OPTIMISATION OF THE TREATMENT AND DISPOSAL OF SOLID WASTES IN NORTHERN CYPRUS

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Approval of the Chair of the Board of Graduate Programs

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

OPTIMISATION OF THE TREATMENT AND DISPOSAL OF SOLID WASTES IN NORTHERN CYPRUS

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M. Sc., Sustainable Environment and Energy Systems

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Solid waste management has been a key issue of Northern Cyprus for many years as only half of the wastes are properly handled at a sanitary landfill whereas the rest are currently being burned or buried inappropriately at many open dumping areas all over Northern Cyprus which is a serious threat to the public health and the environment. In this study, we propose a mixed integer nonlinear programming model to determine which treatment facilities to build and their sizes, whether the current landfill should be extended or not, and when to extend the current landfill if it is to be extended so that all solid wastes generated in Northern Cyprus are properly handled and the total cost of the proposed system is minimised. Among several treatment facilities, anaerobic digestion, composting, waste-to-energy facilities, landfill, and clean and dirty material recovery facilities are considered in the model besides recycling of solid wastes through source-separation by households. The proposed optimisation model has been applied to the case of Northern Cyprus and solved by an open source optimisation solver. The results revealed that if sufficient landfill capacity is available and a good participation to recycling can be achieved, recovery of recyclable materials, landfilling the remaining wastes and sometimes building a composting facility is the least cost solution of the solid waste management problem. On the other hand, building a waste-to-energy facility becomes inevitable if the landfill capacity is insufficient. However, the total cost of a system with a waste-to-energy facility is very high compared to the case without such a facility.

Keywords: Integrated Solid Waste Management, Treatment Facilities, Recycling, Optimisation, Mathematical Programming

ÖZ

KUZEY KIBRIS'TA KATI ATIKLARIN İŞLENMESİ VE BERTARAF EDİLMESİNİN ENİYİLENMESİ

Barışsever, Coşku

M. Sc., Sürdürülebilir Çevre ve Enerji Sistemleri

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Katı atık yönetimi yıllardır Kuzey Kıbrıs için önemli bir sorun olmuştur. Kuzey Kıbrıs'ta mevcut toplam atığın sadece yarısı düzenli depolama alanında toplanmakta ve geriye kalanlar ise açık alanlarda uygunsuz bir şekilde gömülmekte veya yakılmaktadır. Bu uygulama çevre ve insan sağlığı için önemli bir tehdit oluşturmaktadır. Bu çalışmada, atıkların işlenmesi ve bertaraf edilmesi için hangi tesislerin açılacağına ve büyüklüklerine, mevcut düzenli depolama alanının genişletilip genişletilmeyeceğine ve eğer genişletilecekse ne zaman genişletileceğine karar vermek için bir karışık tam sayılı doğrusal olmayan programlama modeli önerilmektedir. Bu sayede Kuzey Kıbrıs'taki bütün katı atıkların düzenli bir şekilde bertaraf edilmesi ve kurulacak sistemin toplam maliyetinin enküçüklenmesi amaçlanmaktadır. Modelde çeşitli bertaraf tesisleri arasından anaerobik sindirim, kompostlama, çöp depolama alanı, atıktan enerji üretimi, kirli ve temiz malzeme kurtarma tesisleri ve katı atıkların kaynağında ayrıştırılarak geri dönüşümü dikkate alınmıştır. Önerilen optimizasyon modeli Kuzey Kıbrıs'a uygulanmış ve bir açık kaynak en iyileme çözücüsü ile çözülmüştür. Bu çalışmada elde edilen sonuçlar yeterli depolama kapasitesi mevcut ise ve geri dönüşüm için iyi bir katılım elde edilebilirse eğer, geri dönüştürülebilir malzemelerin gerikazanımı, kalan atıkların depolanması ve bazen kompostlama tesisi kurulmasının katı atık yönetimi sorunu için en az maliyetli bir çözüm olduğunu ortaya koydu. Öte yandan, depolama kapasitesi yetersiz ise atıktan enerji üretimi tesisi kurulması kaçınılmaz hale gelir. Ancak, atıktan enerji üretimi tesisi kurulduğu zaman sistemin toplam maliyeti tesisin açılmadığı durumlara göre çok yüksektir.

Anahtar kelimeler: Entegre Katı Atık Yönetimi, Bertaraf Tesisleri, Geri Dönüşüm, Eniyileme, Matematiksel Programlama

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LIST OF ABREVIATIONS AND SYMBOLS

ACRONYMS

AND	Anaerobic Digestion
CB	Cardboard
CM	Composting
CMRF	Clean Material Recovery Facility
CPI	Consumer Price Index
DMRF	Dirty Material Recovery Facility
EPD	Environmental Protection Department
FW	Food Waste
GL	Glass
INC	Incineration
LF	Landfill
LP	Linear Programming
MBT	Mechanical Biological Treatment
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MT	Metal
OTH	Other waste
P	Paper
PL	Plastic
RDF	Refuse Derived Fuel
RPR	Recycling Participation Rate
SWM	Solid Waste Management
TRNC	Turkish Republic of Northern Cyprus
TS	Transfer Station
USAID	U.S. Agency for International Development
WTE	Waste-to-Energy
YAGA	Cyprus Turkish Investment Development Agency
YW	Yard waste
Z	Objective function

INDICES

i	Denotes components of MSW; $i = 1$ for Paper, $i = 2$ for Cardboard, $i = 3$ for Plastic, $i = 4$ for Metal, $i = 5$ for Glass, $i = 6$ for Food Waste, $i = 7$ for Yard Waste, and $i = 8$ for Other Wastes.
j	Denotes the facilities; $j = 1$ for AND, $j = 2$ for CM, $j = 3$ for CMRF, $j = 4$ for DMRF, $j = 5$ for WTE, and $j = 6$ for LF.
t	Denotes the years

PARAMETERS

C_{Lot2}	Capital cost of landfill Lot 2
C_{Lot3}	Capital cost of landfill Lot 3
CPI_t	Consumer price index value for year $t \in \{2002,2003,2006,2014\}$
D	Total amount of MSW in Northern Cyprus
D_R	Discount rate
ε_1	Electrical energy conversion efficiency for the AND facility
ε_5	Electrical energy conversion efficiency for the WTE facility
LCV	Lower calorific value of methane
LHV_i	Lower heating value of waste component *i*
L_j	Lower limit on the size of treatment facility *j*
MP_i	Methane potential of component *i*
M_i	Market price of recyclable component *i*
OTW	The amount of other wastes in Northern Cyprus
P/A	Present value factor to convert annual values into present value
P_i	Percentage of waste component *i* in MSW
Q_{Lot1}	Capacity of landfill Lot 1
Q_{Lot2}	Capacity of landfill Lot 2
Q_{Lot3}	Capacity of landfill Lot 3
rev	Revenue from the sale of 1 kWh of electrical energy generated
RPR_i	Recycling participation rate for component *i*
R'_j	Residual percentage for treatment facility *j* if wastes are coming from DMRF
R_j	Residual percentage for treatment facility *j* if wastes are directly coming from source
r_{ij}	Residual percentage of waste component *i* after processed by treatment facility *j*
T	Length of planning horizon
U_j	Upper limit on the size of treatment facility *j*

VARIABLES

$X_{4,j}$	Amount of waste to be sent from DMRF to treatment facility *j*
$X_{S,j}$	Amount of waste to be sent from source to facility *j*
$X_{j,6}$	Amount of waste to be sent from treatment facility *j* to landfill
Y_j	Binary variable which is equal to 1 if facility *j* is opened, and 0 otherwise.
Z_{2t}	Binary variable which is equal to 1 if landfill Lot 2 is constructed in year *t*, and 0 otherwise.
Z_{3t}	Binary variable which is equal to 1 if landfill Lot 3 is constructed in year *t*, and 0 otherwise.

CHAPTER 1

INTRODUCTION

Solid waste management (SWM) has become a major issue of both developed and developing countries due to the increasing amount of solid waste generated each year (Ghiani et al., 2014). According to the estimations in 2006, the total global amount of municipal solid waste (MSW) generated reached 2.02 billion tonnes with an annual 7% increase as compared to the amount in 2003 (UNEP, 2009). Furthermore, it was estimated in 2006 that MSW generated will globally increase by 37.3 % between 2007 and 2011 which approximately corresponds to 8% increase per year. Therefore, it is essential for countries to organize an effective solid waste management plan in order to cope with the increasing amounts of solid waste generated.

The current economy heavily relies on non-renewable fossil fuels and use of natural resources for economic growth. Effective SWM is essential for a sustainable environment because it not only reduces the negative effects of solid wastes on the environment and human health (International Solid Waste Association, 2013) but also helps preserving the depleting natural resources of world.

Integrated SWM is commonly used for the solution of solid waste problem which is concerned with finding suitable techniques, technologies and management programs for SWM issues (Tchobanoglous et al., 1993). Integrated SWM is essential for health and safety of public. Inappropriate management of solid waste can cause water, soil and atmosphere contamination which in turn can cause serious health issues. For instance, diseases such as cholera are a common problem of contaminated water (Giusti, 2009). When bacteria and viruses of solid waste contaminate water and soil through leachate (i.e., liquid leaking from solid wastes), food chain can be affected as well. In addition, open air dumping of solid wastes causes the release of greenhouse gases to the atmosphere. Furthermore, as the natural resources are limited, there should be a limit on the consumption of the materials or the used materials should be reused and/or recycled.

In the integrated SWM, treatment options that ensure the health and safety of people should be chosen considering the minimisation of the environmental impact and the cost of these options. The SWM hierarchy is used to show the classification of the management options from the least preferred to the most preferred considering economic, environmental, and social benefits (UNEP, 2009). In this hierarchy, waste prevention is in the highest rank which means minimising the amount of waste produced is the most effective way of waste management. In other words, it is better to avoid generating waste than handling it. Waste prevention is followed by reusing the materials, after which comes recycling the materials that have economic value. The subsequent option is waste-to-energy which includes burning waste to generate electricity. This option can be environmentally unsafe. The least preferred option in the hierarchy is landfilling which is disposing waste to identified areas.

The SWM includes collection of solid wastes from the sources that they are generated and transportation of them to treatment facilities (Nganda, 2007). In treatment plants, wastes can be either recycled or converted into electrical energy, fuel or compost. Residues from the treatment plans and unrecoverable waste can be either transferred directly to the landfill from the source or through treatment facilities. An effective management system provides selection of these treatment facilities, taking into account the composition of solid wastes, and the costs of treatment facilities.

1.1 Problem statement

There is a high amount of solid waste produced annually in Northern Cyprus that needs to be managed effectively. In Northern Cyprus, solid wastes are either transferred to Güngör sanitary landfill area which started to serve in 2012 or disposed and burned in several geographically dispersed open dumping areas. When established, Güngör landfill was estimated to serve until 2033 and no landfill site has been chosen that can be used after Güngör landfill is completely filled. Güngör landfill consists of three lots: Lot 1 is already opened; Lot 2 is to be opened when Lot 1 is full; and Lot 3 will be at the top of Lots 1 and 2.

There is currently no waste treatment at Güngör landfill and only 11 municipalities in Northern Cyprus transfer their solid wastes to the landfill. The remaining 17 municipalities still dispose their wastes to open dumping areas close to their collection areas and sometimes burn them which is a threat to the environment and public health. Although less than half of all municipalities in Northern Cyprus bring the collected wastes to Güngör landfill, it is getting filled rapidly. It is essential that the amount of waste that goes to Güngör is reduced by recycling or any other treatment. There is currently no recycling facility in Northern Cyprus. Only a limited amount of waste is collected by some companies which sell it to either Turkey or Southern Cyprus for recycling by taking permission from the Environmental Protection Department of Turkish Republic of Northern Cyprus (TRNC).

Before Güngör landfill was built, solid wastes were accumulated in Dikmen open dumping area for many years which was threatening public health and caused unintentional fire many times. The odour of the wastes can be harmful to the health of people who are exposed to the smell when waste is accumulated inappropriately. Another issue of open dumping areas is the leachate which is very harmful to environment and public health. Unless properly handled, leachate can go through soil and run into water resources. Dikmen open dumping area had been closed down in 2011 and rehabilitated with the financial aid of European Union and Güngör sanitary landfill has been built. Also, other open dumping areas which require rehabilitation have been identified in the order of priority. In addition to the Güngör landfill, a transfer station in Gazimağusa has been built with the financial aid of the European Union.

The locations of five additional transfer stations (Akdoğan, Güzelyurt, İskele, Pamuklu, Girne) have been determined by the Ministry of Internal Affairs and Local Governments of TRNC (Tekeli, 2015). However, those five transfer stations have not been built yet. The open dumping areas are planned to be closed down and rehabilitated in the order of priority so that all the collected waste will be accumulated in Güngör landfill.

In Northern Cyprus, local governments (i.e., municipalities) are responsible for collecting solid wastes from the source and carrying them to the transfer station or to the Güngör landfill if the landfill is closer than the transfer station. This responsibility includes covering the cost of the transportation of solid wastes. The central government, on the other hand, is responsible for finding a solution to the problem for the solid wastes that are transported by local governments. There is an urgent need for planning the management of these wastes which is the main aim of this thesis. Thus, this study includes the analysis of treatment and final disposal of wastes that are collected at transfer stations and Güngör landfill as depicted in Figure 1.1.

Either the central government or a selected private company that will operate under the build-operate-transfer scheme should find a solution for the management of waste that is collected at the transfer stations and brought to the Güngör landfill area. This solution should determine which treatment facilities to be built at Güngör and their size, whether the current landfill should be extended or not, and when to extend the current landfill if it is to be extended so that all solid wastes generated in Northern Cyprus are properly handled at Güngör and the total cost of the proposed system is minimised.

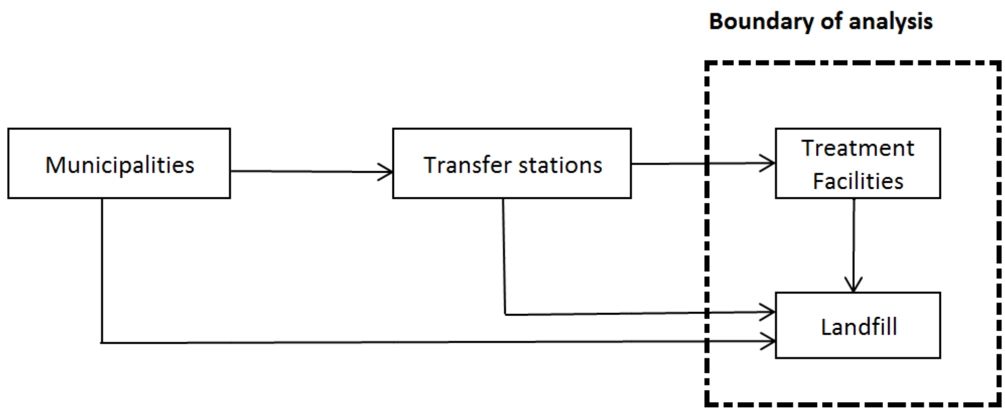

Figure 1.1 Boundary of analysis

1.2 Aim of the study

The aim of this study is to present detailed information about the past and current SWM programs applied in Northern Cyprus and to propose an optimisation model that would be helpful to the decision makers while seeking a solution to the SWM problem discussed in Section 1.1. The proposed optimisation model can be used as a tool for the decision makers to choose among the available treatment facility options considering their effectiveness and costs.

Composting, Anaerobic Digestion, Material Recovery Facilities, Waste-to-Energy and Landfilling are the treatment facility options considered in the proposed optimisation model. Recycling through source-separation by households is also considered in the model.

The SWM problem in Northern Cyprus, as briefly stated in Section 1.1, is formulated as a mixed integer nonlinear programming (MINLP) model that minimises the total cost of establishing and operating the treatment facilities less the revenues generated from the solid wastes. The total cost includes the sum of landfill extension costs, investment, operation and maintenance costs of the selected treatment facilities less revenues. The revenues include those obtained from the sale of recyclables and the electricity generated from solid wastes. The proposed model is solved to optimality using an open source MINLP solver. The solution of the proposed model yields the best decisions on waste management options and enables the decision makers to make a comparison of different scenarios. Based on the recycling participation rate (RPR) and prospective capacity of landfill Lot 3, several scenarios are analysed and managerial insights are obtained using the results of the model.

The contribution of this study is twofold. The first contribution of this study is related with its practical impact because a real-life problem which significantly affects the health, economy and quality of life of individuals living in Northern Cyprus is modelled and solved. The results of this study will guide the public authorities in making decisions regarding the SWM. The second contribution of this study is its contribution to the scientific literature. As can be seen in Chapter 2, the majority of studies in the literature use linear optimization models with integer variables or nonlinear optimization models with continuous variables whereas this study presents a more realistic optimization model with nonlinearities as well as integer variables.

1.3 Study outline

The rest of the thesis is as follows. In Chapter 2, a detailed review of the related literature is given. In Chapter 3, SWM strategies and regulations in Northern Cyprus, solid waste characterization results in Güngör landfill, municipalities and open dumping areas in Northern Cyprus are presented. Chapter 4 includes information about SWM strategies in general. Information about the life cycle of MSW and waste hierarchy are given and explained. Main solid waste treatment methods like waste-to-energy, anaerobic digestion, composting, mechanical biological treatment and landfilling are described. In Chapter 5, a detailed description of the addressed problem is given. Cost functions, waste quantities, capacities, the value of the parameters and the composition of MSW are defined. The formulation of the problem as a MINLP model is presented and the parameters and decision variables used in the model are described. Chapter 6 contains the results of different scenarios and present discussions of the findings. Chapter 7 summarises the results obtained, concludes the thesis and provides further research avenues.

CHAPTER 2

LITERATURE REVIEW

A number of studies in the literature examined the options for SWM treatment mostly by optimizing the cost of managing waste and also optimizing the effects of managing strategies on the environment (Ghiani et al., 2014). The studies aimed to choose the type and the location of treatment options by defining them as an optimisation problem.

The optimisation models can be named as linear programming / integer programming / nonlinear programming models depending on the type of variables and the linearity of objective function and constraints (Hillier & Lieberman, 2005). Linear programming models optimise a linear objective function with respect to a set of linear constraints with all continuous decision variables. Nonlinear programming involves at least one nonlinear term in the objective function and/or in one of the constraints. In integer programming, the decision variables have to take integer values. If there are both continuous and integer variables in the model, then it is called mixed integer linear/nonlinear programming model. Hybrid models are also possible. For example, if an optimization model has all linear terms in the objective function and constraints with both continuous and integer decision variables, then that model is called a mixed integer linear programming model whereas the same model with at least one nonlinear term in the objective function or one of the constraints is called a mixed integer nonlinear programming model. There are also multi-objective models which consider two or more objective functions simultaneously rather than including objectives separately (Caramia & Dell'Olmo, 2008).

Exact and heuristic methods are used to solve the problems that are formulated as optimisation models. Exact methods are those that are used to solve the optimisation models to guaranteed optimality. In other words, they yield the optimal solution of the problem. On the other hand, heuristic methods have a different form such as local search and imitation of natural processes like biological evolution (Hooker, 2015) and they try to obtain the optimal solution but they cannot guarantee finding the optimal solution. Some well-known heuristics among many others are simulated annealing, tabu search, and genetic algorithms (Hillier and Lieberman, 2005).

Ghiani et al. (2014) developed a classification scheme in order to identify specific variants of solid waste management systems. The classification is based on four fields: *p* / *s* / *c* / *o* where *p* denotes the number of periods, *s* the network structure, *c* the additional constraints of the problem, and *o* the objective(s) of the problem.

