DYNAMICS OF MUNICIPAL SOLID WASTE AND LANDFILL AREAS OF ISTANBUL

by

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ABSTRACT

DYNAMICS OF MUNICIPAL SOLID WASTE AND LANDFILL AREAS OF ISTANBUL

Waste management is a critical issue, and municipal solid waste constitutes a considerably important part of the waste that should be properly handled. With rapidly increasing population, urbanization and industrialization in Istanbul, available lands have become extremely limited. However, lands occupied by waste in Istanbul have been increasing due to growing population and increasing waste generation per person. Thus, the undesirable pattern which constitutes the dynamic problem in this study is the unrestrained expansion of areas allocated for waste accumulation (i.e. landfills) year by year. Therefore, this research aims to find out how fast the existing landfills in Istanbul become full (i.e. how much the landfills in Istanbul expand over the next 40 years) and how these landfills can be more efficiently utilized with additional investments on waste treatment facilities and source separation improvements. Seven different scenarios which all contain different budget and source separation combinations are examined to determine an effective strategy for waste management. Analyses indicate that source separation rate is as critical as the budget for capacity investments in waste management strategies. Moreover, it is shown that budget required to make capacity investments decreases with the increasing source separation. Therefore, source separation should be integrated to waste management strategies along with the capacity investments, since it is a more cost effective way of reducing waste sent to landfills.

ÖZET

BELEDİYE ATIĞI VE DÜZENLİ DEPOLAMA ALANI DİNAMİKLERİ

Belediye atıklarının uygun bir şekilde bertaraf edilmesi çok önemlidir. İstanbul'da hızla artan nüfus, kentselleşme ve sanayileşme ile kullanıma açık mevcut alanlar oldukça azalmaktadır. Atık depolamaya ayrılan alanlar, yani düzenli depolama sahalarının alanları ise artan nüfus ve kişi başı üretilen atık miktarı ile hızla genişlemektedir. Bu nedenle, bu çalışmadaki dinamik problemi oluşturan örüntü, İstanbul'daki düzenli depolama sahalarının alanlarının yıldan yıla giderek artmasıdır. Bu çalışmanın amacı İstanbul'daki mevcut düzenli depolama sahalarının ne kadar sürede dolacağı ve var olan sahaların ne tür yatırım faaliyetleriyle daha verimli bir şekilde kullanabileceğini araştırmaktır. Farklı bütçe ve kaynakta ayrım oranı kombinasyonlarından oluşan yedi farklı senaryo etkili bir atık yönetimi stratejisi belirlemek için incelenmiştir. Analizler, kaynakta ayrım oranının atık yönetimi için kapasite yatırımlarına ayrılan bütçe kadar önemli olduğunu göstermektedir. Ayrıca, kapasite yatırımlarını yapmak için gereken bütçenin, kaynakta ayrımın artmasıyla azaldığı gösterilmiştir.Kaynakta ayrım, düzenli depolama sahalarına gönderilen atığı azaltmanın yeni tesisler inşa etmekten daha az maliyetli bir yolu olduğundan, kapasite yatırımlarıyla birlikte atık yönetim stratejilerine entegre edilmesi gerektiği belirlenmiştir.

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kt	Kiloton
ha	Hectare
TSI	Turkish Statistical Institute

1. INTRODUCTION

According to the report of World Bank, municipal solid waste generation will be doubled by 2025 [1]. Turkey, a developing country, had already begun to experience this issue. In the most of the developing countries, municipal authorities do not have the sufficient resources to meet the needs of their rapidly growing populations by providing the necessary facilities and services for solid waste management. Even though strict regulations on waste management exist, inappropriate disposal methods like open dumping, open burning and discharge into surface water had been used in Turkey due to the insufficiency of the required waste treatment facilities. In fact, Istanbul had encountered the consequences of inefficient waste management strategies. An accident occurred at Umraniye–Hekimbasi open dump site on 1993, was caused by the explosion of gases arising from uncontrolled waste accumulation in the dumping area, and it resulted in the death of 39 people [2].

Inefficient waste management strategies which basically depend on dumping or unrestrained landfilling were the situation in many European countries in the past as well. Emerging leachate and landfill gas due to these poor waste management strategies causes all sorts of pollution such as the atmosphere, groundwater, surface water and soil pollution. Since waste dumping has negative effects on the environment, it should be replaced with sanitary landfilling. However, it does not mean sanitary landfill is the best option for waste disposal. According to waste hierarchy, recycling and composting are better options for waste treatment, followed by energy recovery. If the generated waste can not be used for any of these options, then it should be directed to landfills.

The Landfill Directive 1999/31/EC was issued by the European Union in 1999 to reduce landfilling, and Member States were asked to present national strategies to decrease biodegradable municipal waste sent to landfills. European countries, thus, have utilized alternative methods such as separate collection of municipal waste, incineration, mechanical-biological treatment and composting in order to manage the generated waste [3].

Composting, recycling and incineration are the common treatment options employed for effective waste management.

- Composting: Composting is a process in which organic substances are biologically decomposed and stabilized under controllable conditions in composting facilities. The compost product obtained as a result of composting process can be widely used in park gardens, agricultural areas, greenhouses depending on product quality [4].

