the unit cost of collection, transfer, and transport of solid waste (%) was calculated for changes in parameters between −50% and +50% in steps of 10% for scenario 1 TS-04 and is shown in Figure 4.4.

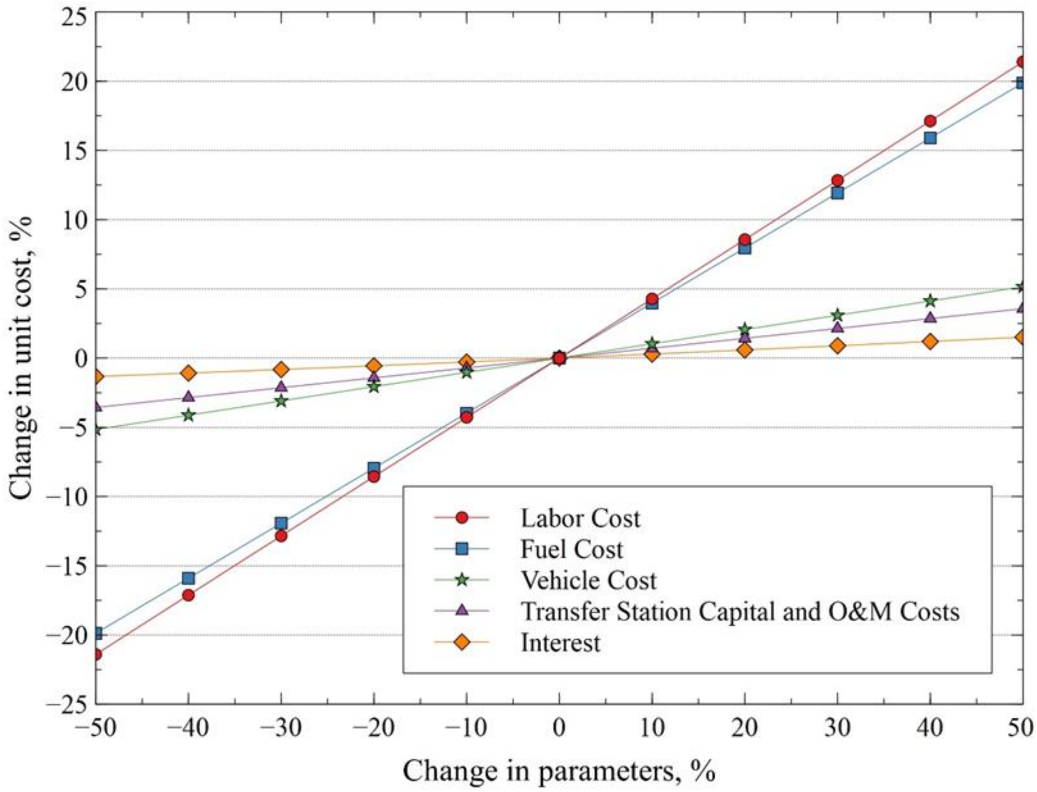

Figure 4.4: Sensitivity analysis results

The results indicate that labor cost (43%) and fuel cost (40%) have the highest impact on the unit cost (scenario 1 TS-04 in Table 4.2). Therefore, the system is more sensitive to changes in labor costs and fuel costs. It is estimated that if an increase of 439% in labor costs or 498% in fuel costs occurs, TS addition will be economical. Vehicle cost, capital and O&M costs, and interest rate each resulted in a change of 5% in maximum. The effects of waste amount on the system were considered neither in the sensitivity analysis nor in the scenario analysis. Because the VRP model is required to be revised accordingly at every change in waste amount, an increase in waste amount simultaneously with an increase in fuel costs and labor costs can also make operating a TS economically feasible in the near future considering the fluctuating economy of Turkey.

Table 4.2: Comparison of collection, and transfer and transport costs for baseline scenario (BS), scenario 1 (S1) and 2 (S2)