The first field *p* takes the value of 1 for single period problems and *T* for multi-period problems. The second field *s* can include the following subfields separated by commas:

- *C* if optimal location of new collection centres are considered
- *S* if existing or new transfer stations is taken into account,
- *P* if opening additional processing facilities or improving the functioning of the existing ones is considered,
- *L* if new or existing landfill, disposal or market facilities are taken into account

The third field *c* can be "*multiwaste*" if multiple kinds of waste are taken into account and/or "*uncert*" if uncertainty occurs in waste generation. The last field *o* can include the following subfields:

- *TC* if transportation cost is considered
- *PC* if treatment costs of facilities are taken into account
- *FC* if fixed costs of operating existing facilities or opening a new facility are considered
- "*multiobj*" if multi-objective optimisation is taken into account

When the model does not contain precise assumptions for any of the fields mentioned above, it is designated by "–".

The literature review is done by separating single period and multiple period studies.

2.1 Single period models

Antunes (1999) considered a 1/*S*, *L*/–/*TC*, *FC* problem and developed a mixed integer linear programming (MILP) model to define a link between landfills and transfer stations that covers the whole region of Central Portugal. He solved the model to optimality using a commercial solver and evaluated the variation of the costs associated with transfer stations and transportation of waste.

Antunes et al. (2007) studied a 1/*S*, *P*/–/*TC* problem and made the analysis of selecting the best location for an incinerator to be built. A three stage MILP model has been developed in order to find the optimal way to reorganize the existing SWM system. The solution of the problem of locating the incinerator includes the following suggestions: an incinerator can be considered as a heavy industrial facility; therefore, the incinerator should be located at the industrial site which guarantees that the environmental impacts are limited, planning regulations are adapted, easy access for transportation and availability of water, energy etc. Also, the hostility from people living around the location, opposition of politicians and environmental non-governmental organizations should be taken into account while selecting the location. The MILP model is solved to minimize transportation costs and the number of people living within five kilometres of the incinerator simultaneously. In the first stage, the municipality of Agueda was chosen as it is close to the centre that is more densely populated and larger amount of waste is generated there. In the second stage, nine industrial sites are determined as efficient, and in the third stage, these sites were classified as good, fair, poor and inadequate according to the availability of land, energy, water, local access, the number of people exposed to air pollution and the number of people exposed to noise pollution. The model was solved to optimality using a commercial solver. The industrial sites which were classified as good in the third stage considered to be the best location for the incineration.

Badran and El Haggar (2006) considered a 1/*S*, *P*, *L*/–/*TC*, *PC*, *FC* problem in Egypt and proposed a MILP model where the aim is to minimize system-wide costs. Locations of several collection stations were evaluated and MSW included hazardous, construction and demolition waste. Three main issues that were considered include (i) whether the demolition and hazardous waste should be transferred to the landfill through composting facility or directly to the landfill, (ii) whether the collection station capacity should be 10 tons, 15 tons or the combination of two and (iii) whether the waste collected in each source should be only in the available collection points in that source or not. The model was exactly solved using a commercial solver. The solution of the MILP model showed that the best scenario is mixed capacities where there are no limitations on waste flow from the source to the site where it is collected.

Bloemhof-Ruwaard et al. (1996) studied a 1/*P*, *L*/*multiwaste*/*TC*, *FC* problem which has the objective of minimising the total fixed costs of opening treatment plants and waste disposal sites. Also, minimising variable costs of product and waste flows is included in the objective. Formulations for the capacitated distribution and problem of waste disposal are presented. The quality of multiple lower bounds is analysed and heuristics for obtaining feasible solutions are proposed. A computational study was done to check whether the lower and upper bounding procedures were effective or not. The conclusion is that the lower capacitated problems are harder to solve compared to the higher capacitated problems and as the capacities and fixed costs gets higher in variability, it gets harder to solve problems.

Caruso et al. (1993) considered a *1/P, L/multiwaste/TC, FC, multiobj* problem with multiple commodities and three different objectives (total cost, the residue of recyclable resources and environmental impact) are taken into account. They propose a number of heuristic techniques to solve the problem. Three objectives are united by weighting method to get a parametric single objective. The study considered the stages of transportation, processing and disposal of wastes. In the processing phase, the incineration, composting and recycling facilities are considered and in the disposal phase landfills are taken into account. Their approach has been applied in the Lombardy region, Italy. The results revealed that there is an economic advantage in working with medium-large plants (about 15-20 units of process plants and 10-12 units of landfills in Lombardy region). The results also indicated a correlation between plant size and technology selection. Similarly, the results showed that geographical and population characteristics can be correlated with the choice of technology.

Eiselt (2007) considered a 1/*S*, *L*/–/*TC* problem and developed a MILP model for locating landfills and transfer stations in New Brunswick, Canada. In the model, waste is either transferred directly from the source to the landfill or through transfer stations. The model was exactly solved using a commercial solver. The results of the study showed that the optimal solution is 10% to 40% less costly than the observed solutions.

Erkut et al. (2008) developed a MILP model for a 1/*S*, *P*, *L*/–/*TC*, *PC*, *FC*, *multiobj* problem in Central Macedonia region, Greece which includes the selection of technology for transfer stations, treatment facilities, and landfills. The objective of the model includes minimising the greenhouse effect, minimising the final disposal to the landfill, maximising the energy recovery and material recovery, and minimising the total cost. They considered the minimisation of total cost by considering landfills, transfer stations, and the facilities such as anaerobic digestion, composting, mass-burn, gasification, pyrolysis, and rotary kiln. They assumed a single commodity for the types of waste. In Greece, the composition of waste contains high amount of biodegradable materials and low amount of packaging materials; therefore, the solution mostly included anaerobic digestion and composting. They used a lexicographic minimax method for finding a solution, which can be described as the solution that minimises the value that is the worst objective. A commercial solver was used to solve the MILP model to optimality. In general, no solution exists in multi-objective mathematical programming which optimizes all objectives simultaneously. Instead, Pareto optimal solutions (i.e., solutions that are not dominated by others) were considered.

Fiorucci et al. (2003) aimed to design a decision support system which would help authorities in municipalities to make decision about the facilities of incineration, disposal, treatment and recycling. A *1/P, L/multiwaste/TC, PC, FC* problem is considered in the decision support system. They developed a nonlinear model that aims to minimise recycling costs, transportation costs, installation and maintenance of the plant costs and maximising economic benefits of selling electric energy and refuse derived fuel (RDF). The model has been applied to the municipality of Genova, Italy. A commercial solver is used for the exact solution of the model. The results indicated that a case with minimum cost is not environmentally sustainable; a facility for organic material treatment and a RDF plant should be built; one incinerator should be built which saturates the landfill in 20 years or if no incinerator is built, a high percentage of recycling should be achieved which saturates the landfill in 40 years.

Galante et al. (2010) studied a *1/S/–/TC, FC, multiobj* problem and developed an integrated multi-objective optimisation method containing the objectives of minimising the total cost and the effect on the environment. The study includes determination of the location and dimension of transfer stations, and transportation of solid waste from municipalities to an incinerator. They propose a MILP model which considers both the investment costs and operational costs of transportation and transfer stations. The model was applied to Palermo, Italy and solved to optimality using a commercial solver. The result of the paper highlights the importance of the preferences of decision maker as it significantly affects the performance of the system when the objectives are considered. Also, the results demonstrate that when the cost is taken as the main optimisation objective, centralized system design is the solution. On the other hand, when environmental impacts are taken as the main objective, a decentralized solution is obtained which minimises fuel consumption.

Ghiani et al. (2012) developed an integer programming model that is helpful for administrations to make decisions about how to choose the location of mixed waste collection bins at the source and the size of bins. The model minimises the total cost of collecting waste. Also, through the model, individuals are allocated to the collection sites in an optimal way such that the bins of each individual are collected. The solution of the problem includes both an exact solution of the optimisation model using a commercial solver and a construction heuristic. Computational results of a real-life problem show how effective the optimisation model and the useful heuristics are by reducing the number of bins that is allocated up to 73% and collection sites that are active up to 62%.

Jenkins (1982) developed a method that involves solving a MILP at point values of the variation parameters and joining the results by the linear programming (LP) parametric analysis. He developed a model to solve the 1/*S*, *P*, *L*/–/*PC*, *FC* problem. In the parametric integer programming model, various parameter values were considered related to resource recovery. A commercial software was used to solve the model exactly. The results of the parametric analyses aided in deciding which plants to build if a resource recovery policy is implemented.

Kulcar (1996) aims to minimise waste transportation costs by vehicle, rail and canal. Useful strategies that were created for collection allow easier decision making for the administrators. A 1/*S*, *P*/–/*TC*, *FC* capacitated location problem is solved to decide the location and the requisite for opening a new site between the incinerator and collection paths. An exact method has been used for solving the model and efficient solutions were offered to the administrators.

Mitropoulos et al. (2009) considered a *1/S, P, L/–/TC, FC* problem and evaluated the options of transfer stations, treatment plants (mass burn, biological drying with energy utilization, anaerobic digestion, aerobic digestion) and a landfill by assuming a single commodity. Major problems in making decisions for the development of integrated SWM is choosing between a costly treatment technology which decreases the amount of solid waste that goes to landfill and the costs related to it and a technology without treatment in which all the waste goes to the landfill with a high landfilling cost. The MILP model was solved using a commercial solver. They took into account the variable costs of disposed waste, costs of the landfilling site post-closure, and the replacement of landfill sites rather than considering just the fixed costs of the landfill.

Rahman and Kuby (1995) studied a *1/S/–/TC, FC, multiobj* problem which examines the trade-offs between minimising the total cost and public disapproval. Their model chooses the location of transfer stations. Projected public disapproval is modelled considering the distance from the facility. They developed an exact algorithm to solve their model to optimality. The results of the study showed that the current assignment of waste collection zones to the two city-owned landfills in the city of Phoenix is nearly optimal. The model also shows the importance of transfer stations as landfills are located far from the urban boundaries sue to the public concern.

Minoglou and Komilis (2013) considered a *1/P, L/–/PC, FC, multiobj* problem and proposed a nonlinear programming model for the minimisation of the total cost of the MSW management system and minimisation of CO_2 emissions generated by the system. The proposed model aims to find an optimal solution which assigns eight MSW components (paper, cardboard, plastics, metal, glass, food wastes, yard wastes, and other wastes) to four technologies (incineration, composting, anaerobic digestion, and landfilling) after the separation of recyclables at source. The model was applied to East-Macedonia and Thrace, Greece and solved to optimality using a commercial solver. The results indicated that incineration and composting were chosen as the preferred treatment technologies whereas landfilling was always the least favoured option. The RPR played a significant role in all scenarios.

Tralhao et al. (2010) studied a *1/P/multiwaste/TC, FC, multiobj* problem and used a MILP model to locate multi-compartment sorted waste containers for recycling in Coimbra, Portugal. The model is used to identify the sites and sizes of multi-compartment containers. The objectives of the model include minimising the sum of investment cost, the distance between dwellings and multi-compartment container, minimising the number of individuals who are close to the containers and maximising the number of dwellings that are close to containers. The model was solved using a commercial MILP solver. The solution of the model included ten different combinations of containers for the disposal of four types of sorted waste in 12 cities. The ideal solution depends on the objectives and preferences of decision maker in a particular application. By minimising each objective individually, the best solution was determined.

2.2 Multiple period models

Baetz and Neebe (1994) developed a model for the recycling of by-product materials in the whole waste system. The model aims to improve a development program that includes optimal recycling facility. The problem can be classified as *T/L/multiwaste/TC, PC , FC*. The treatment facilities considered to dispose the generated by-product materials include material recycling, waste-to-energy, and landfilling. The problem was formulated as a mixed integer linear programming (MILP) model which is optimally solved using a commercial solver. The optimal solution includes the combination of recycling, waste-to-energy and direct landfilling. The results indicated that as recycling activity increases the portion of the waste stream incinerated tends to decrease.

Baetz et al. (1989) considered a *T/L/–/TC, PC, FC* problem and compared the models for the initial sizing and timing of facilities for three municipalities which are Mecklenburg County in North Carolina, A Long Island Community in New York and the Regional Municipality of Halton in Ontario, Canada. Demand for waste disposal, waste-to-energy capacity and landfill capacity of three municipalities were compared. The aim of the proposed MILP model of Baetz et al. (1989) was to provide capacity planning for the municipalities which could be used to evaluate the costs of various management types and the demand of waste disposal. In Mecklenburg County, an additional waste-to-energy facility which was planned to be developed would optimally satisfy 65-70% of waste disposal demand in the 30-year time horizon and 50-55% of the total demand in the remaining part. Also the existing landfill in 1988 would be sufficient until 1992 and a new landfill of 12 million meters capacity will hold the disposal of waste for the rest of the planning horizon. In the Long Island Community of New York, no current or projected landfill was available within the boundaries of the municipality; therefore, landfill capacity was not included as a decision variable in the case study. A new waste-to-energy facility was planned to be developed in 1992 and to optimally handle 100% of waste. The demand for waste disposal decreases as recycling of materials increases. The optimal capacity planning results for the Regional Municipality of Halton include a new landfill requirement in 1988, a new waste-to-energy facility development in 1996 with capacity expansion of 50 percent in 2012.

Cai et al. (2009) developed a model to be applied to MSW management under uncertainty. They used fuzzy sets to handle uncertain information. The study attempted to integrate interval-parameter programming and fuzzy robust-programming methods so as to apply the resulting method on solid waste management design. The results showed that the suggested methodology could be used in solving practical problems which are related to highly complex and uncertain data. The results also revealed that the system stability increases as the amount of money that individuals are willing to pay increases. Otherwise, the system may be instable.

Guo et al. (2008) improved an indefinite random mixed integer semi-infinite programming model under uncertainty for MSW management. Functional interval and random parameters are used for the model. The method has been used in a SWM system involving three cities and three disposal facilities with three time periods. Two different scenarios are considered. The first scenario includes the expansion of waste-to-energy and composting facilities and the other includes expansion of waste-to-energy, composting, and landfill facilities. A heuristic has been used in the solution of the problem. The model helps decision makers in arranging waste division and facility developments that include minimum system cost and in stating interchanges among environmental, economic and system consistency level under complex uncertainties.

Ferrell and Hizlan (1997) considered a *T/P, L/–/TC , PC, FC* problem and constructed a MILP model to design a SWM system in South Carolina counties, USA. The model selects the best combination of alternatives for minimising the total cost over a 20-year planning horizon. The alternatives considered include recycling at source separation, commingled recyclables separation, mass sorting, incineration, convenience centre, composting, construction and operation of sanitary and inert landfills and construction of private landfills. The MILP model was solved to optimality using a commercial solver. The optimal solution indicates that mass-sorting alternative should be used as much as possible, even after most aggressive recycling efforts, remaining waste should be further processed (composted or buried). Also, the model recommends that county should made private landfill contract instead of constructing and operating its own public landfill as it is costly.

Li and Huang (2006) studied a *T/P, L/uncert/TC, PC* problem and proposed an interval-parameter two-stage minimax regret interval LP model. The developed model was applied to a case study for a long term MSW management design under uncertainty and solved with a commercial solver. The results revealed the interchanges among the cost of the system, the regret level and the risk of system failure.

Maqsood and Huang (2003) considered a *T/P, L/uncert/TC, PC* problem which was formulated as a two-stage interval-stochastic programming model. The model provides connection between the environmental policies that are defined and related economic effects and enables presenting the uncertain information as intervals and probability distributions which can be linked to optimisation process and the solutions. A heuristic has been used for the solution of the problem. Solutions of the model include preferred waste flow design by minimising the system cost and maximising the system feasibility.

Shekdar et al. (1991) developed a MILP model for a *T/P, L/–/TC, FC* problem to minimise SWM costs in the long term. The model considers the time horizon and developmental stages. They applied the model to real-life through a case study. An exact method was used for the solution of the model. It is determined that the resource requirements for the long term can be determined by defining optimal locations and loading of the landfill areas and assigning different areas of collection to different disposal sites and processing facilities.

CHAPTER 3

WASTE MANAGEMENT IN NORTHERN CYPRUS

3.1 Legal framework and institutional structure

According to 18/2012 Environment Law in TRNC, waste management plan is prepared by Environmental Protection Department (EPD) with the cooperation of municipalities and non-governmental organizations and is presented to ministries for confirmation (EPD, 2012). Also, according to this law, EPD is responsible for determining the standards for monitoring and controlling the facilities of waste management while collection, transportation, recovery and disposal of waste are the responsibilities of municipalities. Municipalities also establish and operate or help in establishing and operating municipal solid waste disposal facilities. Ministry responsible from municipalities ensures that there is cooperation between municipalities and if needed, eliminates waste on behalf of municipalities and receive fees from the municipalities for the disposal.

EPD gives permission to private companies for collecting, transporting and recycling the packaging waste. Only the general requirements for waste management are set under current legislation and the way of implementing legislations includes major weaknesses (Master Plan on Solid Waste Management, 2007). The legislation requires permit for waste disposal installation but the requirements are insufficient, informal and poorly applied as there are many final disposal areas which do not have permits. Thus, these final disposal areas should be considered as open dumping areas. According to the findings, there are 72 open dumping areas in Northern Cyprus. The open dumping areas have negative effects on the public health and the environment. Release of greenhouse gases to the atmosphere, contamination of water and soil through leachate and fire are possible problems of open dumping areas.

3.2 Waste inventory

Municipality of Beyarmudu executed an U.S. Agency for International Development (USAID) project and took 99 samples from the residences. The results of this study show that in each house 2.6 kg waste is produced daily and assuming that approximately 3.1 people live in a house waste production per person per day can be calculated as 0.85 kg. As a part of the Master Plan on SWM in Northern Cyprus in 2007, a waste inventory study has been done by taking samples from the houses in Lefkoşa, Gazimağusa, Girne, Güzelyurt, Lefke, Büyükkonuk, Değirmenlik, Kalkanlı and Ozanköy in June-July and September-October. The results of the study include the amount of waste produced per person, waste composition and the types of waste. The type and the amount of waste produced per person are given below in the Table 3.1. The composition of municipal waste is given in Table 3.2. According to the records of Güngör landfill, the amount of waste coming to the landfill daily, monthly and annually are 151 tons, 15,450 tons and 185,400 tons, respectively.

Table 3.1 The type and the amount of waste produced per person (Master Plan on SWM in Northern Cyprus, 2012)

Type of waste	**Waste production (tons / person / year)**	**Total Annual amount (tons/year)**	**Percentage (%)**
Municipal waste	0.405	107,200	38.8
-Household waste	0.277	73,300	25.2
-Commercial waste	0.128	33,900	11.6
Construction/demolition waste	0.487	129,100	44.4
Industrial waste	0.149	39,500	13.6
Green waste	0.56	14,900	5.1
Total	**1.097**	**290,800**	**100**

Table 3.2 The composition of municipal solid waste collected at Dikmen (Master Plan on SWM in Northern Cyprus, 2007)

Waste	**Percentage (%)**
Organic waste	45.7
Recyclable waste	37.7
-Plastic	18.5
-Paper/ Cardboard	9.0
-Glass	5.7
-Textile	2.6
-Metal	1.9
Hazardous waste	9.9
Others	6.9

The estimated production of specific waste streams are 12,000 tons of vehicles that completed life, 2,000 tons of used tyres, 500 tons of broken down accumulators, 1,500 tons of waste oil, and 4,000 tons of waste electrical and electronics equipment per year (TRNC feasibility report of solid waste management plan, 2008). The types and the amount of waste that are accepted in Güngör landfill are given in Table 3.3 The results were obtained by using the data taken from Erkan Tekeli which includes the type and the amount of waste accepted at Güngör area daily. Also, the document includes the information about where the waste comes from.