- Recycling: In this method, wastes are reprocessed in order to obtain the raw material for the purpose of using it either producing the same or other items in recycling facilities [5].

- Incineration: Incineration is the process of converting waste into energy and other by-products at high temperature. This process can achieve energy recovery by using the heat resulting from the process while reducing the area needed for the storage of waste. This process decreases the volume and weight of the waste by 80-90% and 75-80%, respectively. Bottom ash, non-combustible residue, arises out of the process in the amount of approximately 15-20% of the waste and is disposed to landfills [6, 7].

Another component of an effective waste management system is source separation. The processes of sorting recyclable or compostable materials at the place where the waste is generated, and putting them into different containers for collection is called source separation. Source separation decreases the waste directed to landfills by recovering more recyclable and compostable waste. The main objectives of source separation are recycling, reusing, recovering and reducing environmental consequences along with economic burden. Source separation affects the performance of waste management system since it influences quantity and quality of waste reaching final disposal [8].

2. PROBLEM IDENTIFICATION AND RESEARCH OBJECTIVES

Waste management is a critical issue, and solid waste constitutes a considerably important part of the waste that should be properly handled. Solid waste management covers the concept of waste prevention, materials recovery, waste treatment and disposal [9]. The decision on what extent these strategies are employed in a region can change with respect to several factors like topography, population, existing transportation infrastructure, socioeconomics and environmental regulations [10]. Although some undesirable disposal methods like discharge into surface water, open burning, waste burial, storing in municipal waste dumps have been implemented throughout the country with a decreasing rate, waste burial ended in 2001, discharge into surface water in 2003, open burning and storing in municipal waste dumps in 2006, for Istanbul [11].

Waste generation is driven by population and per capita waste generation [9]. As it can be seen through Figure 2.1., population keeps growing in Istanbul. The statistics obtained from TSI (2013) indicate that Istanbul's population in 2023 is expected to reach approximately 16.5 million [12]. Since both population and waste generation per person has been increasing, landfill waste has been increasingly growing [13]. Landfill waste dynamics between 1995 and 2015 is presented in Figure 2.2.

With rapidly increasing industrialization and urbanization in Istanbul, available lands have become extremely limited, and lands occupied by waste in Istanbul have been increasing due to growing population and increasing waste generation per person.When generated waste increases, waste treatment facilities should be adjusted accordingly. If the suitable strategies and required facilities are not determined and necessary actions are not taken, damaging effects of poor waste management on the environment and resource utilization will increase. However, building new waste treatment facilities is highly expensive and municipality has a limited budget that can be

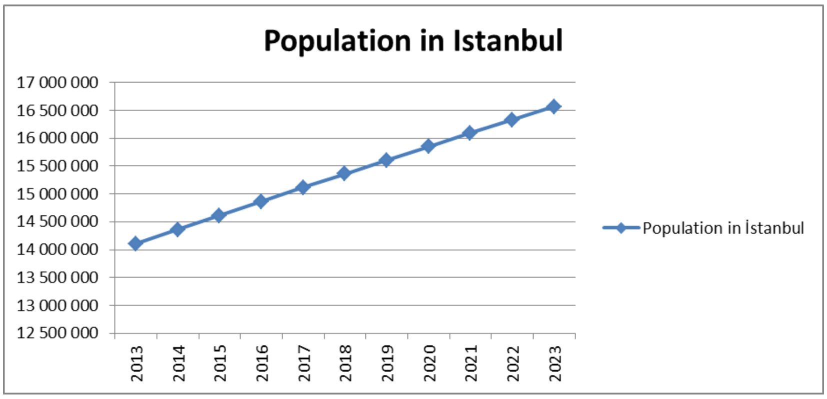


Figure 2.1. Population projection of Istanbul.

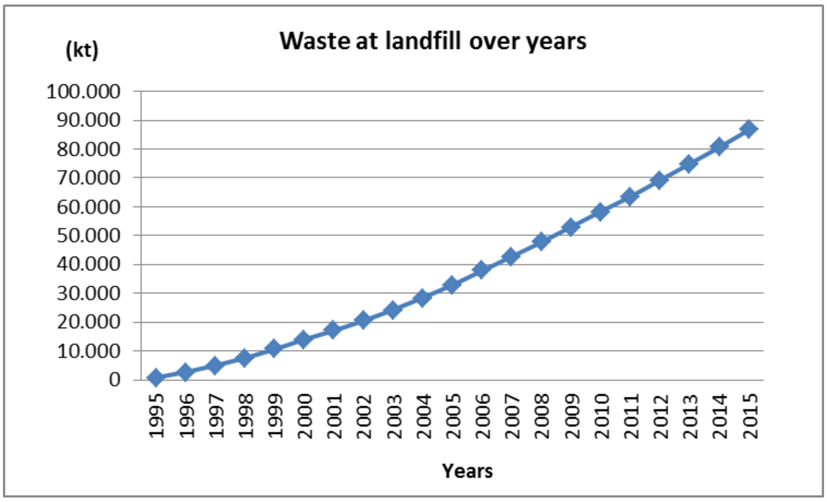


Figure 2.2. Landfill Waste Dynamics between 1995 and 2015.

allocated to the capacity investments for waste treatment facilities, so dumping waste to the landfills which is the cheapest way of waste disposal has been commonly preferred. Thus, the undesirable pattern which constitutes the dynamic problem in our case is the unrestrained expansion of area allocated for waste accumulation (i.e. landfills) year by year.