Scenario	TS ID	Annual collection costs US$			Annual transportation costs US$			Annual Total (US$)	Change in cost	Change in fuel consumption
		Fuel	Labor	Vehicle	Capital and O&M	Fuel	Vehicle			
BS-small	-	696,232	752,076	143,137	-	-	-	1,591,445	-	-
S1	06	628,046	719,377	143,137	157,007	20,129	93,918	1,761,614	10.7%	-6.9%
S1	11	633,140	686,678	127,233	157,007	24,774	93,918	1,722,750	8.3%	-5.5%
S1	04	627,018	686,678	127,233	157,007	44,593	46,959	1,689,489	6.2%	-3.5%
S1	01	630,369	686,678	127,233	157,007	48,309	93,918	1,743,514	9.6%	-2.5%
S1	03	615,100	719,377	127,233	157,007	37,161	46,959	1,702,837	7.0%	-6.3%
S1	25	668,031	752,076	143,137	157,007	34,684	93,918	1,848,853	16.2%	0.9%
S1	13	687,874	752,076	143,137	132,700	6,193	46,959	1,768,940	11.2%	-0.3%
BS-large	-	833,421	621,280	204,010	-	-	-	1,658,711	-	-
S2	06	806,605	588,581	204,010	157,007	20,129	93,918	1,870,250	12.8%	-0.8%
S2	11	799,516	588,581	204,010	157,007	24,774	93,918	1,867,806	12.6%	-1.1%
S2	04	793,871	555,882	204,010	157,007	44,593	46,959	1,802,322	8.7%	0.6%
S2	01	787,535	555,882	204,010	144,854	36,460	46,959	1,775,700	7.1%	-1.1%
S2	03	786,665	588,581	204,010	157,007	37,161	46,959	1,820,383	9.7%	-1.2%
S2	25	832,603	588,581	204,010	157,007	34,684	93,918	1,910,802	15.2%	4.1%
S2	13	830,431	621,280	204,010	132,700	6,193	46,959	1,841,574	11.0%	0.4%

Chapter 5

Conclusions

This thesis investigates the optimum siting and economic impacts of municipal solid waste transfer stations through a VRP-based scenario analysis in the southeastern part of İzmir, Turkey. Approximately 97% of the study area was excluded in the pre-screening analysis due to technical and legal reasons.

26 potential TS sites were identified at the end of the land suitability analysis. Seven sites out of 26 received two or more visits in the preliminary VRP analysis and were considered as potential transfer station sites in the scenario analysis.

GIS-based VRP models were constructed and solved for seven potential TS sites with small (5,000 kg) and large (11,000 kg) collection vehicles named scenario 1 and scenario 2, respectively. In addition, a 'no TS' case was investigated with small and large collection vehicles in the baseline scenario. In total, 16 VRP models were constructed and solved. The TS addition in the study area reduced the collection time and number of shifts by 9%. It also reduced fuel consumption which may help in a reduction of solid waste collection-induced air pollution. However, the unit cost of waste collection, transfer, and transport increased from 17.52 US$ $(Mt)^{-1}$ waste to 18.60 US$ $(Mt)^{-1}$ waste with TS addition because of the additional costs of TS capital and O&M. Collection with large vehicles decreased the collection time and the number of shifts by 25% and 17%, respectively. However, doubling the collection vehicle capacity did not help decrease the fuel consumption due to the greater horsepower of large vehicles. The sensitivity analysis indicated that the system is more sensitive to changes in labor costs and fuel costs.

In conclusion, TS addition is not economically feasible in the study area because of the small vehicle collection fleet (eight collection vehicles), the proximity of the landfill to regions with high waste density, and district level collection (hard zones). It should be noted that the future projection of waste generation was not considered in the study. An increase in waste generation, labor prices, and fuel prices over the years can make a TS economically feasible in the study area.

This study contributes to the waste management literature through its holistic methodology to determine the optimum siting and economic impacts of transfer stations. Although the investigation of siting and economic feasibility of transfer stations was based on a case study, the methodology developed in this study can guide similar studies in different regions.

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Appendices

Appendix A

Publications from the Thesis

Conference Papers

1. Höke MC, Yalcinkaya S. Modeling the location and performance of municipal solid waste transfer stations via GIS based VRP analysis. In: 1st International Ankara Multidisciplinary Studies Congress; 2020 Aug 11-12; Ankara/Turkey. Farabi Publishin House; 2020. 239-240

Journal Articles

1. Höke MC, Yalcinkaya S. Municipal solid waste transfer station planning through vehicle routing problem-based scenario analysis. Waste Management & Research. 2021 Jan; 39 (1): 185-96.

Republic of Turkey

İzmir Kâtip Çelebi University

Graduate School of Natural and Applied Sciences

A Vehicle Routing Problem Based Scenario Analysis for Optimum Siting of Municipal Solid Waste Transfer Stations

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Master’s Thesis

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2. Höke MC, Yalcinkaya S. Modeling the location and performance of municipal solid waste transfer stations via GIS based VRP analysis. In: 1st International Ankara Multidisciplinary Studies Congress; 2020 Aug 11-12; Ankara/Turkey. Farabi Publishin House; 2020. 239-240