Table 3.3 The types and the amount of waste that are accepted in Güngör landfill (Tekeli, 2015)

Type of waste	**Amount (tons/year)**	**Percentage (%)**
Demolition	2,132.66	1.30
Hazardous waste	610.92	0.37
Animal waste	3,392.96	2.06
Construction waste	20,338.16	12.35
Industrial and commercial waste	16,328.84	9.91
Household waste	121,868.9	74.01
Total	**164,672.44**	**100**

3.3 Types of wastes in Northern Cyprus

Nine municipalities (Lefkoşa, Alayköy, Girne, Gönyeli, Çatalköy, Alsancak, Lapta, Değirmenlik and Dikmen) and the garrisons of Lefkoşa and Girne bring their domestic wastes to the landfill in Güngör area (Rızza, 2014). Also, the municipalities of Akıncılar and Güzelyurt bring their domestic wastes to Güngör landfill since 2015. 19 municipalities store their hazardous wastes in hazardous waste storages, and according to the data of 2007, there are 75 hazardous waste storages used by the municipalities. The other garrisons apart from Lefkoşa and Girne dispose their hazardous wastes into the hazardous waste storages.

The municipalities of Lefkoşa, Gazimağusa, Güzelyurt and Girne have wastewater treatment facilities which generate sewage sludge. According to the EPD, sewage sludge in Northern Cyprus is not hazardous but it is not accepted to Güngör and is suggested to be used as an agricultural fertilizer. In Haspolat, wastewater treatment facility operated by the municipality of Lefkoşa produces about 30 tonnes of sewage sludge per day and it is digested to generate electricity. Similarly, sewage sludge in Gazimağusa and Güzelyurt is used to generate electricity.

Although recycling facilities do not exist in Northern Cyprus, there are licensed firms which collect recyclable materials and export to either Turkey or Southern Cyprus (Özverel, 2014). In Table 3.4, the names of the collector companies and the type of materials that they collect are given. This table is taken from the thesis of Cemaliye Özverel (2014) but it has been updated by personal communication with İbrahim Alkan from EPD.

Table 3.4 Collectors of recyclable materials in Northern Cyprus (Alkan, 2015)

No	Name of the company	Facility
1	Mahmut Özdemir	Plastic and Paper collection
2	Greenwise Environment Ltd.	Paper/ Cardboard and plastic collection
3	Denaz Trading Ltd.	Plastic collection
4	Cypron Ltd.	Plastic collection
5	Sezer Akü	Batteries and accumulator
6	Atağ Akü	Batteries and accumulator
7	Yavuz Türksan	Waste mineral oil
8	Birel Ltd	Waste mineral oil
9	Ali Can	Waste mineral oil
10	Asbuzu Ltd.	Waste mineral oil
11	Omega development & recycling	Waste mineral oil
12	Rubberland	Waste tyres
13	Yababa	Waste tyres
14	Hüseyin Beton Ltd.	Waste tyres
15	Öcal Özbahadır	Waste vegetable oil
16	Diner Yağ Ltd.	Waste vegetable oil
17	Tamöz Ltd.	Waste vegetable oil

3.4 Solid Waste Characterization in Güngör landfill area

The Investment Development Agency of TRNC, called YAGA, carried out a study on solid waste characterization in Güngör landfill area. Solid wastes were collected from different points of the city of Nicosia and according to the levels of income (low, middle, high) (YAGA, 2014). Locations of the collecting points and weekly waste collection days are given in the Table 3.5.

Table 3.5 Location of waste collection points and weekly collection days (YAGA, 2014)

Sample	Location	Weekly waste collection
High Income	Hamitköy; Anıttepe street west side villas	Tuesday, Friday
Middle Income	Ortaköy-Kermiya; Öğretmen Evleri 1., 2., 3. Street	Tuesday, Friday
Low Income	Haspolat; Council homes	Monday, Thursday
City Centre	Dereboyu street	Everyday

For the characterization of waste, 16 components are determined and they are given in Table 3.6. Collected waste was brought to Güngör landfill area without compacting and two sample groups (one of them represents the waste produced in the weekend and the other one represents the waste produced during the week) were studied in different days. 650 kg waste has been evaluated per sample of waste. The results of the percentage of the amount of waste derived from three socioeconomic classes (high, middle, low) and the town centre are given in Table 3.7.

Table 3.6 Solid waste components (YAGA, 2014)

1. Kitchen Waste	Leftovers, bread, vegetable, fruits
2. Paper	Newspaper, magazine, notebook
3. Cardboard	Milk box, juice box
4. Bulky Cardboard	Cardboard box
5. Plastic	All plastics
6. Glass	Glass bottle, glass jar, glass
7. Metal	Tin box, fork, knife
8. Volume Metal	Metal closet, table etc.
9. Waste electrical and electronics	Phone, radio etc.
10. Hazardous Waste	Batteries, paint box, detergent
11. Green Waste	Branch, grass
12. Other Non-combustible Waste	Stone, sand, ceramic
13. Other Combustible Waste	Cloth, diaper, shoes, slipper, pillow, carpet, rug,
14. Other Combustible Bulky	Furniture, wooden materials etc.

Table 3.7 Average % of waste according to socioeconomic income level and town centre (YAGA, 2014)

Waste Type	**High**	**Middle**	**Low**	**Average**	**Town**
Kitchen Waste	46.31	33.49	29.96	36.59	14.52
Paper	2.96	4.05	2.82	3.27	3.63
Cardboard	6.22	5.00	3.03	4.75	0.78
Bulky Cardboard	1.45	1.07	1.86	1.46	44.13
Plastic	16.02	10.45	13.86	13.44	11.28
Glass	7.16	6.32	6.23	6.57	16.07
Metal	1.65	0.99	2.48	1.71	0.78
Large Metal	0.00	0.00	0.68	0.23	0.00
Waste Electric and	1.10	0.17	0.00	0.43	5.44
Hazardous Waste	0.77	2.56	2.16	1.83	0.13
Green Waste	0.37	6.43	5.93	4.24	0.00
Other Inflammable	0.23	2.56	2.18	1.66	0.00
Other Flammable	14.90	20.04	25.95	20.30	3.24
Other Flammable	0.86	6.86	2.87	3.53	0.00

According to the results of the average income, the highest amount of waste is kitchen waste with 36.59% which is followed by other combustible waste with 20.30% and thirdly plastic with 13.44%. If we look at the results of the town centre, bulky cardboard has the highest percentage of 44.13 which is followed by glass, kitchen waste and plastic with the percentages of 16.07, 14.52, and 11.28, respectively. In Figure 3.1, percentages of five waste groups (organic waste, recyclable waste, other flammable waste, hazardous waste, and other waste) are given according to income levels and town centre. In all income levels, the highest percentage of waste is organic waste which is followed by recyclable waste and other flammable waste.

A similar study was done by Özverel (2014) which characterized the waste composition of the Middle East Technical University, Northern Cyprus Campus. Solid wastes coming from different areas of campus were measured in each season and the results show that there is no significant difference in the waste composition measured in each season. Also, the results show that the highest amount of waste is organic waste in the campus and the potential for recycling and composting is around 37% and 34%, respectively.

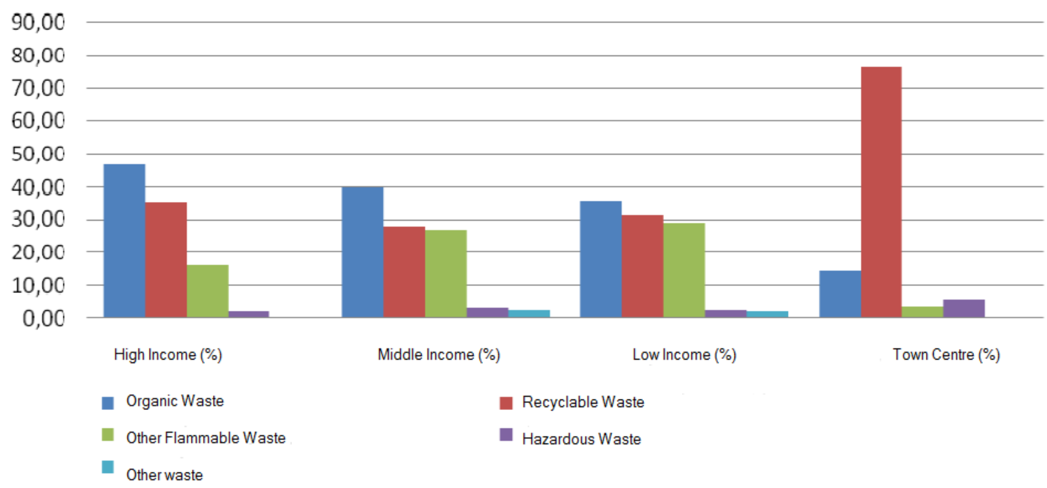

Figure 3.1 Percentage of waste group of the socioeconomic income level groups and town centre (YAGA, 2014)

3.5 Former and current solid waste management system in Northern Cyprus

In Northern Cyprus, until 2012, solid wastes were mainly being accumulated in Dikmen dumping area where waste was partly being burned and partly buried into the ground inappropriately (Ünlü and Akıntuğ, 2013). Burning wastes had negative effects to the atmosphere and caused fire in Dikmen area many times. In addition, burying wastes into the ground was threatening the public health and the environment. Hence, Dikmen dumping area was closed down and rehabilitated in 2012. Also, there are 72 other open dumping areas in Northern Cyprus where wastes are burned and buried inappropriately so has to be closed down and rehabilitated.

European Union (EU) financial support programme allocated a budget of €21.2 million for finding a solution to the solid waste issue in Northern Cyprus. For the solution of the problem, waste management policies and waste management plan of TRNC were prepared and approved in 2008. According to this plan, waste disposal areas which require rehabilitation had to be identified in the order of priority, a new landfill had to be built in Güngör area, and transfer stations connected to this landfill had to be founded in Güzelyurt, İskele and Gazimağusa. Dikmen dumping area have been closed down and rehabilitated and a new landfill has been built in Güngör area with the cost of €7 million given as a part of EU financial support programme. Güngör has the area of 12 hectares and the capacity of the plant is 2.3 m^3 which was estimated to serve until 2033. Rehabilitation of Dikmen landfill costed €6.2 million and within the rehabilitation plan, 1.3 million m^3 wastes in an area of 27.5 hectares were accumulated in an area of 11.5 hectares and were covered with an impermeable soil and material. Other open dumping disposal areas which were decided to be closed down and rehabilitated were in Güzelyurt/Kalkanlı and Gazimağusa according to the priority. Güzelyurt/Kalkanlı disposal area was closed down in 2015 and the solid wastes collected by Güzelyurt municipality are being transported to Güngör.

Only one transfer station was built at Gazimağusa. However, this transfer station is not in service yet because of financial reasons and lack of organization. In addition to the transfer station in Gazimağusa, additional transfer stations are planned to be built in Akdoğan, Girne, Güzelyurt, İskele and Pamuklu. The distance of those transfer stations to Güngör landfill area is given in Table 3.8.

The cost of building the transfer station in Gazimağusa was €500,000 and the cost of the truck for transferring the solid waste is €300,000 (Tekeli, 2015). The cost of building the other transfer stations is expected to be similar. The truck weights 17,560 kg when it is empty and the solid waste transfer capacity is 15,000 kg approximately.

Table 3.8 Distance to Güngör area from the transfer stations (Tekeli, 2015)

Transfer Station	Distance (km)
AKDOĞAN	33.8
GAZİMAĞUSA	51.8
GİRNE	28.4
GÜZELYURT	55.6
İSKELE	47.3
MEHMETÇİK	69.1

The recovery and recycling facilities are insufficient in Northern Cyprus because of the population being small. Thus, collected recyclables are exported to either Turkey or Southern Cyprus (Master Plan on Solid Waste Management, 2007). In addition, incineration facilities do not exist in North Cyprus. Because waste collection is also inefficient in Northern Cyprus, the existing services need to be improved.

3.6 Municipalities and waste management

In TRNC, there are 28 municipalities in total. As mentioned in Section 3.1, municipalities are responsible for collection, transportation, recovery and disposal of waste but they are experiencing serious issues about administration, finance, infrastructure, equipment, and employees. Especially the open dumping areas used by municipalities to dispose the wastes are threatening public health and the environment. Municipalities are listed in Table 3.8 according to the districts. In Table 3.9, the results of the study done in 2007-2008 about open dumping areas in Northern Cyprus are given.

Table 3.9 Distribution of municipalities according the districts (Rızza, 2014)

Lefkoşa	Gazimağusa	Girne	Güzelyurt	İskele
Lefkoşa *	Gazimağusa	Girne *	Güzelyurt*	İskele
Gönyeli *	Yeni Boğaziçi	Alsancak *	Lefke	Mehmetçik
Alayköy *	İnönü	Lapta *		Büyükkonuk
Değirmenlik *	Geçitkale	Esentepe		Dipkarpaz
Akıncılar*	Serdarlı	Dikmen *		Yeni Erenköy
	Beyarmudu	Çatalköy *		
	Paşaköy			
	Tatlısu			
	Akdoğan			
	Vadili			

*: Municipalities that bring their wastes to Güngör landfill

Table 3.10 The open dumping areas in Northern Cyprus (Rızza, 2014)

NO	Place	Capacity m^3	Distance to Güngör landfill (km)
1	AKDOĞAN NEW	7900	28
2	AKDOĞAN OLD	6560	28
3	AKINCILAR	11110	26
4	ALAYKÖY	32000	18
5	BEYARMUDU	18970	35
6	BÜYÜKKONUK	7315	53
7	DEĞİRMENLİK	121350	17
8	DİPKARPAZ NEW	6815	98
9	DİPKARPAZ OLD	12655	98
10	ESENTEPE OLD	7000	17
11	ESENTEPE OLD 2	4990	17
12	GAZİMAĞUSA	580000	46
13	GEÇİTKALE	46275	29
14	GÜNGÖR	93000	1
15	GÜZELYURT	156150	40
16	İNÖNÜ	10250	27
17	İSKELE	90500	43
18	MEHMETÇİK	43950	60
19	PAŞAKÖY NEW	23500	17
20	PAŞAKÖY OLD	72000	17
21	SERDARLI	28500	27
22	TATLISU	7515	34
23	VADİLİ	12420	25
24	YENİ BOĞAZİÇİ	26420	43
25	YENİ ERENKÖY NEW	11800	77
26	YENİ ERENKÖY NEW	50815	77
27	ALTINOVA	3360	37
28	BAHÇELİ	3820	21
29	CİHANGİR	5785	9
30	ÇAMLIKÖY	2870	53
31	DOĞANCI	24285	50
32	ERDEMLİ NEW	3485	32
33	ERDEMLİ OLD	4940	32
34	ERGAZİ	2815	49
35	İNCİRLİ	7580	37
36	KALAVAÇ	1980	11
37	KALEBURNU	3720	85
38	KAPLICA	4860	48
39	KİLİTKAYA	2335	51
40	KORUÇAM	3605	41

Table 3.10 Continued

NO	Place	Capacity m^3	Distance to Güngör landfill (km)
41	KOZANKÖY	4130	28
42	KUMYALI	6670	67
43	MALLIDAĞ	380	27
44	MEVLEVİ	5375	34
45	MORMENEKŞE	9530	40
46	ÖZHAN	29210	31
47	SADRAZAMKÖY	900	46
48	ŞİRİNEVLER	9200	24
49	TEPEBAŞI	72735	38
50	TİRMEN	265	21
51	TÜRKMENKÖY	785	32
52	ULUKIŞLA	5620	20
53	YEŞİLIRMAK	6470	63
54	YEŞİLKÖY	11105	73
55	YEŞİLYURT	18530	51
56	YILMAZKÖY	24000	25
57	LEFKE	NO INFORMATION	55

3.7 Population in Northern Cyprus

According to the State Planning Organization consensus in 2011, the population of Northern Cyprus was 286,257. The State Planning Organization of TRNC states that the population was 256,644 in 2006 and 268,011 in 2007 (Atasoy, 2011). The increase of population in Northern Cyprus from 1977 to 2011 is shown in Figure 3.2 (State Planning Organisation, 2011). The population and area of each municipality are given in Table 3.10.

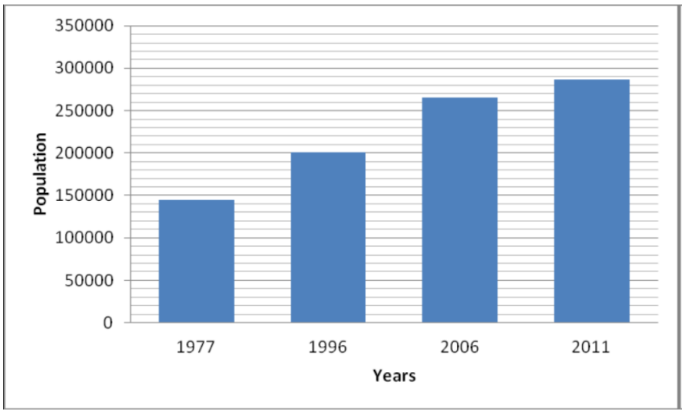

Figure 3.2 Increase of population in Northern Cyprus (Atasoy, 2011)

Table 3.11 Area and population of municipalities (Rızza, 2014)

Municipalities	Area (km^2)	Population according to census in 2011	Population per km^2
LEFKOŞA	87	61,378	706
GAZİMAĞUSA	86	40,920	476
GİRNE	66	33,207	503
GÜZELYURT	201	18,946	94
GÖNYELI	33	17,277	524
LEFKE	114	11,091	97
LAPTA	263	12,118	46
BEYARMUDU	144	4,125	29
DEĞİRMENLİK	252	11,895	47
ALSANCAK	22	6,597	436
İSKELE	230	7,906	34
YENİ BOĞAZİÇİ	128	6,618	52
AKDOĞAN	44	2,471	56
VADİLİ	42	2,390	57
ALAYKÖY	96	3,884	40
DİKMEN	156	9,120	58
ÇATALKÖY	42	5,652	135
İNÖNÜ	69	2,927	42
DİPKARPAZ	173	2,349	14
PAŞAKÖY	63	3,561	57
YENİ ERENKÖY	179	5,627	31
GEÇİTKALE	140	2,380	17
ESENTEPE	89	2,414	27
MEHMETÇİK	111	3,729	34
TATLISU	77	1,459	19
SERDARLI	121	2,411	20
BÜYÜKKONUK	142	2,860	20
AKINCILAR	10	390	39
TOTAL	3,180	285,702	

CHAPTER 4

MANAGEMENT OF SOLID WASTE

Effective management of solid waste would consider waste hierarchy and choose treatment facilities to build accordingly. Based on the hierarchy, solid waste can be reduced or prevented before going through treatment facilities or final disposal area when effectively managed. Solid wastes arising from various sources require treatment such as volume reduction, composting, recovery, adequate transport, and disposal techniques which should be controlled carefully for the protection of public health and the environment (Thomas-Hope, 1998). The processes from generation to final disposal of wastes include solid waste generation in regions, collection of wastes from the generating regions to transfer stations (if transfer station exists), separation of waste at the source or at separation plants, waste management through incinerating, energy recovery, and reclamation plants or composting, and waste disposing through landfilling or land spreading. In Figure 4.1, a complete cycle of MSW is given. As depicted in Figure 4.1, collected unseparated waste goes either to thermal treatment (i.e., waste-to-energy) and comes back as energy where produced ash goes to the landfill, or to the landfill where methane gas is obtained and converted into energy, or it goes to mechanical biological treatment where metals and compost are obtained and the remains go to landfill. Collected separated waste is transported to either material reclamation facility where paper, plastic, metal and glass are obtained or to biological treatment where compost and methane is produced. In both facilities remains go to landfill.