Therefore, the objective of this research is to investigate how fast the existing landfills in Istanbul become full (i.e. how much the landfills in Istanbul expand over the next 40 years), how to slow down this process and how these landfills can be more efficiently utilized with additional investments on waste treatment facilities and source separation improvements. In other words, the dynamics of waste accumulation and waste treatment are examined with different budget and source separation values. By examining and evaluating different capacity investment and source separation scenarios, investment policies that provide better results are investigated.

3. LITERATURE REVIEW

In the literature, many different approaches are adopted to come up with a solution for waste management problems. However, in only a small subset of these approaches, dynamic properties of waste management system are thoroughly represented.

Huang *et al.* used a grey dynamic programming model to solve a capacity planning problem for a municipal solid waste management system. Grey solutions for capacity expansion of waste management facilities and corresponding waste flow allocation are obtained and evaluated to provide effective decision alternatives [14]. Lu *et al.* proposed an inexact dynamic optimization model to evaluate municipal solid waste management systems under uncertainty. The proposed model can reflect the interrelationships between solid waste management and climate-change impact associated with it [15]. Leao *et al.* utilized urban dynamics modelling in a GIS (geographic information system) environment to asses and quantify the relationship between the demand and supply of suitable land for waste disposal over time [16]. Eriksson examined different waste treatment alternatives for municipal solid waste by using system analysis. Various combinations of incineration, materials recycling of separated plastic and cardboard containers, and biological treatment of biodegradable waste, were analysed and compared to landfilling option. A model based on life cycle assessment was used in the study. It is indicated that reducing landfilling while increasing recycling of energy and materials is economically and environmentally more advantageous [17]. Ghinea *et al.* used prognostic tools and regression analysis to forecast MSW generation [18] whereas Mesjasz-Lech *et al.* investigated the dynamics of municipal waste quantities and management ways [19].

More specifically, system dynamics methodology is also applied to various aspects of waste management. Marshall *et al.* employed system dynamics approach to examine the waste management in terms of countries' level of development. It is suggested that existing approaches for solid waste management are inadequate even in developed countries, since the current approaches are reductionist. In other words, waste generation, collection and disposal are handled as independent from each other even though operational causalities exist among them. The current approaches thus can not cope with the complexity of the system. It is therefore stated that an integrated solid waste management system which includes all components of waste management should be adopted [20]. Furthermore, waste management is studied by Chaerul *et al.* [21], Marzouk and Azab [22], Ding *et al.* [23] and Yuan and Wang [24] by using system dynamics. Marzouk and Azab utilized system dynamics modelling to make a qualitative assessment on environmental and economic impact of demolition waste disposal [22]. Chaerul *et al.* made quantitative assessments by utilizing systems dynamics to analyse hospital waste management [21]. Ding *et al.* developed a system dynamic model for construction waste reduction management at the construction phase [23]. Yuan and Wang utilized this approach to determine the waste disposal charging fee in construction [24]. Therefore, it is possible to say that system dynamics approach is preferred to investigate the management of different types of waste.

System dynamics has also been specifically utilized for municipal solid waste management. Sufian *et al.* made policy analysis through system dynamics to examine an urban solid waste management system where solid waste generation, collection capacity, and electricity generation from solid waste were examined in detail. Since this system covers interdependent factors such as public health, the environment, population, public concern, untreated waste, and recyclable waste; system dynamics approach is preferred. The model is able to evaluate the waste treatment facilities to make an environmental quality improvement. Simulation results indicate that untreated waste will increase due to insufficient collection capacity and shortage of treatment facilities. Therefore, it is emphasized that if immediate actions are not taken for allocating more funds to solid waste management, the quality of the environment will worsen [25]. Dyson and Chang also studied solid waste generation at municipal base, where municipal waste generation in an urban region was forecasted. Five different scenarios which differ from each other with respect to the inclusion level of the driving factors like total income per service center, people per household, population, income per household and so on were modelled. As a result, the scenario that involves all of the driving factors is selected to forecast municipal solid waste generation [26]. In the study by Karavezyris *et al.*, municipal solid waste model involves several interdependent factors such as environmental behaviour, recycling, treatment price, collected waste and regulations, thus system dynamics approach was used to forecast MSW and fuzzy logic was incorporated to the model to use expert knowledge in a quantitative form. It was claimed that employing fuzzy logic to forecast municipal solid waste might improve confidence in terms of validity of the model, since expert knowledge on influences and parameter estimation might be dramatically different [27]. Kollikkathara *et al.* employed system dynamics modelling to evaluate municipal solid waste generation, landfill capacity and related cost management issues. The influence of alternative decision options on the waste generation, on the remaining landfill capacity, and on the economic cost or benefit of different waste treatment options were investigated [28]. Kum *et al.* used system dynamics to investigate solid waste recovery policies. To what extent composting and informal recycling affects the waste diversion was examined in the study. The simulation results indicated that waste recovery through small-scale composting and informal recycling can not significantly affect to the waste diversion unless some other supporting policies are integrated to the system [29].

4. RESEARCH METHODOLOGY

System dynamics approach provides a basis to comprehend how things change over time [30]. System dynamics approach suggests that the internal structure of a system is the main cause of the dynamics. The primary objective of this approach is to figure out the causes of undesirable dynamics and propose new policies to eradicate them [31].

The dynamic problems are harder to analyse for human mind due to the complexity of the system. This complexity arises from the human factor, non-linearity, existence of feedback loops, delays, and large number of variables [31]. It can be clearly seen that the problem which is stated in chapter 2 is dynamic, and elements in the waste management system have strong interactions among them. Thus, it is possible to say that system dynamics approach provides a better understanding of the dynamics of landfill expansion in Istanbul and it provides an opportunity to investigate which strategies can be adopted to utilize existing landfills more efficiently.

In addition to the advantage of handling system complexity, system dynamics approach enables the modeller to examine and evaluate the accuracies of assumptions and the impacts of parameter changes on the system's behaviour via sensitivity analysis. Furthermore, in the existence of a properly constructed and credible model, system dynamics approach enables the modeller to design new policies and to examine these new policies through simulation runs [32].

The model formed for this study is employed to simulate possible behaviours generated by the system and to examine cause and effect relationships in the system by facilitating feedback analysis via causal loop diagrams, and stock flow diagrams with equations. Thus, the ultimate modelling purpose is to be able to observe the possible outcomes of several alternative capacity investments and source separation strategies.

5. OVERVIEW OF THE MODEL

In this research, the questions of “How long will it take to fill the existing landfills?” and “How will the utilization of waste treatment facilities and source separation affect landfill expansions in Istanbul over the next 40 years?” are investigated. This is a complex task, because it has many interdependent factors, reinforcing and balancing loops. The causal loop diagram has seven main loops, six of them are negative and one of them is positive. As the population and waste generation per person grow, waste generation rate increases. Waste generation rate has a positive impact on composting rate, recycling rate, incineration rate and waste sent to landfills because certain fractions of waste generated are qualified as organic, recyclable and combustible. Waste sent to landfills thus decreases with the increase of composting rate, recycling rate and incineration rate. Source separation positively affects composting and total recycling rate since when the mixed waste is sent to these facilities, additional initial processes are required, and in such cases, some portion of the arriving waste can undergo composting or recycling operations. However, when source separated waste is received by these facilities, no effort is required to sort the waste and facility can use all of its resources for composting and recycling operations. On the other hand, since source separation has a positive impact on private recycling, and it can negatively affect recycling rate by municipality. As composting and total recycling rate increases, incineration rate can decrease because recycling and composting are better options for waste treatment, followed by energy recovery according to waste hierarchy. Depreciation has negative impacts on composting, recycling and incineration capacities. As the capacities of composting, recycling and incineration increase, composting, recycling and incineration rates go up. Expected composting, recycling and incineration needs represent the forecasted needs of five years later. However, expected composting and recycling rates negatively affect expected incineration need since expected incineration need is determined according to recycling and composting rate because of waste hierarchy. Expected composting, recycling and incineration capacity additions correspond to the average capacity additions for these facilities in the past five years. Expected composting, recycling and incineration rates increase along with the expected capacity additions. Moreover, expected composting, recycling and incineration rate is the sum of their current rate and expected increase in composting, recycling and incineration rates, respectively. Composting gap is the difference between expected composting need and expected composting rate. The same structure is valid for recycling and incineration gaps as well. Therefore, an increase in expected composting, recycling and incineration rates yields a decrease in composting, recycling and incineration gaps. On the other hand, as expected composting, recycling and incineration needs increase, composting, recycling and incineration gaps increase as well.