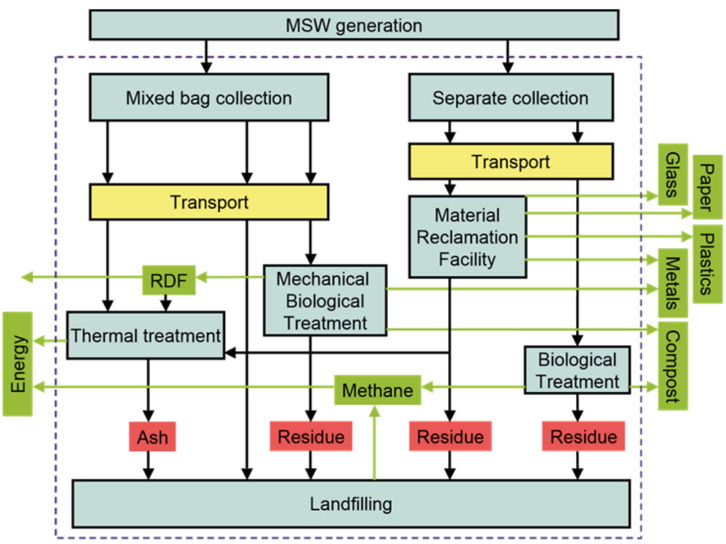

Figure 4.1 Complete life cycle of MSW (Abeliotis, 2011).

In Figure 4.2, waste management activities are prioritised in the order of waste minimization, reuse, recycling, waste-to-energy and landfill.

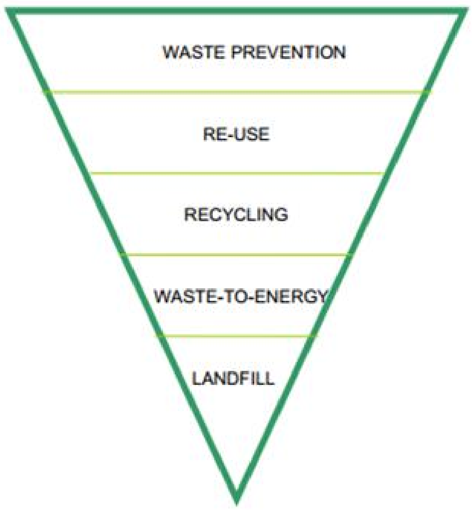

Figure 4.2 Waste hierarchy (UNEP, 2010).

The highest rank of waste hierarchy is the waste prevention, as it is the most effective way to reduce the quantity of waste. Waste prevention is taking action before waste is generated (CalRecycle, 2014). It simply means using fewer products so that produced waste is minimised. However, consumers may not be able to use less stuff to produce less waste as they are exposed to use more stuff by the producers of goods. Therefore, it may not be so easy for people to use fewer materials. However, consumers can prevent generation of waste by avoiding use of products such as napkins and buying items that last longer.

Second rank in the hierarchy is reuse which is using the object or material again. Note that reuse is not the same as recycling. The former does not change the physical form of the object or material whereas the latter does. Reuse is more beneficial than recycling as it uses less energy and resources. In Northern Cyprus, charity events are organised where unused materials can be donated and sold occasionally. However, those organisations are insufficient and are not regular.

Reuse is followed by recycling which helps to reduce the demand on resources and the amount of waste that is disposed to the landfill. Recycling is an effective way of waste management as it decreases the amount of waste that goes to the landfill and increases the value of disposed materials but there are difficulties in implementing recycling facilities. Difficulties of implementing recycling facilities include installation cost of recycling facilities which can be expensive; therefore, may not be desirable for investment, waste with economical value that may not be sufficient for such an investment, and people who may not be willing to participate in recycling or need to be educated. If it is possible to overcome those obstacles, recycling facilities have many benefits. In the master plan on SWM in Northern Cyprus, benefits of reuse and recycling are indicated as follows: reduction in reliance on energy and natural resources, reduction in waste management costs, increase in the life of landfills by diverting waste, and local employment in organisations of recycling (Master Plan on Solid Waste Management, 2007).

Troschinetz and Mihelcic (2009) summarised the factors that influence the implementation of recycling as a part of sustainable MSW management in developing countries as follows: MSW management personnel education has the highest degree of acting as a barrier against recycling (barrier in 83% of case studies), then comes the waste collection and segregation (barrier in 79% of case studies) which shows that the efficiency of collecting and separating waste is important. Other important barriers to recycling in SWM are government funds, operation costs, budget share to MSW management and the stability of finances. Household education, waste categorization and government policy are other factors that act as an obstacle against recycling in developing countries. In Northern Cyprus, the lack of government policy and absence of the budget allocation to MSW management are the major barriers of recycling. Also, there is almost no household education about recycling in Northern Cyprus.

Another method of waste management is the waste-to-energy (WTE) which includes burning food waste with other municipal wastes that are combustible in order to eliminate waste and obtain energy (Uçkun et al., 2014). It should be noted that this method has its drawbacks as food waste includes high level of moisture and when it is combusted with other wastes it produces dioxins. Also, burning food waste can cause air pollution and the chemical values of food waste are lost when burned. WTE is an expensive investment and it is the most expensive way of producing electricity (World Energy Resources: Waste-to-Energy, 2013). Moreover, WTE facilities have adverse effects on human health. Chemicals that are emitted by those facilities are resistant to degradation in the environment, form matters in living organisms and are toxic which make them the most problematic chemicals on environment and human health. Some of the chemicals that are emitted cause cancer.

The WTE facilities do not accept all waste types. Food scraps that are rich in water and glass which cannot be combusted are not accepted. The most preferable types of waste accepted to the WTE facilities are paper and plastic. Therefore, these facilities compete with recycling facilities for paper and plastic and reduce the effort of recycling. Also, incinerators require minimum waste flow through the facility and if the amount of waste generated is not enough to compensate the expenses of the facility, the government or a private company who pays for the facility may face financial problems. This can be the case for Northern Cyprus because of the small population size of the country.

Additionally, burning wastes which is a commonly applied waste management strategy in Northern Cyprus releases toxic gases and CO_2 to the environment and it contributes to global warming (UNEP, 2010). It is essential to emphasize that burning wastes in Northern Cyprus is not related with WTE as there is no energy recovery and no emission control. It is simply burning wastes inappropriately in the open air.

The last method of waste management, landfilling, is a widely used method and it will continue to be used because it is not possible to eliminate waste completely, even after treatment facilities there will be residuals that need to be landfilled.

4.1 Processing and transformation of solid waste

In order to reduce the volume and weight of waste, chemical and biological transformation processes are used (Tchobanoglous et al., 1993). Composting, Anaerobic Digestion and Mechanical Biological Treatment are biological processes whereas incineration is a chemical process. Incineration is the most commonly used type of WTE technology that involves combustion of waste. Combustion is the chemical transformation that is used the most frequently and the most commonly used biological transformation process is aerobic composting.

4.2 Management of biodegradable waste

Food waste and agricultural waste which are considered as biodegradable wastes degrade in landfills under anaerobic conditions and generate methane gas. Diverting biodegradable waste from landfills reduces greenhouse gas emissions and extends the lifetime of landfills as the amount of waste received by the landfills is reduced. Note that biodegradable waste can be used as compost. The options of biodegradable waste management include composting, mechanical biological treatment, and anaerobic digestion.

4.2.1 Composting

Composting is a natural microbiological process where wastes are broken down by bacteria. Bacteria turn wastes into simpler organic materials and mineral nutrients (called compost) which can be used to improve soil quality and help the growth of plants. Water vapour and carbon dioxide is produced at the end of composting. In Northern Cyprus, biodegradable waste can be diverted from landfills by collecting and sending vegetable and orchard wastes to composting facilities. The compost obtained from composting facilities can be used as a fertilizer in agricultural activities.

4.2.2 Mechanical Biological Treatment

Mechanical Biological Treatment (MBT) is a general term which is used for waste management practices such as Materials Recovery Facilities (MRFs), sorting and composting plant, and Refuse Derived Fuel (RDF) plant. RDF is an aerobic digestion that recovers material and energy (Erkut et al., 2008). MRFs have two options as clean and dirty MRFs. A Clean Material Recovery Facility (CMRF) processes source-separated waste whereas a Dirty Material Recovery Facility (DMRF) processes mixed waste that needs to be first separated within the facility (Minoglou and Komilis, 2013). MBT plants include different process technologies. It has been suggested that there are more than 50 different combinations of technologies that would be categorised as a MBT plant.

The outputs of MBT process include 50% as partially stabilized residue for further treatment such as composting, 20% as water vapour and carbon dioxide, 5-20% as recyclable materials, 10-25% as residues to landfill and wastewater. For Northern Cyprus, as a MBT plant would be an advanced facility, a detailed feasibility study is needed to be carried out taking into account the cost and practicality. In the master plan of SWM in Northern Cyprus, Northern Cyprus was compared with other countries with similar stage and it was stated that a MBT plant with capital cost between 50 to 60 million Euros could be implemented and this would reduce the amount of biodegradable waste that goes to landfill by 65%.

4.2.3 Anaerobic digestion

Anaerobic digestion is a method of treating sewage sludge although it can also be used for the treatment of biodegradable solid wastes. It is similar to composting as it aims to degrade biodegradable waste but it is done in the absence of air with anaerobic digestion. Final outputs of anaerobic digestion are biogas (methane gas) that can be used for generating electricity and digested sludge which can be used as a soil improver. It is a biological process where organic waste is decomposed into biogas and digested sludge. It is the only waste-to-energy technology that can be regarded as a sustainable way of generating energy from waste (World Energy Resources: Waste-to-Energy, 2013).

4.2.4 Incineration

Incineration is a method that organic and combustible waste are destructed at high temperatures in the range of 650-1100˚C (Erkut et al., 2008). The most common technology for incinerating is mass-burn which treats non-shredded, unseparated and no sized raw waste. Note that large objects like refrigerators, hazardous materials and batteries are removed before incineration. For the municipal waste that contains high moisture content, it is better to use rotary kiln incinerator. Thermal processes called pyrolysis and gasification use high temperatures to treat carbon containing waste. Three stages that are found after pyrolysis are solid, liquid and gas, then remaining hydrocarbons is broken down into fuel gas that has low calorific value and thus can be used as fuel. Burning waste produce flue gas and controlling air pollution is a problem. Pollution control equipment is highly expensive as it can constitute more than the half of the total burning cost. Using an incineration facility for municipal solid waste is the most expensive SWM option and needs qualified staff and attentive maintenance. Nevertheless, incineration facilities can remove large amounts of waste at once and generate electricity from waste.

CHAPTER 5

PROBLEM DESCRIPTION AND FORMULATION

In this chapter, the problem addressed in detail is described and its mathematical programming formulation is presented.

5.1 Problem description

According to the planned system in Northern Cyprus, municipalities will collect solid wastes with multiple collection vehicles from their regions and take the collected wastes to the nearest transfer station (TS) or to the landfill in Güngör if it is closer than the nearest TS. Using high-volume transfer vehicles, wastes are to be transferred from TSs to Güngör landfill which is the final disposal place. TSs are planned to be built in Akdoğan, Girne, Güzelyurt, İskele, Gazimağusa, and Pamuklu. Among these TSs, the one in Gazimağusa has already been built but it is not in use yet. Because the collection and transfer of solid wastes from the sources to TSs are to be performed by municipalities and the number and locations of TSs have already been determined, this part of the system is not considered in the analysis. In Figure 1 it is shown that this part is out of the system boundary.

In this study, the treatment and final disposal of wastes that are collected at TSs and Güngör landfill are considered. The aim is to determine the treatment facilities to be opened and their sizes at Güngör disposal area and the opening years of landfill Lot 2 and Lot 3 such that the total investment, operation and maintenance costs of facilities and the extension costs of landfill less the revenues from the sale of electricity and recyclable materials is minimised. The treatment facilities that are considered for the integrated SWM in Northern Cyprus are Clean Material Recovery Facility (CMRF), Dirty Material Recovery Facility (DMRF), Waste-to-Energy (WTE), Composting (CM), Anaerobic Digestion (AND), and Landfill (LF) facilities. These facilities are to be built in Güngör disposal area if they are determined to be opened. The LF Lot 1 is already in use at Güngör. When LF Lot 1 is full, LF Lot 2 is planned to be built next to LF Lot 1. Also, when both LF Lot 1 and 2 are full, LF Lot 3 is to be built on top of Lot 1 and 2. Note that the costs of building the five transfer stations, the collection of solid wastes by municipalities and the transfer of wastes from the transfer stations to Güngör landfill are not considered as these costs have no impact on the decisions of which treatment facilities to open and when to open the other Lots of Güngör landfill.

Using the classification scheme proposed by Ghiani et al. (2014), the problem studied here can be considered a T/P, L/–/PC, FC problem. This study can be considered as an extension of Minoglou and Komilis (2013), because this study considers extension of the existing landfill over multiple periods and a DMRF in addition to the other facilities, and also directly contains lower and upper limits on the size of the treatment facilities unlike Minoglou and Komilis (2013).

The planned system for the integrated SWM in Northern Cyprus is depicted in Figure 5.1, which shows that wastes coming from source (i.e., TSs) can go either to the CMRF, DMRF, AND, CM, and WTE for processing if these facilities are built or to the LF for final disposal.

The CMRF captures recyclable materials from the source separated recyclable wastes and sends these materials to recovery facilities rather than landfill or disposal sites (EPA, 2010). Similarly, the DMRF separates, processes and consolidates recyclable waste from the mixed wastes for transfer to recovery facilities (EPA, 2010). After DMRF, wastes go to either AND, CM , WTE or LF facilities. Finally, all residuals of AND, CM, and WTE facilities, and CMRF go to LF.

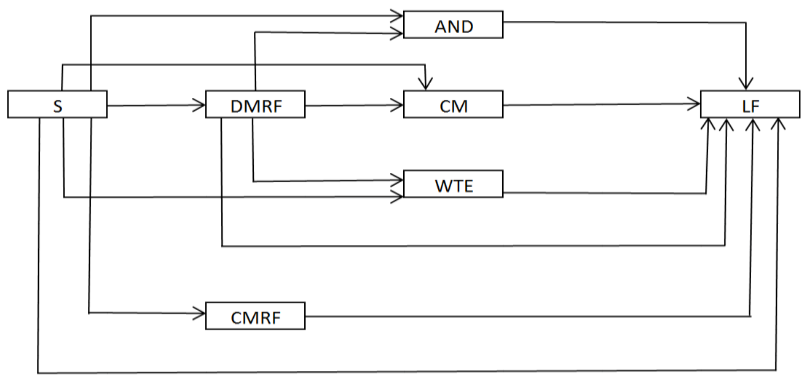

Figure 5.1 Schematic view of planned system

The capital costs, operation and maintenance (O&M) costs and size limits of the treatment facilities are given in Table 5.1, where *X* denotes the yearly amount of waste in tonnes processed by the facility. There is no biogas recovery at LF. Similarly, no methane recovery occurs at WTE and CM. Note that source separation of solid wastes by households should be done in order for a CMRF to be built. Because the cost terms belong to different years, all of them are converted to their equivalent values in 2014 using the consumer price index (CPI) values given in Table 5.1. The amount of residues based on % of inlet rate from each treatment facility is given in Table 5.2.

Table 5.1 Cost functions and size limits for treatment facilities.

Facility type	Capital cost (€)	O&M cost (€)	Facility size limits (in tonnes)
AND[a]	$35{,}000X^{0.6}$	$17{,}000X^{0.4}$	$2{,}500 \leq X \leq 100{,}000$
CM[a]	$2{,}000X^{0.8}$	$2{,}000X^{0.5}$	$2{,}000 \leq X \leq 120{,}000$
CMRF[b]	$51{,}515(X/365)^{0.73}$	Included in capital cost	$0 \leq X \leq 500{,}000$
DMRF[c]	$11{,}411X^{0.623}$	$7{,}160X^{0.458}$	$2{,}500 \leq X \leq 20{,}000$
WTE[a]	$5{,}000X^{0.8}$	$700X^{0.7}$	$50{,}000 \leq X \leq 600{,}000$

[a]: Minoglou and Komilis (2013) in 2003 prices.
[b]: Tsilemou and Panagiotakopoulos (2007) in 2006 prices. The cost term denotes total cost.
[c]: Jamasb and Nepal (2010) in 2002 prices.
[d]: CPI values used: 93.58, 95.59, 97.77, 100, 102.31, 104.73, 118.43, 120.88 in years 2002, 2003, 2004, 2005, 2006, 2007, 2012, 2014 respectively. (EUROSTAT, 2015)
[f]: Annual discount rate of 6% is used.

Table 5.2 Residues of waste components after each treatment facility in % of the inlet rate on a wet weight basis.

Component	CMRF[b]	DMRF[a]	WTE[b]	CM[b]	AND[b]
Paper (P)	30	80	11	65	75
Cardboard (CB)	30	80	16	65	75
Plastic (PL)	30	80	2	100	100
Metal (MT)	30	80	97	100	100
Glass (GL)	30	80	98	100	100
Food waste (FW)	N/A	100	1	35	45
Yard waste (YW)	N/A	100	5	50	60
Other (OTH)	N/A	100	25	100	100

[a]: Strange, 2002
[b]: Minoglou and Komilis, 2013

YAGA studied the composition of waste in Northern Cyprus and prepared a report on Solid Waste Characterisation in 2014 (YAGA, 2014). The result of the study is given in the second column of Table 5.3 as composition in % per component. The results are taken from the average of income values given in Table 3.7 in Chapter 3. Lower Heating Value (kWh/wet ton) and Methane Potential (L CH_4/wet kg) of each component are also given in Table 5.3.

Table 5.3 Chemical composition of MSW.

Component	Composition [a] (%)	Lower Heating Value [b] (kWh/wet ton)	Methane Potential [b] (LCH_4/wet kg)
Paper (P)	3.27	3930	145.8
Cardboard (CB)	6.21	3864	84.4
Plastic (PL)	13.44	10,880	0
Metal (MT)	1.94	0	0
Glass (GL)	6.57	0	0
Food waste (FW)	36.59	1,193	300.7
Yard waste (YW)	4.24	2,542	59.4
Other (OTH)	27.75	0	0

[a]: YAGA report on Solid Waste Characterisation, 2014
[b]: Minoglou and Komilis, 2013

In Table 5.4, the total quantity of MSW and quantity of other wastes in Northern Cyprus are given. The amount of waste that is collected at Güngör area is given in Chapter 3, by using the population of the municipalities that bring waste to Güngör area the amount of waste produced per person is calculated. Hence, the total amount of waste produced in Northern Cyprus is calculated by using the population and the amount of waste that is collected at Güngör. Also, the remaining capacity of LF Lot 1, total capacity of LF Lot 2 and capital cost of LF Lot 2 are given in Table 5.4. The information about the quantity of wastes, the capacity and capital cost of landfill is taken from the Ministry of Internal Affairs and Local Governments of TRNC.

Table 5.4 Quantity of wastes in Northern Cyprus, capacity of landfill in Güngör area and capital cost of landfill.

Quantity of MSW	216,502 tonnes
Quantity of other wastes [a]	76,041 tonnes
Capacity of landfill - Lot 1[b]	552,000 m^3
Capacity of landfill - Lot 2[c]	1,423,000 m^3
Capacity of landfill - Lot 3[c]	at most 2,300,000 m^3
Capital cost of landfill - Lot 2[c]	€ 2,500,000

[a]: includes commercial and industrial waste, animal wastes, hazardous wastes.
[b]: built capacity is 877,000 m^3 in April 2012; the remaining capacity is 420,960 m^3 in August 2015; estimated capacity is 242,933 m^3 at the end of 2016.
[c]: estimated by the Ministry of Internal Affairs and Local Governments of TRNC.

The default values of some parameters used in the mathematical formulation of the problem are presented in Table 5.5. These parameters are the percentage of methane in biogas, the biogas recovery efficiency of the AND facility, the lower calorific value of methane, the electrical energy conversion efficiency of the WTE and AND facilities, the market price of recycled components, MSW compost and anaerobic digestate, the revenue from the sale of one kWh electricity, and the conversion rate for converting volume into mass are given in Table 5.5.

Table 5.5 Default values of some parameters used in the mathematical formulation.