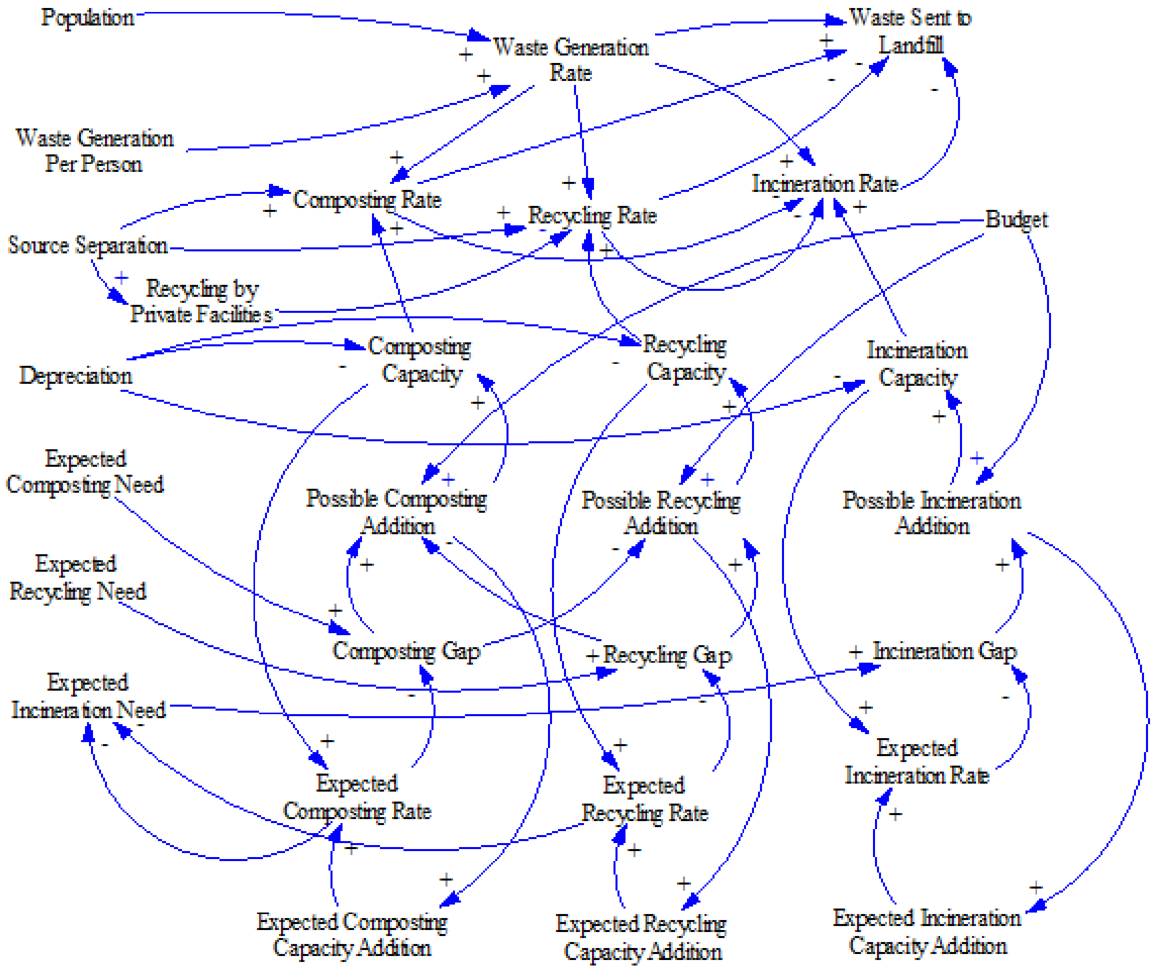


Figure 5.1. Causal Loop Diagram.

6. DESCRIPTION OF THE MODEL

In this part, main structures and variables are elaborated. The complete list of model variables, their units and brief definitions are provided in Table 6.1. The model has various interrelated components so the model is divided into sub-models. The relations between these components and model assumptions are presented below in detail. General structure of the whole model is presented in Figure 6.1.

Table 6.1. Types, Units and Description of Variables.

Variable	**Type**	**Unit**	**Definition**
waste generation per person	Converter	kg/(day *person)	Waste generation per person
population	Converter	person	Population
source separation effect comp	Converter	Unitless	Source separation effect on composting
Actual sourceSep	Converter	Unitless	Actual source separation
Desired sourceSep	Converter	Unitless	Desired source separation
source separation effect Recycling	Converter	Unitless	Source separation effect on recycling
projected waste generation per person	Converter	kg/(day *person)	Projected waste generation per person
projected population	Converter	person	Projected population
expected recycling need	Converter	kt/year	Expected recycling need
expected compost need	Converter	kt/year	Expected compost need
expected incin need	Converter	kt/year	Expected incineration need

Table 6.1. Types, Units and Description of Variables (cont.).

Variable	**Type**	**Unit**	**Definition**
expected incin cap	Converter	kt/year	Expected incineration capacity
expected recycling cap	Converter	kt/year	Expected recycling capacity
expected composting cap	Converter	kt/year	Expected composting capacity
gapIncin	Converter	kt/year	Incineration gap
gapCompost	Converter	kt/year	Composting gap
gapRecycling	Converter	kt/year	Recycling gap
Possible IncinAdd	Converter	kt/year	Possible incineration addition
Possible CompAdd	Converter	kt/year	Possible composting addition
Possible RecyAdd	Converter	kt/year	Possible recycling addition
DelayInc	Converter	kt/year^2	Delayed incineration addition
DelayRecycle	Converter	kt/year^2	Delayed recycling addition
DelayCompost	Converter	kt/year^2	Delayed composting addition
DepAddComp	Converter	kt/year^2	Composting capacity addition to compensate depreciation
DepAddRec	Converter	kt/year^2	Recycling capacity addition to compensate depreciation
DepAddIncin	Converter	kt/year^2	Incineration capacity addition to compensate depreciation
OneUnit IncinCost	Converter	TL/kt	Cost of one unit incineration capacity
OneUnit CompostingCost	Converter	TL/kt	Cost of one unit composting capacity
OneUnit RecyclingCost	Converter	TL/kt	Cost of one unit recycling capacity
compostable fr	Converter	Unitless	Compostable fraction of waste
recylable fraction	Converter	Unitless	Recyclable fraction of waste

Table 6.1. Types, Units and Description of Variables (cont.).

Variable	**Type**	**Unit**	**Definition**
ageing time	Converter	year	Ageing time
ExpWaste GenRate	Converter	kt/year	Expected waste generation rate
expected capacity addition compost	Converter	kt/year	Expected capacity addition to composting in 5 years
expected capacity addition recycling	Converter	kt/year	Expected capacity addition to recycling in 5 years
expected capacity addition incin	Converter	kt/year	Expected capacity addition to incineration in 5 years
expected increase in compost rate	Converter	kt/year	Expected composting rate increase in 5 years
expected increase in recycling rate	Converter	kt/year	Expected recycling rate increase in 5 years
expected increase in incin rate	Converter	kt/year	Expected incineration rate increase in 5 years
C&R Fund	Converter	TL/year	Composting and recycling fund
composting capacity	Converter	kt/year	Capacity of composting facility
recycling capacity	Converter	kt/year	Capacity of recycling facility
incineration capacity	Converter	kt/year	Capacity of incineration facility
PossibleBudget For CompostingInvestments	Converter	TL	Composting budget left after deducting depreciation expense
PossibleBudget For RecyclingInvestments	Converter	TL	Recycling budget left after deducting depreciation expense

Table 6.1. Types, Units and Description of Variables (cont.).

Variable	**Type**	**Unit**	**Definition**
PossibleBudget For IncinerationInvestments	Converter	TL	Incineration budget left after deducting depreciation expense
fraction of private recycling	Converter	Unitless	Private recycling fraction of waste
capacity utilization	Converter	Unitless	Utilization of the existing capacity
waste generation rate	Flow	kt/year	Waste generation rate
composting rate	Flow	kt/year	Composting rate
recycling rate	Flow	kt/year	Recycling rate
incineration rate	Flow	kt/year	Incineration rate
capacity addition compost	Flow	kt/year^2	Capacity addition for composting
capacity addition recycle	Flow	kt/year^2	Capacity addition for recycling
capacity addition incin	Flow	kt/year^2	Capacity addition for incineration
Depreciation Recycle	Flow	kt/year^2	Depreciation of recycling capacity
Depreciation Compost	Flow	kt/year^2	Depreciation of composting capacity
Depreciation Incin	Flow	kt/year^2	Depreciation of incineration capacity
Depreciation ExpComp	Flow	TL/year	Depreciation expenses of composting
Depreciation ExpRec	Flow	TL/year	Depreciation expenses of recycling

Table 6.1. Types, Units and Description of Variables (cont.).

Variable	**Type**	**Unit**	**Definition**
Depreciation ExpIncin	Flow	TL/year	Depreciation expenses of incineration
Incineration Fund	Flow	TL/year	Incineration Fund
Composting Fund	Flow	TL/year	Composting Fund
Reycling Fund	Flow	TL/year	Recycling Fund
Investment ToComp	Flow	TL/year	Investment to composting capacity
Investment ToRec	Flow	TL/year	Investment to recycling capacity
Investment Incin	Flow	TL/year	Investment to incineration capacity
ChangeIn SmoothIncin	Flow	kt/year^2	Change in average possible incineration addition
ChangeIn SmoothRecycle	Flow	kt/year^2	Change in average possible recycling addition
ChangeIn SmoothComp	Flow	kt/year^2	Change in average possible composting addition
capacity wear comp	Flow	kt/year^2	Wearing capacity amount for composting
capacity wear recycle	Flow	kt/year^2	Wearing capacity amount for recycling
capacity wear incin	Flow	kt/year^2	Wearing capacity amount for incineration
recycling by private facilities	Flow	kt/year	Amount of recycled waste by private facilities
waste at landfill	Stock	kt	Landfill waste
SmoothOf PossibleIncinAdd	Stock	kt/year	Average possible incineration addition

Table 6.1. Types, Units and Description of Variables (cont.).

Variable	**Type**	**Unit**	**Definition**
SmoothOf PossibleRecycleAdd	Stock	kt/year	Average possible recycling addition
SmoothOf PossibleCompostAdd	Stock	kt/year	Average possible composting addition
Composting Budget	Stock	TL	Composting budget
Recycling Budget	Stock	TL	Recycling budget
Incineration Budget	Stock	TL	Incineration budget
old composting cap	Stock	kt/year	Composting capacity that depreciate
old recycling cap	Stock	kt/year	Recycling capacity that depreciate
old incineration cap	Stock	kt/year	Incineration capacity that depreciate
new composting cap	Stock	kt/year	Composting capacity that does not depreciate
new recycling cap	Stock	kt/year	Recycling capacity that does not depreciate
new incineration cap	Stock	kt/year	Incineration capacity that does not depreciate