Parameter	Default value
Percentage of methane in biogas[a]	55%
AND biogas recovery (collection) efficiency[a]	100%
Lower calorific value of methane (kWh/Nm^3)[a]	10.5
Electrical energy conversion efficiency of WTE facility[a]	27%
Electrical energy conversion efficiency of AND facility[a]	33%
Market price of recycled components (€/t)	PL: 120[b], MT: 300[c], P: 0, CB: 0, GL: 0
Market price of MSW compost and anaerobic digestate (€/t)[a]	0
Revenue from the sale of 1 kWh of electrical energy[d]	0.08 €/kWh
Conversion rate for converting volume to mass (kg/m^3)[e]	1,234
Length of planning horizon (years)[a]	15

[a] Minoglou and Komilis, 2013
[b] Price suggested by a company to collect plastic wastes from METU NCC
[c] Price given to Doğan Sahir who is the secretary of Cyprus Green Action Group
[d] This amount is the price paid by Cyprus Turkish Electricity Utility (KIB-TEK) to the private sector (AKSA) for electricity generation.
[e] Conversion rate is calculated as (Annual MSW quantity brought to LF Lot 1 / ((Built capacity of LF Lot 1 – Remaining capacity of LF Lot 1) / Time between measurements in years); i.e., 164,672,440 / (877,000 – 420,960/3.417) where 3.417 years is the time between April 2012 and August 2015.

It is important to know what amount of waste remains after processing in a given treatment facility. When the wastes are directly coming from the source, the residual percentage from each facility is calculated by taking the sum of multiplications of percentage of each component in MSW by the percentages of residues of components for each facility that are given in Table 5.2. Let RPR_i be the recycling participation rate for waste component i, P_i be the percentage of component $i \in \{P, CB, PL, MT, GL, FW, YW, OTH\}$ in MSW and r_{ij} be the residual percentage of waste component $i \in \{P, CB, PL, MT, GL, FW, YW, OTH\}$ after processed by treatment facility $j \in \{AND, CM, CMRF, DMRF, WTE\}$. Then, the residual percentage R_j from a treatment facility $j \in \{AND, CM, DMRF, WTE\}$ when the wastes are directly coming from the source is calculated for $j \in \{AND, CM, DMRF, WTE\}$ as follows:

$$\begin{aligned} R_j = {} & (1 - RPR_P)P_P r_{P,j} + (1 - RPR_{CB})P_{CB} r_{CB,j} + (1 - RPR_{PL})P_{PL} r_{PL,j} \\ & + (1 - RPR_{MT})P_{MT} r_{MT,j} + (1 - RPR_{GL})P_{GL} r_{GL,j} + P_{FW} r_{FW,j} + P_{YW} r_{YW,j} \\ & + P_{OTH} r_{OTH,j} \end{aligned}$$

R_{CMRF}, on the other hand, is calculated as follows:

$$\begin{aligned} R_{CMRF} = {} & RPR_P P_P r_{P,CMRF} + RPR_{CB} P_{CB} r_{CB,CMRF} + RPR_{PL} P_{PL} r_{PL,CMRF} \\ & + RPR_{MT} P_{MT} r_{MT,CMRF} + RPR_{GL} P_{GL} r_{GL,CMRF} \end{aligned}$$

For example, if the RPR is 30% for all waste components, R_{WTE} is found as:

$$R_{WTE} = (1-0.3)(P_P \times 0.11 + P_{CB} \times 0.16 + P_{PL} \times 0.02 + P_{MT} \times 0.97 + P_{GL} \times 0.98) + P_{FW} \times 0.01 + P_{YW} \times 0.05 + P_{OTH} \times 0.25 = 0.145$$

In other words, if one unit of waste enters into the WTE facility and the RPR is 30%, only 0.145 units of waste remain which are landfilled. On the other hand, when the wastes are coming from DMRF, the wastes are further eliminated by DMRF. Thus, the residual percentage R'_j from a treatment facility $j \in \{AND, CM, WTE\}$ when the wastes are coming from DMRF is calculated as follows:

$$R'_j = (1 - RPR_P)P_P r_{P,j} r_{P,DMRF} + (1 - RPR_{CB})P_{CB} r_{CB,j} r_{CB,DMRF} + (1 - RPR_{PL})P_{PL} r_{PL,j} r_{PL,DMRF} + (1 - RPR_{MT})P_{MT} r_{MT,j} r_{MT,DMRF} + (1 - RPR_{GL})P_{GL} r_{GL,j} r_{GL,DMRF} + P_{FW} r_{FW,j} r_{FW,DMRF} + P_{YW} r_{YW,j} r_{YW,DMRF} + P_{OTH} r_{OTH,j} r_{OTH,DMRF}$$

For example, if the RPR is 30% for all waste components, R'_{WTE} is found as:

$R'_{WTE} = (1 - 0.3) \times (P_P \times 0.11 \times 0.8 + P_{CB} \times 0.16 \times 0.8 + P_{PL} \times 0.02 \times 0.8 + P_{MT} \times 0.97 \times 0.8 + P_{GL} \times 0.98 \times 0.8) + P_{FW} \times 0.01 \times 1 + P_{YW} \times 0.05 \times 1 + P_{OTH} \times 0.25 \times 1 = 0.131$

In other words, if one unit of waste enters first into DMRF and then into the WTE facility with a RPR of 30% for all waste components, only 0.131 units of waste remain which are landfilled.

5.2 Mathematical formulation of the problem

We formulate the problem as a mixed integer nonlinear programming model in the following. First, we define the parameters and decision variables used in the model.

Indices

i: denotes the components of MSW; $i = 1$ for Paper, $i = 2$ for Cardboard, $i = 3$ for Plastic, $i = 4$ for Metal, $i = 5$ for Glass, $i = 6$ for Food Waste, $i = 7$ for Yard Waste, and $i = 8$ for Other Wastes.

j: denotes the facilities; $j = 1$ for AND, $j = 2$ for CM, $j = 3$ for CMRF, $j = 4$ for DMRF, $j = 5$ for WTE, and $j = 6$ for LF.

t: denotes the years

Parameters

C_{Lot2}: Capital cost of landfill Lot 2

C_{Lot3}: Capital cost of landfill Lot 3

CPI_t: Consumer price index value for year $t \in \{2002,2003,2006,2014\}$

D (tonnes): Total amount of MSW in Northern Cyprus

D_R: Discount rate

ε_1: Electrical energy conversion efficiency for the AND facility

ε_5: Electrical energy conversion efficiency for the WTE facility

L_j: Lower limit on the size of treatment facility $j \in \{1,2,3,4,5\}$

LHV_i: Lower heating value of waste component *i*

LCV (kWh/N$m^3 CH_4$): Lower calorific value of methane

M_i: Market price of recyclable component $i \in \{1,2,3,4,5\}$

MP_i: Methane potential of component *i*

OTW (tonnes): The amount of other wastes in Northern Cyprus

P/A: Present value factor to convert annual values into present value ($\frac{(1+D_R)^{T-1}}{D_R(1+D_R)^T}$)

P_i: Percentage of waste component *i* in MSW

Q_{Lot1} (m^3): Capacity of landfill Lot 1

Q_{Lot2} (m^3): Capacity of landfill Lot 2

Q_{Lot3} (m^3): Capacity of landfill Lot 3

rev: Revenue from the sale of 1 kWh of electrical energy generated

RPR_i: Recycling participation rate for waste component *i*

R_j: Residual percentage for treatment facility $j \in \{1,2,3,4,5\}$ if wastes are directly coming from source

R'_j: Residual percentage for treatment facility $j \in \{1,2,5\}$ if wastes are coming from DMRF

r_{ij}: Residual percentage of waste component *i* after processed by treatment facility *j*

T: Length of planning horizon in years

U_j: Upper limit on the size of treatment facility $j \in \{1,2,3,4,5\}$

Decision Variables:

$X_{S,j}$: Amount of waste to be sent from source to facility $j \in \{1, 2, 3, 4, 5, 6\}$

$X_{4,j}$: Amount of waste to be sent from DMRF to treatment facility $j \in \{1, 2, 5\}$

$X_{j,6}$: Amount of waste to be sent from treatment facility $j \in \{1, 2, 3, 4, 5\}$ to landfill

Y_j: Binary variable which is equal to 1 if facility *j* is opened and 0 otherwise.

Z_{2t}: Binary variable which is equal to 1 if landfill Lot 2 is constructed in year *t*, and 0 otherwise.

Z_{3t}: Binary variable which is equal to 1 if landfill Lot 3 is constructed in year *t*, and 0 otherwise.

$$\text{Min } -P/A \times D \times \sum_{i=1}^{5} RPR_i(1-r_{i3})\, M_i\, P_i - P/A \times X_{S,4} \times \sum_{i=1}^{5}(1-RPR_i)(1-r_{i4})\, M_i\, P_i - P/A \times rev \times \varepsilon_5 \times X_{S,5} \times \sum_{i=1}^{8}(1-RPR_i)(1-r_{i5})P_i LHV_i - P/A \times rev \times \varepsilon_5 \times X_{4,5} \times \sum_{i=1}^{8}(1-RPR_i)r_{i4}(1-r_{i5})P_i LHV_i - P/A \times rev \times LCV \times \varepsilon_1 \times (X_{S,1} \times \sum_{i=1}^{8}(1-RPR_i)MP_i(1-r_{i1})P_i + X_{4,1} \times \sum_{i=1}^{8}(1-RPR_i)MP_i(1-r_{i1})P_i\, r_{i4}) + (CPI_{2014}/CPI_{2003}) \times 35{,}000\left(X_{S,1}+X_{4,1}\right)^{0.6} + (CPI_{2014}/CPI_{2003}) \times 2{,}000\left(X_{S,2}+X_{4,2}\right)^{0.8} + (CPI_{2014}/CPI_{2006}) \times 51{,}515\left(X_{S,3}/365\right)^{0.73} + (CPI_{2014}/CPI_{2002}) \times 11{,}411\left(X_{S,4}\right)^{0.623} + (CPI_{2014}/CPI_{2003}) \times 5{,}000(X_{S,5}+X_{4,5})^{0.8} + \frac{P}{A} \times \left((CPI_{2014}/CPI_{2003}) \times 17{,}000\left(X_{S,1}+X_{4,1}\right)^{0.4} + (CPI_{2014}/CPI_{2003}) \times 2{,}000\left(X_{S,2}+X_{4,2}\right)^{0.5} + (CPI_{2014}/CPI_{2002}) \times 7{,}160\left(X_{S,4}\right)^{0.458} + (CPI_{2014}/CPI_{2003}) \times 700\left(X_{S,5}+X_{4,5}\right)^{0.7}\right) + C_{Lot2} \times \sum_{t=1}^{T} Z_{2t}/(1+D_R)^t + C_{Lot3} \times \sum_{t=1}^{T} Z_{3t}/(1+D_R)^t \quad (1)$$

Subject to

$$\sum_{\substack{j=1 \\ j\neq 3}}^{6} X_{S,j} = D \times \left(1 - \sum_{i=1}^{5} RPR_i P_i\right) \quad (2)$$

$$X_{S,3} = D \times \sum_{i=1}^{5} RPR_i P_i \quad (3)$$

$$R_3 \times X_{S,3} = X_{3,6} \quad (4)$$

$$R_4 \times X_{S,4} = X_{4,1} + X_{4,2} + X_{4,5} + X_{4,6} \quad (5)$$

$$R_j \times X_{S,j} + R'_j \times X_{4,j} = X_{j,6} \qquad \forall j \in \{1,2,5\} \quad (6)$$

$$t \times \left(X_{S,6} + \sum_{j=1}^{5} X_{j,6}\right) \le Q_{Lot1} - (t \times OTW) + \sum_{k=1}^{t} Q_{Lot2}\, Z_{2k} + \sum_{k=1}^{t} Q_{Lot3}\, Z_{3k} \qquad \forall\, 1 \le t \le T \quad (7)$$

$$\sum_{t=1}^{T} Z_{2t} \le 1 \quad (8)$$

$$\sum_{t=1}^{T} Z_{3t} \le 1 \quad (9)$$

$$Z_{3t} \le \sum_{k=1}^{t} Z_{2k} \qquad \forall\, 1 \le t \le T \quad (10)$$

$$L_j Y_j \le X_{S,j} \le U_j Y_j \qquad \forall\, j \in \{3,4\} \quad (11)$$

$$L_j Y_j \le X_{S,j} + X_{4,j} \le U_j Y_j \qquad \forall\, j \in \{1,2,5\} \quad (12)$$

$$X_{S,j} \ge 0 \qquad \forall j \in \{1,2,3,4,5,6\} \quad (13)$$

$X_{4,j} \geq 0$ $\forall j \in \{1,2,5\}$ (14)

$X_{j,6} \geq 0$ $\forall j \in \{1,2,3,4,5\}$ (15)

$Y_j \in \{0,1\}$ $\forall j \in \{1,2,3,4,5\}$ (16)

$Z_{2t}, Z_{3t} \in \{0,1\}$ $\forall\, 1 \leq t \leq T.$ (17)

The objective function (1) minimizes the total cost of the system less revenues. In the objective function, the first two terms calculate the revenue from the sale of recyclable materials by multiplying percentage of waste components, market price, RPR, and the percentage of components processed by CMRF and DMRF, respectively. Note that multiplication with P/A would take the annual recurring values to their equivalent present worth. The third and fourth terms are for the calculation of revenue from the sale of electricity generated by the WTE facility In this case, the sum of the waste that goes from source to WTE and from DMRF to WTE is multiplied by the percentage of each waste component, lower heating value for each waste component, electrical conversion efficiency of incineration facility and revenue from the sale of one kWh of electrical energy generated by the WTE facility in Northern Cyprus. The fifth term calculates the revenue from the sale of electricity from the AND facility. For the revenue from the sale of electricity generated by the AND facility, the amount of waste flow from source (DMRF) to the AND facility is multiplied by the AND removal percentage for each waste component for the wastes coming from source (DMRF), methane potential for each waste type, electrical energy conversion efficiency of the AND facility, lower calorific value of methane and revenue from the sale of one kWh of electrical energy generated by the AND facility in Northern Cyprus. In the next five terms, investment costs of AND, CM, CMRF, DMRF, and WTE facilities are added to the total cost, respectively. These terms are followed by adding the operation and maintenance costs of AND, CM, DMRF, and WTE facilities, respectively. The landfill extension costs for Lot 2 and Lot 3 are the last two terms in the objective function, respectively.

Note that all values are converted into 2014 values. Eqs. (2) – (6) are the flow balance equations of the system. Equation (3) ensures that the amount of waste that goes from source to CMRF includes only recyclable wastes (P, CB, PL, GL, MT). Equations (4) - (6) make sure that the amounts of residuals from each facility (CMRF, DMRF, AND, CM, WTE) are equal to the amount of waste that goes from the facilities to the landfill. Constraints (7) ensure that the total amount of waste that goes to LF from each facility is not bigger than the sum of the capacity of LF Lot 1 (remaining capacity), Lot 2 and Lot 3. Constraints (8) and

(9) ensure that landfill Lot 2 and Lot 3 can be opened at most once over the planning horizon, respectively. Constraints (10) guarantee that landfill Lot 3 cannot be opened before landfill Lot 2. Constraints (11) and (12) ensure that lower and upper limits of each facility are not exceeded. Constraints (13)–(15) are for nonnegativity of variables whereas constraints (16)–(17) are for the integrality of variables. Specifically, constraints (16) and (17) make sure that if a facility is opened it takes the value 1 in the model, and 0 otherwise.

CHAPTER 6

RESULTS AND DISCUSSIONS

In this chapter, the MINLP model proposed in Chapter 5 is applied to the SWM problem of Northern Cyprus. Several cases in seven scenarios are analysed to provide managerial insights regarding the SWM problem of Northern Cyprus. The impact of increase in total waste amount on the system is also analysed. The MINLP models constructed for all cases are solved using Opensolver Advanced 2.7.1 (Mason, 2012), which is an open source MINLP solver add-in for Microsoft Excel and available for free. All models are solved within a few seconds on a Windows PC with a 1.6 Ghz CPU and 4 GB RAM. The RPR is considered the same for all waste components in all cases. The results are presented in the following.

6.1 Scenario 1

In the first scenario, the RPR is varied in order to observe the impact of RPR on the proposed system and its cost. Therefore, the RPR is varied between 0% and 75% with a step size of 5%. The capacity of landfill Lot 3 is actually unknown but it is known that once Lot 1 and Lot 2 are full, Lot 3 will be built on top of them. Therefore, various predictions are made about the capacity of Lot 3. In this scenario, the capacity of landfill Lot 3 is considered to be exactly the same size as the sum of the sizes of Lot 1 and Lot 2.

Detailed information about the results of the cases of first scenario is given in Table 6.1. In this table, the first column shows the RPR, the second column the objective function value found, third column opening year of landfill Lot 3, columns 4–6 the amount of waste in tonnes that goes from source to the CMRF facility, from source to landfill, and from CMRF to landfill, respectively, seventh column the amount to be paid for opening landfill Lot 2, eighth column the amount to be paid for opening landfill Lot 3, ninth column the revenue obtained from the sale of recyclable materials, and lastly columns 11–12 operation and maintenance costs of landfill and investment as well as O&M cost of CMRF facility, respectively.

The objective function values found for each value of the RPR are displayed in Figure 6.1. The key comments from Figure 6.1 and Table 6.1 are as follows:

- The objective function value ranges from €14,764,276 to – €8,956,123 in this scenario. The RPR plays a significant role in the decrease of the total cost of the system. The total cost decreases approximately at a linear rate as the RPR increases. The total cost is €14,764,276 when the RPR is 0% whereas the former decreases to – €8,956,123 (i.e., profit rather cost) when the latter is 75%. Thus, profit is obtained from the SWM system when the RPR is greater than or equal to 50%.

- Regardless of the RPR, the WTE facility is never opened in this scenario. This result is due to having sufficient landfill capacity and the high cost of WTE facilities. The availability of landfill area and not opening a WTE facility have a significant role in the dramatic decrease of the total cost because the WTE facility is quite expensive while it is very effective for reducing the amount of waste to be disposed. As will be seen in the forthcoming sections, in other scenarios where WTE facility is opened, the total cost is much higher compared to the first scenario.

- As the RPR increases, the amount of waste that goes from source to CMRF and from CMRF to LF increases whereas the amount that goes from source to LF decreases.

- Landfill Lot 2 should be opened in year 2 and Lot 3 should be opened in year 8 when the RPR varies between 0% and 55%. If the RPR is greater than or equal to 60%, the lifetime of Lot 3 increases by one year and thus, Lot 3 should be opened in year 9.