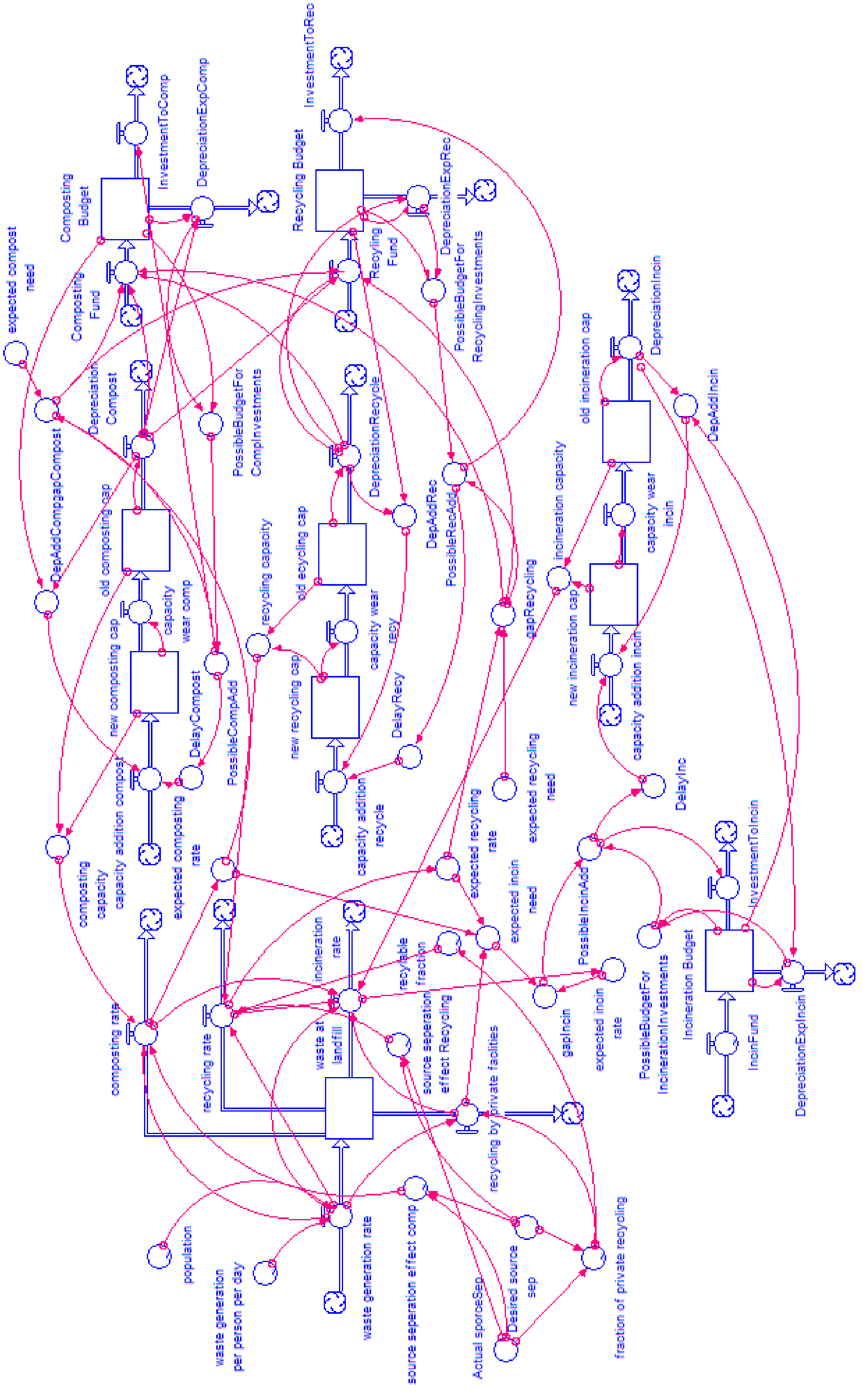


Figure 6.1. General Structure of the Whole Model.

6.1. Landfill Waste Sub-model

As it was stated, the main drivers of waste generation are population and waste generation per person. Some part of the generated waste is sent to treatment facilities whereas the rest accumulates at landfills. After mixed waste arrives at the composting facility, organic waste (i.e. compostable waste) needs to be separated to undergo composting processes. The waste in the facility which is not suitable for composting is sent to landfill (see Figure 6.2). Similarly, mixed waste arrives at the recycling facility, recyclable waste needs to be separated before it is subjected to further operations. The waste in the facility which is not suitable for recycling is sent to landfill. Thus, it is possible to say that composting and recycling capacities reflect the waste arriving at the composting and recycling facilities, respectively. However, composting and recycling rates are not always equal to their capacities. If one ton mixed waste arrives at the composting facility, organic waste, which constitutes approximately 54% of the total waste, is initially separated, then it undergoes composting processes. The rest, 46% of the arriving waste, is sent to landfill. Therefore, composting rate is equal to the amount of compostable waste arriving at the facility with respect to its capacity in a year. The same principle applies to the recycling facility as well.

The effect of source separation on composting is that as the source separation increases, composting rate increases. However, the effect of source separation on recycling is a little bit complicated. As source separation increases, recyclable fraction of the waste collected by the municipalities can decrease, because as source separated waste increases, recycling fraction by private facilities increases. For instance, when existing source separation is 0, mixed waste is sent to facilities and requires to be separated as compostable or recyclable before it undergoes further operations. However, if existing source separation reaches the ideal point, equal to 1, composting facilities would receive only compostable waste and recycling facilities would receive only recyclable waste. Since there would be no need to separate the waste, these facilities could use all of their capacity for composting and recycling operations. On the other hand, recyclable fraction of the waste collected by the municipalities decreases with the increase in source separation. Thus, increase in the source separation rate makes com-