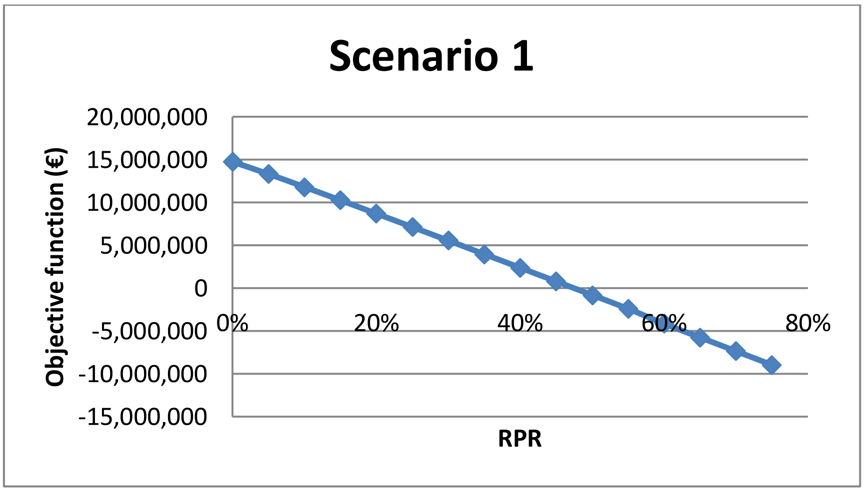

Figure 6.1 Objective function value with respect to the RPR in scenario 1

Table 6.1 Results of scenario 1

RPR	Objective Function (€)	Lot 3 opening year	$X_{S,CMRF}$	$X_{S,LF}$	$X_{CMRF,LF}$	Landfill extension cost Lot 2 (€)	Landfill extension cost Lot 3 (€)	Sale of recyclables (€)	Landfill O&M cost (€)	Investment cost of CMRF (€)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
0%	14,764,276	8	0	216,502	0	2,224,991	2,535,222	0	10,004,063	0
5%	13,349,730	8	3,402	213,100	16	2,224,991	2,535,222	1,615,268	9,894,284	310,501
10%	11,829,737	8	6,805	209,697	64	2,224,991	2,535,222	3,230,535	9,784,955	515,064
15%	10,283,133	8	10,207	206,295	144	2,224,991	2,535,222	4,485,802	9,676,266	692,456
20%	8,721,471	8	13,609	202,893	257	2,224,991	2,535,222	6,461,070	9,568,069	854,259
25%	7,149,671	8	17,012	199,490	401	2,224,991	2,535,222	8,076,337	9,460,375	1,005,420
30%	5,570,396	8	20,414	196,088	577	2,224,991	2,535,222	9,691,605	9,353,254	1,148,534
35%	3,985,336	8	23,816	192,686	786	2,224,991	2,535,222	11,285,318	9,246,677	1,285,318
40%	2,395,636	8	27,219	189,283	1,027	2,224,991	2,535,222	12,922,140	9,140,617	1,416,945
45%	802,104	8	30,621	185,881	1,299	2,224,991	2,535,222	14,537,407	9,035,144	1,544,153
50%	-794,637	8	34,023	182,479	1,604	2,224,991	2,535,222	16,152,675	8,930,230	1,667,594
55%	-2,394,106	8	37,426	179,076	1,941	2,224,991	2,535,222	17,767,942	8,825,848	1,787,775
60%	-4,139,430	9	40,828	175,674	2,310	2,224,991	2,391,719	19,383,210	8,722,067	1,905,003
65%	-5,743,288	9	44,230	172,272	2,711	2,224,991	2,391,719	20,998,477	8,618,859	2,019,620
70%	-7,348,924	9	47,663	168,869	3,144	2,224,991	2,391,719	22,613,745	8,516,199	2,131,911
75%	-8,956,123	9	51,035	165,467	3,609	2,224,991	2,391,719	24,229,012	8,414,156	2,242,023

*Landfill Lot 2 is opened in year 2 in each case

6.2 Scenario 2

In scenario 2, the capacity of Lot 3 is considered as 90% of the sum of the sizes of Lot 1 and Lot 2 and the RPR varies from 0% to 75% with a step size of 5%. The results of Scenario 2 are similar to the results of Scenario 1. The objective function value varies between €14,510,754 and – €9,195,295, and it decreases as the RPR increases.

Here, the extension cost of landfill Lot 3 is lower than the cost in scenario 1 as the extension cost of Lot 3 depends on its size. As the extension cost of landfill Lot 3 is lower, the total cost in the results of this Scenario slightly decreased compared to Scenario 1. Similar to the results in Scenario 1, as the RPR increases the amount of waste that is sent from source to CMRF facility increases.

The results are shown in Figure 6.2 and Table 6.2.

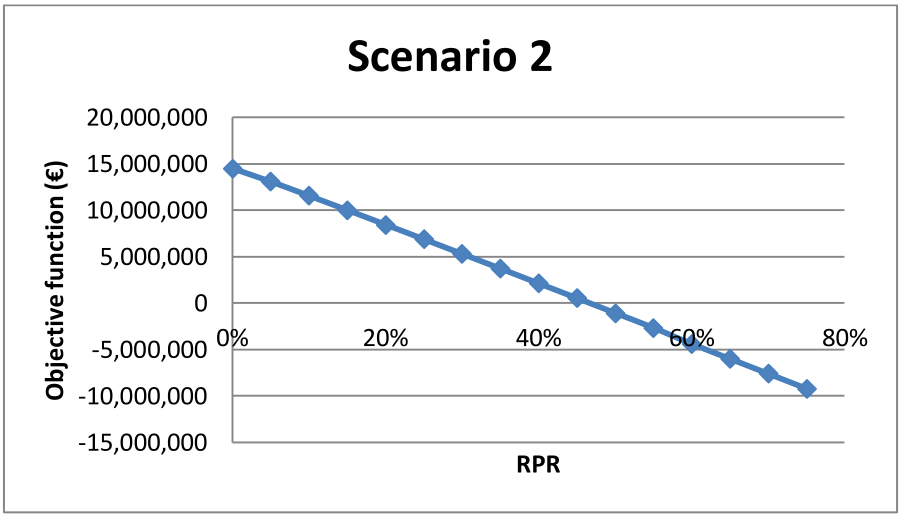

Figure 6.2 Objective function value with respect to the RPR in scenario 2

Table 6.2 Results of scenario 2

RPR	Objective Function (€)	Lot 3 opening year	$X_{S,CMRF}$	$X_{S,LF}$	$X_{CMRF,LF}$	Landfill extension cost Lot 2 (€)	Landfill extension cost Lot 3 (€)	Sale of recyclables (€)	Landfill O&M cost (€)	Investment cost of CMRF (€)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
0%	14,510,754	8	0	216,502	0	2,224,991	2,281,700	0	10,004,063	0
5%	13,096,208	8	3,402	213,100	16	2,224,991	2,281,700	1,615,268	9,894,284	310,501
10%	11,576,215	8	6,805	209,697	64	2,224,991	2,281,700	3,230,535	9,784,995	515,064
15%	10,029,611	8	10,207	206,295	144	2,224,991	2,281,700	4,845,802	9,676,266	692,456
20%	8,467,949	8	13,609	202,893	257	2,224,991	2,281,700	6,461,070	9,568,069	854,259
25%	6,896,149	8	17,012	199,490	401	2,224,991	2,281,700	8,076,337	9,460,375	1,005,420
30%	5,316,874	8	20,414	196,088	577	2,224,991	2,281,700	9,691,605	9,353,254	1,148,534
35%	3,731,814	8	23,816	192,686	786	2,224,991	2,281,700	11,285,318	9,246,677	1,285,318
40%	2,142,114	8	27,219	189,283	1,027	2,224,991	2,281,700	12,922,140	9,140,617	1,416,945
45%	548,582	8	30,621	185,881	1,299	2,224,991	2,281,700	14,537,407	9,035,144	1,544,153
50%	-1,048,160	8	34,023	182,479	1,604	2,224,991	2,281,700	16,152,675	8,930,230	1,667,594
55%	-2,647,628	8	37,426	179,076	1,941	2,224,991	2,281,700	17,767,942	8,825,848	1,787,775
60%	-4,378,602	9	40,828	175,674	2,310	2,224,991	2,152,547	19,383,210	8,772,067	1,905,003
65%	-5,982,460	9	44,230	172,272	2,711	2,224,991	2,152,547	20,998,477	8,618,859	2,019,620
70%	-7,588,096	9	47,663	168,869	3,144	2,224,991	2,152,547	22,613,745	8,516,199	2,131,911
75%	-9,195,295	9	51,035	165,467	3,609	2,224,991	2,152,547	24,229,012	8,414,156	2,242,023

*Landfill Lot 2 is opened in year 2 in each case

6.3 Scenario 3

The size of Lot 3 is taken as 80% of the sum of the sizes of Lot 1 and Lot 2 in this scenario. The RPR varies as in the previous scenarios. The results of this scenario are given in Figure 6.3 and Table 6.3. Main highlights of this scenario are as follows:

- The objective function value varies between €22,314,116 and – €9,434,467. There is a higher rate of decrease in the objective function value when the RPR increases from 0% to 10% compared to the rate of decrease when the RPR increases from 10% to 75%

- The WTE facility is never opened regardless of the RPR.

- The opening years of Lot 2 and Lot 3 are the same as in scenarios 1 and 2.When the RPR is 0% or 5%, a CM facility is opened whereas the CM facility is never opened if the RPR is greater than 5%. This result reveals that a high participation to recycling eliminates the need for the CM facility and reduces the total cost.

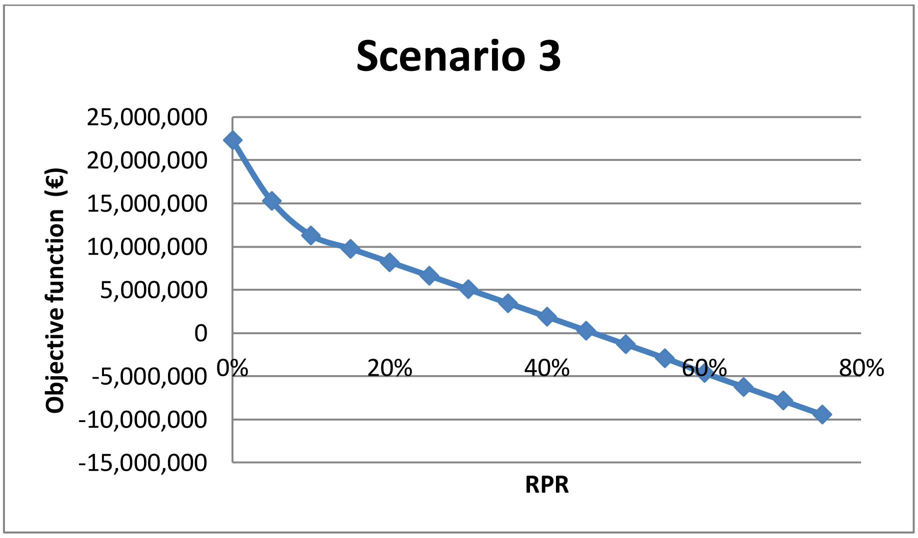

Figure 6.3 Objective function value with respect to the RPR in scenario 3

Table 6.3 Results of scenario 3

RPR	Objective Function (€)	Lot 3 opening year	Landfill extension cost Lot 2 (€)	Landfill extension cost Lot 3 (€)	Sale of recyclables (€)	Landfill O&M cost (€)	Investment cost of CMRF (€)	Cost of CM (€)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0%	22,314,116	8	2,224,991	2,028,178	0	9,870,522	0	8,190,425
5%	15,293,183	8	2,224,991	2,028,178	1,615,268	9,870,522	310,501	2,474,260
10%	11,322,693	8	2,224,991	2,028,178	3,230,535	9,784,995	515,064	0
15%	9,776,088	8	2,224,991	2,028,178	4,845,802	9,676,266	692,456	0
20%	8,214,427	8	2,224,991	2,028,178	6,461,070	9,568,069	854,259	0
25%	6,642,627	8	2,224,991	2,028,178	8,076,337	9,460,375	1,005,420	0
30%	5,063,351	8	2,224,991	2,028,178	9,691,605	9,353,254	1,148,534	0
35%	3,478,291	8	2,224,991	2,028,178	11,306,872	9,246,677	1,285,318	0
40%	1,888,591	8	2,224,991	2,028,178	12,922,140	9,140,617	1,416,945	0
45%	295,059	8	2,224,991	2,028,178	14,537,407	9,035,144	1,544,153	0
50%	-1,301,682	8	2,224,991	2,028,178	16,152,675	8,930,230	1,667,594	0
55%	-2,901,151	8	2,224,991	2,028,178	17,767,942	8,825,848	1,787,775	0
60%	-4,617,774	9	2,224,991	1,913,375	19,383,210	8,722,067	1,905,003	0
65%	-6,221,632	9	2,224,991	1,913,375	20,998,477	8,618,859	2,019,620	0
70%	-7,827,268	9	2,224,991	1,913,375	22,613,745	8,516,199	2,131,911	0
75%	-9,434,467	9	2,224,991	1,913,375	24,229,012	8,414,156	2,242,023	0

*Landfill Lot 2 is opened in year 2 in each case

Table 6.3 Continued

RPR	Objective Function (€)	Lot 3 opening year	$X_{S,CMRF}$	$X_{CM,LF}$	$X_{S,CM}$	$X_{S,LF}$	$X_{CMRF,LF}$
0%	22,314,116	8	0	9,976	14,093	202,409	0
5%	15,293,183	8	3,402	1,656	2,387	210,713	16
10%	11,322,693	8	6,805	0	0	209,697	64
15%	9,776,088	8	10,207	0	0	206,295	144
20%	8,214,427	8	13,609	0	0	202,893	257
25%	6,642,627	8	17,012	0	0	199,490	401
30%	5,063,351	8	20,414	0	0	196,088	577
35%	3,478,291	8	23,816	0	0	192,686	786
40%	1,888,591	8	27,219	0	0	189,283	1,027
45%	295,059	8	30,621	0	0	185,881	1,299
50%	-1,301,682	8	34,023	0	0	182,479	1,604
55%	-2,901,151	8	37,426	0	0	179,076	1,941
60%	-4,617,774	9	40,828	0	0	175,674	2,310
65%	-6,221,632	9	44,230	0	0	172,272	2,711
70%	-7,827,268	9	47,633	0	0	168,869	3,144
75%	-9,434,467	9	51,035	0	0	165,467	3,609

*Landfill Lot 2 is opened in year 2 in each case

6.4 Scenario 4

In scenario 4, the capacity of Lot 3 is considered as 70% of the sum of the sizes of Lot 1 and Lot 2 and as in the previous scenarios, the RPR changes between 0% and 75% with a step size of 5%. The results are shown in Figure 6.4 and Table 6.4. Main results of this scenario are given as follows:

- When the RPR varies between 0% and 20% a WTE facility is opened and in this case landfill Lot 3 is opened in year 9. Also, the objective function varies between €41,681,261and €39,234,150 when the WTE facility is opened.
- When the RPR increases to 25% or 35%, a CM facility is opened. Total cost is €15,785,601 when the RPR is 25% and €5,403,245 when it is 35%.
- When the RPR increases from 20% to 25%, the WTE facility is closed and the CM facility is opened. It is clear that closing the WTE facility and opening the CM facility with the 5% more participation to recycling resulted in a sharp decrease in the total cost from €39,234,150 to €15,785,601.
- Lot 3 is opened in year 8 when the RPR changes between 25% and 55%, because the WTE facility is closed.
- When the RPR increases to 60% or above, the capacity of Lot 3 is used less and it is opened in year 9 instead of year 8.

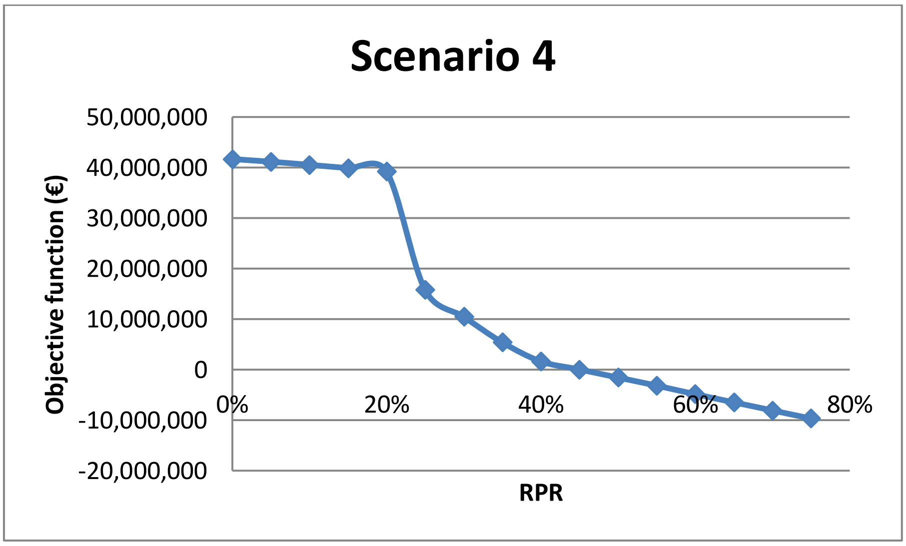

Figure 6.4 Objective function value with respect to the RPR in scenario 4

Table 6.4 Results of scenario 4

RPR	Objective Function (€)	Lot 3 opening year	Landfill extension cost Lot 2 (€)	Landfill extension cost Lot 3 (€)	Sale of recyclables (€)	Sale of electricity (WTE) (€)	Landfill O&M cost (€)	Cost of CM (€)	Investment cost of CMRF (€)	Cost of WTE (€)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
0%	41,681,261	9	2,224,991	1,674,203	0	23,896,016	8,627,414	0	0	53,050,669
5%	41,165,951	9	2,224,991	1,674,203	1,615,268	22,980,905	8,501,760	0	310,501	53,050,669
10%	40,544,987	9	2,224,991	1,674,203	3,230,535	22,065,795	8,376,390	0	515,064	53,050,669
15%	39,897,204	9	2,224,991	1,674,203	4,845,802	21,150,684	8,251,372	0	692,456	53,050,669
20%	39,234,150	9	2,224,991	1,674,203	6,461,070	20,235,574	8,126,671	0	854,259	53,050,669
25%	15,785,601	8	2,224,991	1,774,656	8,076,337	0	9,246,408	9,610,464	1,005,420	0
30%	10,489,446	8	2,224,991	1,774,656	9,691,605	0	9,246,408	5,786,462	1,148,534	0
35%	5,403,245	8	2,224,991	1,774,656	11,306,872	0	9,220,532	2,204,621	1,285,318	0
40%	1,635,069	8	2,224,991	1,774,656	12,922,140	0	9,140,617	0	1,416,945	0
45%	41,537	8	2,224,991	1,774,656	14,537,407	0	9,035,144	0	1,544,153	0
50%	-1,555,204	8	2,224,991	1,774,656	16,152,675	0	8,930,230	0	1,667,594	0
55%	-3,154,673	8	2,224,991	1,774,656	17,767,942	0	8,825,848	0	1,787,775	0
60%	-4,856,946	9	2,224,991	1,674,203	19,383,210	0	8,722,067	0	1,905,003	0
65%	-6,460,803	9	2,224,991	1,674,203	20,998,477	0	8,618,859	0	2,019,620	0
70%	-8,066,440	9	2,224,991	1,674,203	22,613,745	0	8,516,199	0	2,131,911	0
75%	-9,673,639	9	2,224,991	1,674,203	24,229,012	0	8,414,156	0	2,242,023	0

*Landfill Lot 2 is opened in year 2 in each case

Table 6.4 Continued

RPR	Objective Function in (€)	Lot 3 opening year	$X_{S,WTE}$	$X_{S,CMRF}$	$X_{CM,LF}$	$X_{S,CM}$	$X_{S,LF}$	$X_{WTE,LF}$	$X_{CMRF,LF}$
0%	41,681,261	9	50,000	0	0	0	166,502	8,729	0
5%	41,165,951	9	50,000	3,402	0	0	163,100	8,480	16
10%	40,544,987	9	50,000	6,805	0	0	159,697	8,232	64
15%	39,897,204	9	50,000	10,207	0	0	156,295	7,983	144
20%	39,234,150	9	50,000	13,609	0	0	152,893	7,735	257
25%	15,785,601	8	0	17,012	11,308	17,735	181,755	0	401
30%	10,489,446	8	0	20,414	5,303	8,505	187,583	0	1,925
35%	5,403,245	8	0	23,816	1,219	5,024	190,686	0	786
40%	1,635,069	8	0	27,219	0	0	189,283	0	1,027
45%	41,537	8	0	30,621	0	0	185,881	0	1,299
50%	-1,555,204	8	0	34,023	0	0	182,479	0	1,604
55%	-3,154,673	8	0	37,426	0	0	179,076	0	1,941
60%	-4,856,946	9	0	40,828	0	0	175,674	0	2,310
65%	-6,460,803	9	0	44,230	0	0	172,272	0	2,711
70%	-8,066,440	9	0	47,633	0	0	168,869	0	3,144
75%	-9,673,639	9	0	51,035	0	0	165,467	0	3,609

*Landfill Lot 2 is opened in year 2 in each case

6.5 Scenario 5

In this scenario, the size of Lot 3 is taken as 60% of the sum of the sizes of Lot 1 and Lot 2 and the RPR varies between 0% and 75% with a step size of 5%. The results of scenario can be seen in Figure 6.5 and Table 6.5. Key results of this scenario are as follows:

- The total cost varies between €41,698,457 and €35,484,008 when the RPR is between 0% and 45%. The total cost is high due to the opening of a WTE facility for this range of RPR. A CM facility is opened when the RPR is between 50% and 65%. When the CM facility is opened, the objective function value varies between €8,971,770 and – €4,528,125. When the RPR is greater than or equal to 70%, neither a CM facility nor a WTE facility is opened, all wastes go to the CMRF and LF, and a profit in the range of €8,305,612 and €9,912,811 is obtained.
- When the RPR exceeds 50%, a dramatic decrease in the objective function value occurs.
- Lot 3 is opened in year 9 when the RPR is between 0% and 30%; when the rate is between 35% and 45%, it is opened in year 10; and when it is between 50% and 75%, it is opened in year 9. The extension of the lifetime of Lot 3 by one year when the RPR is between 35% and 45% is due to the opening of a WTE facility and the high RPR.

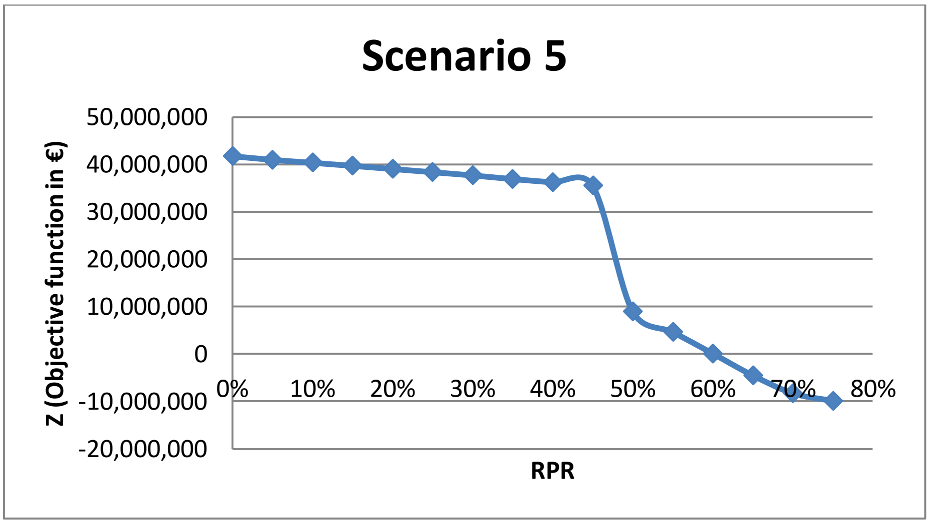

Figure 6.5 Objective function value with respect to the RPR in scenario 5

Table 6.5 Results of scenario 5

RPR	Objective Function (€)	Lot 3 opening in year	Landfill extension cost Lot 2 (€)	Landfill extension cost Lot 3 (€)	Sale of recyclables (€)	Sale of electricity (WTE) (€)	Landfill O&M cost (€)	Cost of CM (€)	Investmen t cost of CMRF (€)	Cost of WTE (€)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
0%	41,698,457	9	2,224,991	1,435,031	0	24,294,582	8,603,676	0	0	53,729,341
5%	40,926,779	9	2,224,991	1,435,031	1,615,668	22,980,905	8,501,760	0	310,501	53,050,669
10%	40,305,815	9	2,224,991	1,435,031	3,230,535	22,065,795	8,376,390	0	515,064	53,050,669
15%	39,658,032	9	2,224,991	1,435,031	4,845,802	21,150,684	8,251,372	0	692,456	53,050,669
20%	38,994,978	9	2,224,991	1,435,031	6,461,070	20,235,574	8,126,671	0	854,259	53,050,669
25%	38,321,563	9	2,224,991	1,435,031	8,076,337	19,320,463	8,002,252	0	1,005,420	53,050,669
30%	37,640,451	9	2,224,991	1,435,031	9,691,605	18,405,353	7,878,183	0	1,148,534	53,050,669
35%	36,872,094	10	2,224,991	1,353,803	11,306,872	17,490,242	7,754,428	0	1,285,318	53,050,669
40%	36,180,087	10	2,224,991	1,353,803	12,922,140	16,575,132	7,630,951	0	1,416,945	53,050,669
45%	35,484,008	10	2,224,991	1,353,803	14,537,407	15,660,021	7,507,820	0	1,544,153	53,050,669
50%	8,971,770	9	2,224,991	1,435,031	16,152,675	0	8,603,676	11,193,153	1,667,594	0
55%	4,634,368	9	2,224,991	1,435,031	17,767,942	0	8,603,676	8,350,837	1,787,775	0
60%	81,762	9	2,224,991	1,435,031	19,383,210	0	8,603,676	5,296,270	1,905,003	0
65%	-4,528,125	9	2,224,991	1,435,031	20,998,477	0	8,586,089	2,204,621	2,019,620	0
70%	-8,305,612	9	2,224,991	1,435,031	22,613,745	0	8,516,199	0	2,131,911	0
75%	-9,912,811	9	2,224,991	1,435,031	24,229,012	0	8,414,156	0	2,242,023	0

*Landfill Lot 2 is opened in year 2 in each case

Table 6.5 Continued

RPR	**Objective Function (€)**	**Lot 3 opening year**	$X_{S,WTE}$	$X_{S,CMRF}$	$X_{CM,LF}$	$X_{S,CM}$	$X_{S,LF}$	$X_{WTE,LF}$	$X_{CMRF,LF}$
0%	41,698,457	9	50,834	0	0	0	165,668	8,875	0
5%	40,926,779	9	50,000	3,402	0	0	163,100	8,480	16
10%	40,305,815	9	50,000	6,805	0	0	159,697	8,232	64
15%	39,658,032	9	50,000	10,207	0	0	156,295	7,983	144
20%	38,994,978	9	50,000	13,609	0	0	152,893	7,735	257
25%	38,321,563	9	50,000	17,012	0	0	149,490	7,486	401
30%	37,640,451	9	50,000	20,414	0	0	146,088	7,238	577
35%	36,872,094	10	50,000	23,816	0	0	142,686	6,989	2786
40%	36,180,087	10	50,000	27,219	0	0	139,283	6,740	1,027
45%	35,484,008	10	50,000	30,621	0	0	135,881	6,492	1,299
50%	8,971,770	9	0	34,023	12,509	22,050	160,429	0	1,604
55%	4,634,368	9	0	37,426	8,018	14,493	164,583	0	1,941
60%	81,762	9	0	40,828	4,027	7,468	168,206	0	2,310
65%	-4,528,125	9	0	44,230	1,050	2,000	170,272	0	2,711
70%	-8,305,612	9	0	47,633	0	0	168,869	0	3,144
75%	-9,912,811	9	0	51,035	0	0	165,467	0	3,609

*Landfill Lot 2 is opened in year 2 in each case

6.6 Scenario 6

In this scenario, the capacity of Lot 3 is taken as 50% of the sum of the sizes of Lot 1 and Lot 2 and the same RPRs are considered as in previous scenarios. The results are shown in Figure 6.6 and Table 6.6. The main results can be summarised as follows:

- As shown in Figure 6.6, the cost of waste management remains high compared to the previous results as the WTE facility is opened for all rates of recycling participation. Here, the total cost of the system varies between €47,642,843 and €30,959,038.
- When the WTE facility remains opened and combined with CMRF, the lifetime of Lot 3 is extended by two years. Lot 3 is opened in year 9 when the RPR is between 0% and 30%; in year 10 when the rate is between 35% and 65%; and in year 11 when the rate is between 70% and 75%. The WTE facility is an expensive option but it is effective for expanding the lifetime of the landfill.
- It is observed that as the RPR increases, the total cost decreases significantly and the minimum objective function is obtained when the RPR is 75%.

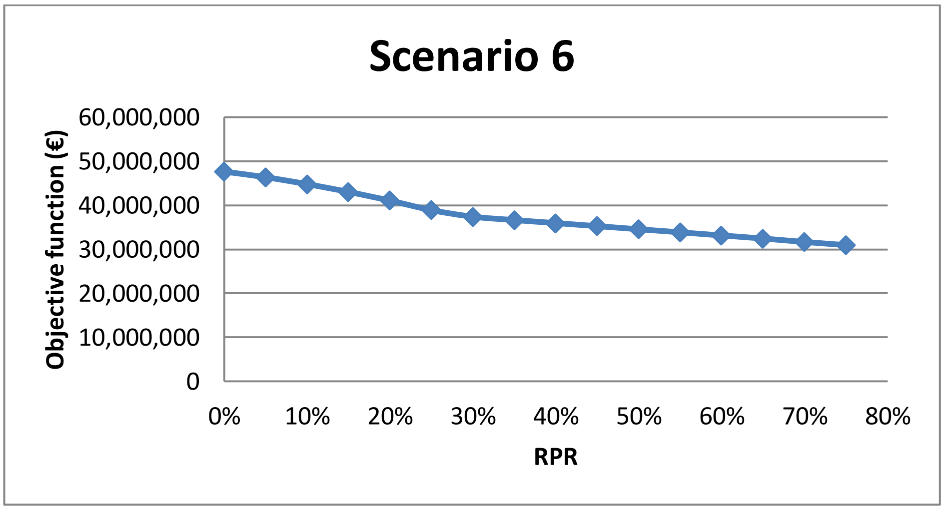

Figure 6.6 Objective function value with respect to the RPR in scenario 6

Table 6.6 Results of scenario 6

RPR	Objective Function (€)	Lot 3 opening year	Landfill extension cost Lot 2 (€)	Landfill extension cost Lot 3 (€)	Sale of recyclables (€)	Sale of electricity (WTE) (€)	Landfill O&M cost (€)	Cost of CMRF (€)	Cost of WTE (€)
1	2	3	4	5	6	7	8	9	10
0%	47,642,843	9	2,224,991	1,195,860	0	35,250,069	7,939,649	0	71,532,413
5%	46,369,274	9	2,224,991	1,195,860	1,615,268	31,823,089	7,939,649	310,501	68,136,631
10%	44,803,156	9	2,224,991	1,195,860	3,230,535	28,601,687	7,939,649	515,064	64,759,815
15%	43,027,493	9	2,224,991	1,195,860	4,845,802	25,581,184	7,939,649	692,456	61,401,524
20%	41,056,635	9	2,224,991	1,195,860	6,461,070	22,755,410	7,939,649	854,259	58,058,357
25%	38,897,749	9	2,224,991	1,195,860	8,076,337	20,118,435	7,939,649	1,005,420	54,726,603
30%	37,401,279	9	2,224,991	1,195,860	9,691,605	18,405,353	7,878,183	1,148,534	53,050,669
35%	36,646,461	10	2,224,991	1,128,169	11,306,872	17,490,242	7,754,428	1,285,318	53,050,669
40%	35,954,453	10	2,224,991	1,128,169	12,922,140	16,575,132	7,630,951	1,416,945	53,050,669
45%	35,258,374	10	2,224,991	1,128,169	14,537,407	15,660,021	7,507,820	1,544,153	53,050,669
50%	34,558,838	10	2,224,991	1,128,169	16,152,675	14,744,911	7,385,000	1,667,594	53,050,669
55%	33,856,315	10	2,224,991	1,128,169	17,767,942	13,829,800	7,262,453	1,787,775	53,050,669
60%	33,151,180	10	2,224,991	1,128,169	19,383,210	12,914,690	7,140,247	1,905,003	53,050,669
65%	32,443,739	10	2,224,991	1,128,169	20,998,477	11,999,579	7,018,347	2,019,620	53,050,669
70%	31,670,381	11	2,224,991	1,064,311	22,613,745	11,084,469	6,896,713	2,131,911	53,050,669
75%	30,959,038	11	2,224,991	1,064,311	24,229,012	10,169,358	6,775,415	2,242,022	53,050,669

*Lot 2 is opened in year 2 in each case

Table 6.6 Continued

RPR	Objective Function (€)	Lot 3 opening year	$X_{S,WTE}$	$X_{S,CMRF}$	$X_{S,LF}$	$X_{WTE,LF}$	$X_{CMRF,LF}$
0%	47,642,843	9	73,757	0	142,745	12,876	0
5%	46,369,274	9	69,238	3,402	143,862	11,743	16
10%	44,803,156	9	64,810	6,805	144,887	10,670	64
15%	43,027,493	9	60,474	10,207	145,821	9,656	144
20%	41,056,635	9	56,226	13,609	146,667	8,698	257
25%	38,897,749	9	52,065	17,012	147,425	7,795	401
30%	37,401,279	9	50,000	20,414	146,088	7,238	577
35%	36,646,461	10	50,000	23,816	142,686	6,989	786
40%	35,954,454	10	50,000	27,219	139,283	6,740	1,027
45%	35,258,374	10	50,000	30,621	135,881	6,492	1,299
50%	34,558,838	10	50,000	34,023	132,479	6,243	1,604
55%	33,856,315	10	50,000	37,426	129,076	5,995	1,941
60%	33,151,180	10	50,000	40,828	125,674	5,746	2,310
65%	32,443,739	10	50,000	44,230	122,272	5,498	2,710
70%	31,670,381	11	50,000	47,633	118,869	5,249	3,144
75%	30,959,038	11	50,000	51,035	115,467	5,001	3,609

*Landfill Lot 2 is opened in year 2 in each case

6.7 Scenario 7

In the last scenario, the capacity of landfill Lot 3 is considered to be zero. In other words, in this scenario, Lot 3 is considered as unavailable. The results of this scenario are given in Figure 6.7 and Table 6.7. It is obvious from Figure 6.7 that as the RPR increases from 0% and 35%, the total cost increases at a decreasing rate whereas as the RPR increases from 35% to 75%, the total cost starts to decay at an increasing rate. However, the total cost of the system is minimised when there is no recycling. The main highlight of the results obtained in Figure 6.7 and Table 6.7 can be summarised as follows:

- The objective function varies between €63,482,768 and €68,421,553 depending on the value of the RPR.
- In all cases, a WTE facility is built regardless of the RPR. This shows that building a WTE facility is inevitable because the space available in landfill Lot 1 and Lot 2 is not sufficient to accommodate the generated waste regardless of the RPR.
- When the RPR increases, the amount of waste that goes to CMRF increases whereas the amount of waste that is directed to WTE facility decreases. Thus, a smaller (resp. larger) size WTE facility (resp. CMRF) is needed as the RPR increases. In line with these facility sizes and the amounts of waste sent to these facilities, the revenue obtained from the sale of recyclable materials and the total cost of CMRF increases whereas the revenue obtained from the sale of electricity and the total cost of the WTE facility decreases.
- The total cost increases when the RPR increases from 0% to 35% because the cost of WTE facility remains high and revenue from sale of electricity and recyclables are not enough to decrease the total cost. As the RPR increases, the revenue from the sale of recyclables increases and the amount of waste that is directed to WTE facility decreases which in turn decrease the total cost of WTE facility. All these start to decrease the total cost when the RPR is 45% and above.
- Lot 2 has to be opened in year 3 regardless of the RPR.

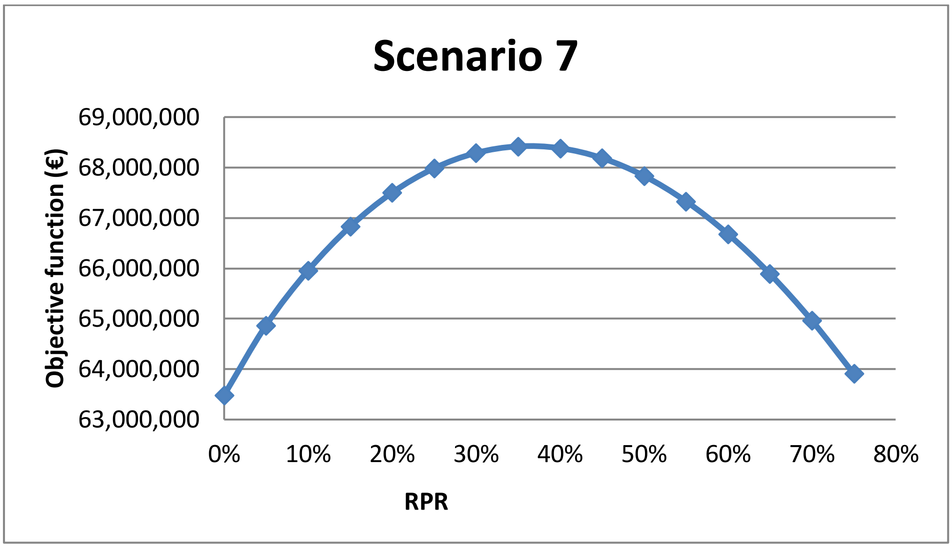

Figure 6.7 Objective function value with respect to the RPR in scenario 7

6.8 Results including all scenarios

In Figure 6.8, the results obtained from each scenario are included. The highest cost is obtained in scenario 7 which is followed by scenario 6. The reason for the high objective function values in those scenarios is the opening of the WTE facility regardless of the RPR value. In scenarios 4 and 5, total cost is high when the WTE facility is opened and it decreases significantly when it is not opened. In scenarios 1, 2, and 3, total cost is lower compared to other scenarios as the WTE facility is never opened in those scenarios.

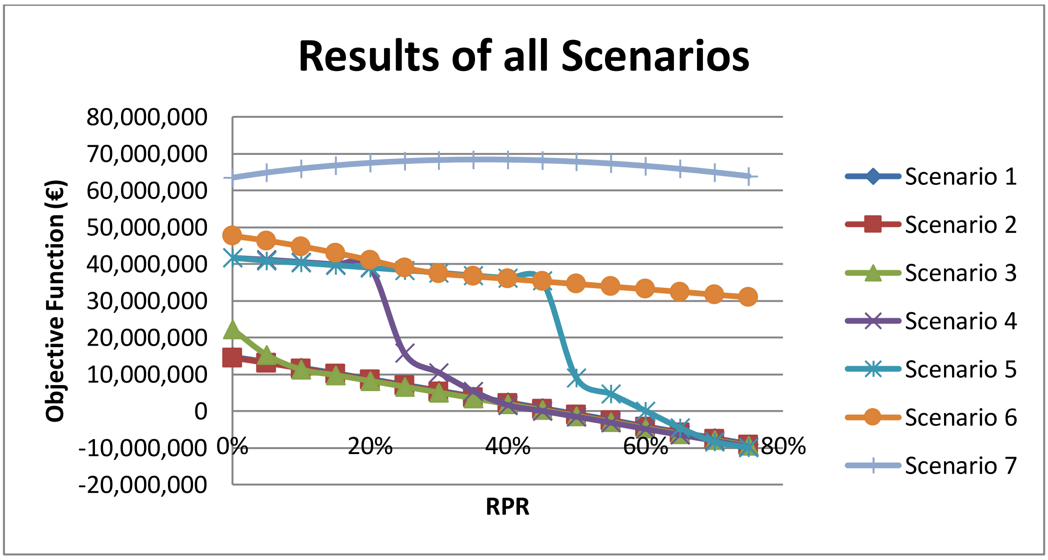

Figure 6.8 Results of all scenarios

Table 6.7 Results of scenario 7

RPR	Objective Function (€)	$X_{S,WTE}$	$X_{S,CMRF}$	$X_{S,LF}$	$X_{WTE,LF}$	$X_{CMRF,LF}$	Landfill extension cost (€)	Sale of recyclables (€)	Sale of electricity (WTE) (€)	Cost of CMRF (€)	Cost of WTE (€)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
0%	63,482,768	188,373	0	28,129	32,866	0	2,099,048	0	90,027,507	0	147,482,768
5%	64,869,209	183,168	3,402	29,932	31,067	16	2,099,048	1,615,268	84,187,420	310,501	144,139,887
10%	65,955,678	178,062	6,805	31,635	29,316	64	2,099,048	3,230,535	78,581,634	515,064	141,031,275
15%	66,826,968	173,056	10,207	33,239	27,631	144	2,099,048	4,845,802	73,204,958	692,456	137,963,736
20%	67,499,997	168,146	13,609	34,747	26,011	257	2,099,048	6,461,070	68,050,729	854,259	134,936,027
25%	67,984,817	163,331	17,012	36,159	24,454	401	2,099,048	8,076,337	63,112,519	1,005,420	131,946,743
30%	68,289,804	158,610	20,414	37,478	22,959	577	2,099,048	9,691,605	58,385,419	1,148,534	128,996,784
35%	68,421,553	153,981	23,816	38,705	21,523	786	2,099,048	11,306,872	53,863,254	1,285,318	126,084,851
40%	68,385,907	149,441	27,219	39,842	20,146	1,027	2,099,048	12,922,140	49,540,085	1,416,945	123,209,678
45%	68,189,161	144,991	30,621	40,890	18,825	1,299	2,099,048	14,537,407	45,411,240	1,544,153	120,372,145
50%	67,836,420	140,628	34,023	41,851	17,560	1,604	2,099,048	16,152,675	41,470,999	1,667,594	117,570,991
55%	67,332,468	136,350	37,426	42,726	16,348	1,941	2,099,048	17,767,942	37,713,874	1,787,775	114,804,999
60%	66,682,953	132,157	40,828	43,517	15,188	2,310	2,099,048	19,383,210	34,135,400	1,905,003	112,075,050
65%	65,892,296	128,047	44,230	44,225	14,079	2,711	2,099,048	20,998,477	30,730,291	2,019,620	109,379,935
70%	64,964,675	124,018	47,633	44,851	13,020	3,144	2,099,048	22,613,745	27,493,457	2,131,911	106,718,456
75%	63,905,391	120,070	51,035	45,397	12,008	3,609	2,099,048	24,229,012	24,420,632	2,242,023	104,091,503

*Landfill Lot 2 is opened in year 3 in each case

6.9 The impact of the increase in the total amount of waste

In this part, the total amount of waste is increased in order to observe its impact on the system. The size of landfill Lot 3 is considered to be 80% of the total size of Lot 1 and Lot 2 as this size is the most likely estimate of the actual size. As in the previous sections, the RPR varies between 0% and 75% with a step size of 5%. The results are presented in the following sections.

6.9.1 Increase in the total waste amount by 10%

When the total amount of waste is increased by 10%, the results are shown in Figure 6.9.1 and Table 6.9.1. When the RPR is between 0% and 15%, the WTE facility is opened. The CM facility is opened when the RPR is between 20% and 25%. As shown in Figure 6.9.1, the total cost decreased sharply from €40,295,869 to €17,983,499 when the RPR increases from 15% to 20%. This significant decrease in the total cost is due to opening the CM facility instead of the WTE facility. Similarly, the total cost substantially decreased from €12,229,856 to €4,930,161 when the RPR increases from 25% to 30%. As the RPR increases, the total cost decreases in this case. For all values of the RPR, Lot 2 is opened in year 2 and Lot 3 is opened in year 8 except for 15% where Lot 3 is opened in year 9.

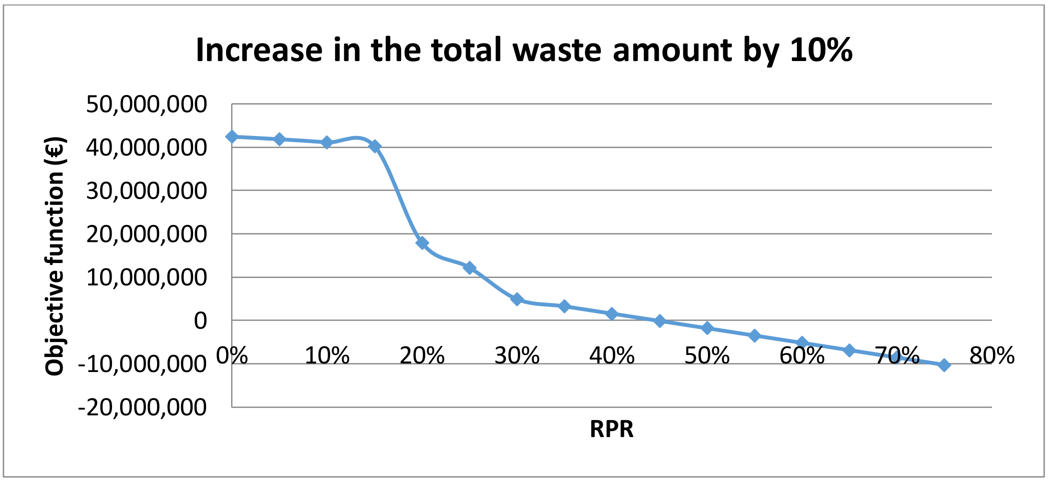

Figure 6.9.1 Objective function with respect to the RPR when the total waste amount is increased by 10%

Table 6.9.1 Results when the total amount of waste is increased by 10%

RPR	$X_{S,CM}$	$X_{CM,LF}$	$X_{S,CMRF}$	$X_{S,LF}$	$X_{CMRF,LF}$	$X_{S,WTE}$	$X_{WTE,LF}$	Lot 3 opening in year	Objective function (€)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**10**	**11**
0%				178,689	0	50,000	8,729	8	42,450,996
5%			3,594	175,095	17	50,000	8,480	8	41,853,499
10%			7,188	171,501	68	50,000	8,232	8	41,146,022
15%			10,782	167,907	152	50,000	7,983	9	40,295,869
20%	18,599	121,120	14,375	195,714	271			8	17,983,499
25%	8,384	5,346	17,969	202,336	424			8	12,229,856
30%			21,563	207,126	610			8	4,930,161
35%			25,157	203,532	830			8	3,255,595
40%			28,751	199,938	1,084			8	1,576,191
45%			32,345	196,344	1,372			8	-107,196
50%			35,938	192,750	1,694			8	-1,793,962
55%			39,532	189,157	2,050			8	-3,483,500
60%			43,126	185,563	2,440			8	-5,175,518
65%			46,720	181,969	2,863			8	-6,869,657
70%			50,314	178,375	3,321			8	-8,565,650
75%			53,908	174,781	3,812			8	-10,263,270

*Landfill Lot 2 is opened in year 2 in each case

6.9.2 Increase in the total waste amount by 20%

In this section, the total amount of waste is increased by 20% and the results are shown in Figure 6.9.2 and Table 6.9.2. When the RPR is between 0% and 35%, the WTE facility is opened whereas the CM facility is opened when RPR is between 40% and 50%. The highest cost, €42,858,718, is observed when the RPR is 0% and the WTE facility is opened. On the other hand, the lowest cost, –€11,213,434, is observed when the RPR is 75%. For all values of the RPR, Lot 2 is opened in year 2 and Lot 3 in year 8 except for 35% in which Lot 3 is opened in year 9.

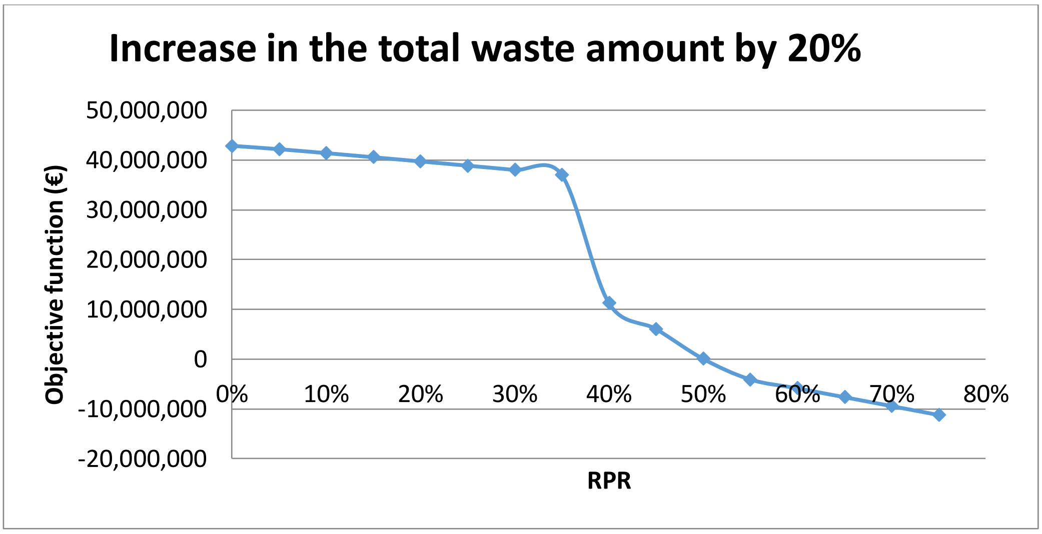

Figure 6.9.2 Objective function with respect to the RPR when the total waste amount is increased by 20%

6.9.3 Comparison of the results when total amount of waste is increased by 0%, 10% and 20%

In this section, the objective function value of the original case is compared with the cases in which the total amount of waste is increased by 10% and 20%, respectively. The results are presented in Figure 6.9.3 where objective function with respect to the RPR is given when the total amount of waste is the same as the original case (i.e., increased by 0%), increased by 10%, and increased by 20%. As shown in Figure 6.9.3, the total cost of the system increases as the total amount of waste increases except for the cases with an RPR value of 55% or more.

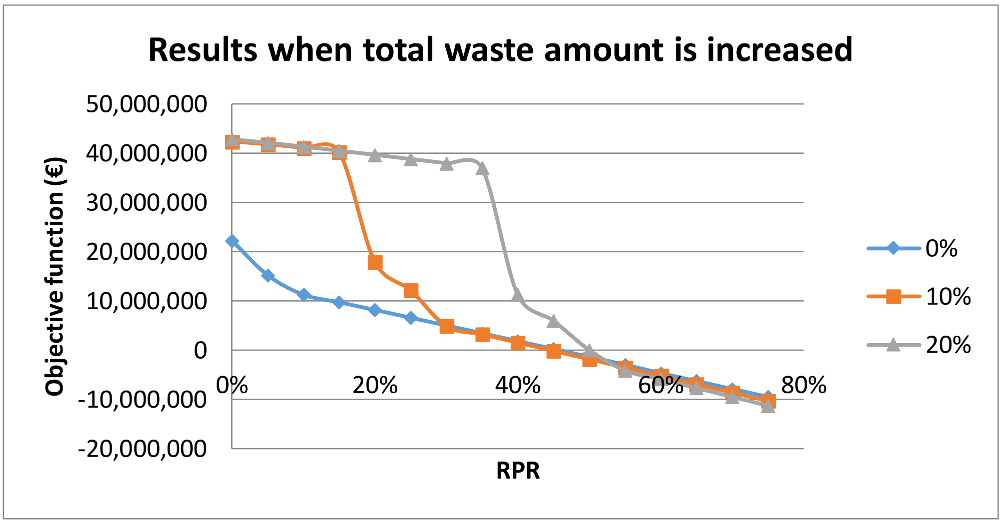

Figure 6.9.3 Objective function with respect to the RPR when total waste amount is increased by 0%, 10% and 20%

Table 6.9.2 Results when the total amount of waste is increased by 20%

RPR	Xs,cm	Xcm,lf	Xs,cmrf	Xs,lf	Xcmrf,lf	Xs,wte	Xwte,lf	Lot 3 opening in year	Objective function (€)
1	2	3	4	5	6	7	8	9	10
0%				190,876		50,000	8,729	8	42,858,718
5%			3,785	187,091	18	50,000	8,480	8	42,178,860
10%			7,571	183,305	71	50,000	8,232	8	41,384,818
15%			11,356	179,520	161	50,000	7,983	8	40,561,871
20%			15,141	175,734	286	50,000	7,735	8	39,722,303
25%			18,927	171,949	446	50,000	7,486	8	38,871,689
30%			22,712	168,164	642	50,000	7,238	8	38,012,751
35%			26,498	164,378	874	50,000	6,989	9	37,032,547
40%	19,554	11,643	30,283	191,039	1,142			8	11,287,428
45%	10,581	6,151	34,068	196,227	1,445			8	6,058,858
50%	2,270	1,288	37,854	200,752	1,785			8	69,665
55%			41,639	199,237	2,159			8	-4,072,362
60%			45,464	195,451	2,570			8	-5,854,617
65%			49,210	191,666	3,016			8	-7,639,008
70%			52,995	187,881	3,498			8	-9,425,359
75%			56,780	184,095	4,015			8	-11,213,434

*Landfill Lot 2 is opened in year 2 in each case

CHAPTER 7
CONCLUSION

SWM has been a key issue of Northern Cyprus for many years as formerly waste was being accumulated in Dikmen dumping area inappropriately until Güngör sanitary landfill area was built in 2012. Nevertheless, there are currently 72 open dumping areas in Northern Cyprus where waste is burned and buried inappropriately. Also, Güngör area is not the final solution of the problem as it is getting filled faster than it was estimated even though only less than half of the municipalities are currently bringing their wastes to Güngör landfill. It is essential not only to minimise the amount of solid wastes that goes to landfill but also to ensure that all municipalities send their solid wastes to Güngör landfill so that the inappropriate open dumping areas can be closed down and rehabilitated.

The ultimate solution of the SWM problem of Northern Cyprus includes building the mentioned transfer stations and enabling all 28 municipalities to bring their wastes to Güngör landfill, closing down and rehabilitating all open dumping areas, and building treatment facilities which would minimise the amount of waste that goes to the landfill. In this way, the lifetime of the landfill will be extended while revenue can be generated from solid wastes.

In this study, a MINLP model is proposed to select the type and size of treatment facilities that will be used for the treatment and disposal of waste, decide whether the other landfill lots should be opened or not, and if the lots are to be opened when it should be. The model takes all associated investment, operation and maintenance costs into consideration and suggests the management system that has the minimum total cost. Note that the costs of constructing the mentioned five transfer stations, the collection of solid wastes by municipalities and the transfer of wastes from the transfer stations to Güngör landfill are not included as these costs do not affect the decisions to be made. Five types of treatment facilities are considered for the treatment and disposal of wastes to see which ones have the lowest cost and are the most appropriate system for Northern Cyprus. Also, the RPR of the society is considered in the model. The costs and benefits of treatment facilities can be compared and the effect of the RPR on the total cost can be seen using the results obtained in this thesis.

The MINLP model that is developed in this study includes the investment, operation and maintenance costs of each facility and the revenues from the sale of recyclable materials and electricity. All monetary terms in the model are converted into their equivalent values in 2014 using inflation and discount rates. The model is solved using an open source and free optimisation solver (i.e., Opensolver Advanced 2.7.1) to minimize the total cost of SWM in Northern Cyprus. The results of the study can be used as a tool for public authorities while making decisions about which treatment facilities to build in Northern Cyprus and their sizes, and when to open other lots of Güngör landfill.

In the solution of the problem, different scenarios are used and compared. As mentioned earlier, in Güngör, only landfill Lot 1 is opened and in use while Lot 2 will be opened when Lot 1 is completely filled and Lot 3 will be on top of Lot 1 and Lot 2. The capacities of Lot 1 and Lot 2 are known but the capacity of Lot 3 is not estimated yet. Therefore, different assumptions are made for the size of landfill Lot 3. Also, problem is solved by considering RPR values between 0% and 75% with the step size of 5%.

In different scenarios, different values are used for the capacity of Lot 3 (0, 50, 60, 70, 80, 90, 100% of the total sizes of Lot 1 and Lot 2). In the first scenario the capacity of landfill Lot 3 is considered to be 100% of the sum of the sizes of Lot 1 and 2. The results of the first scenario show that when the RPR increases, the total cost decreases and the amount of waste that goes from source to CMRF increases. If people can be motivated to participate more in recycling, both depleting natural resources of earth would be prevented and also the amount of money to be paid per household would be much lower. In this case when RPR is 50% or more, profit is made from the system as the income from the sale of recyclables becomes higher than the other costs.

Also, the results demonstrate that the availability of landfill area decreases the demand on the WTE facility. For instance, the WTE facility is never opened in the first scenario. The dramatic impact of not opening a WTE facility is that the total cost decreases by 77%. The results of the second scenario are the same as the first scenario except that the landfill extension cost of Lot 3 is lower in the second scenario as the size is smaller in this case.

In the third, fourth, and fifth scenarios where the capacity of Lot 3 is taken as 80%, 70% and 60% of the total sizes of Lot 1 and Lot 2, respectively, a WTE facility is opened when the RPR is low. When the WTE facility is not opened due to a high RPR, a CM facility is opened. In scenarios 3 and 4, profit is made when the RPR is 50% or greater. In scenario 5, profit is made when RPR is 65% or greater.

In scenario 6 where the capacity of Lot 3 is 50% of total sizes of Lot 1 and Lot 2, the WTE facility is opened for all RPRs but the lifetime of LF is increased. The total cost remains high as the WTE facility is opened for all rates of recycling participation. In scenario 7, the total cost increases as the RPR increases from 0% to 45% but it starts to decrease when the recycling participation is 45% or greater. The main reason of the high total cost in this case is due to the opening of the expensive WTE facility. The main highlight of the results of this scenario is that a WTE facility has to be built and the minimum total cost is obtained when there is no participation to recycling.

Final conclusion for the results of the study is that the RPR plays an important role for a sustainable SWM system. As the RPR increases, the amount of waste that goes to CMRF increases, the amount of waste that goes to LF decreases, the reliance on WTE facilities decreases and the total cost of SWM decreases significantly. Although WTE facilities can significantly decrease the amount of waste at a time, it should be one of the least favourable options to be considered because compared to other facilities it has environmental drawbacks (i.e., emissions) and if it is not well managed it may have negative impacts on human health. Increasing the participation to recycling and opening a CMRF facility should be the priority among the available options. The public awareness about the importance of participation to recycling should be increased.

In Northern Cyprus, unfortunately finding a solution and implementing waste management strategies have been a major problem. In rehabilitation of Dikmen and construction of Güngör landfill, many problems were experienced as there is no political stability in Northern Cyprus. Therefore, whenever the governments changed, the planning of waste management had to start over. By using the results obtained in this thesis, public authorities will be able to make decisions easier as advantages and consequences of each facility are given and financial aspects are taken into account while designing the integrated SWM system.

In this study, the total amount of waste in Northern Cyprus is calculated by using the data taken from the Ministry of Internal Affairs and Local Governments of TRNC. Only the waste data of 2014 was complete for all months of the year. Furthermore, because only 11 municipalities bring their solid wastes to Güngör sanitary landfill area, data for the amount of waste generated in the remaining 17 municipalities were missing. Therefore, population has been used to make an assumption for the amount of waste generated in the regions of the rest of the municipalities.

As only the total amount of waste generated in Northern Cyprus in 2014 was known, the amount of waste that is generated is assumed to be constant over the years. If the amount of waste was changing over the years, it would be possible to extend the proposed optimisation model. However, this would make the model much more difficult to solve. Similarly, the RPR could be assumed to increase over the years. In this case, the model could be changed by adding a subscript to all X and Y variables for the time periods. Again, the resulting model would be very difficult to solve.

Another future research avenue is to focus on the social aspects of participation to recycling and people can be asked about their knowledge and willingness to participate in recycling. Furthermore, instead of taking the amount of waste as a known for each year, it can be considered as uncertain. The SWM problem with uncertain amounts of waste would be significantly more difficult to model and solve than the one with known amounts.

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