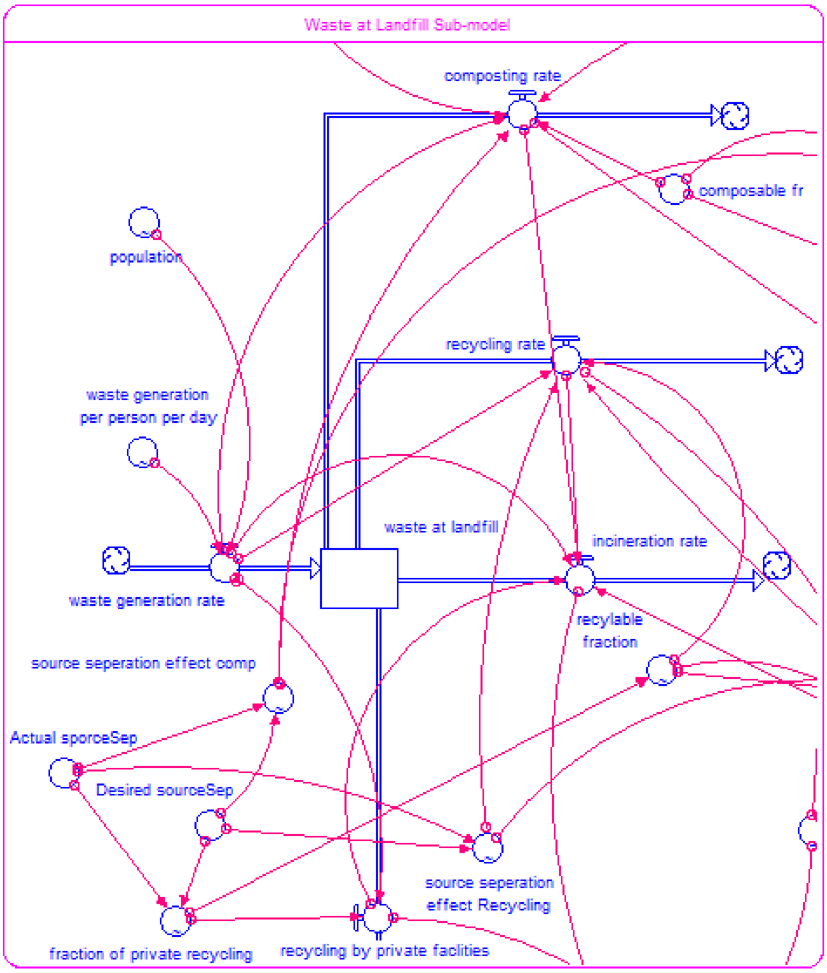
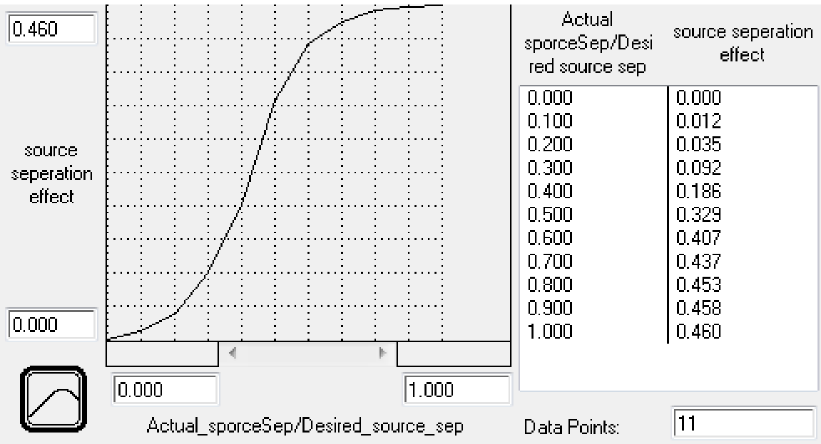


Figure 6.2. Landfill Waste Sub-model.

posting rate increase whereas it can make recycling rate by municipality either increase or decrease. Graphical functions showing the relationship between source separation ratio and source separation effects are given in Figure 6.3 and 6.4.

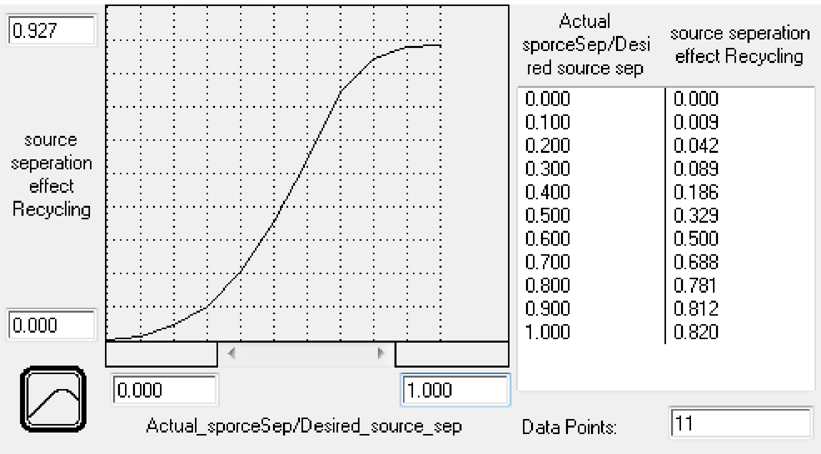
According to the waste hierarchy, composting and recycling are more preferable options than incineration. When mixed waste undergoes the incineration process, residues in the amount of approximately 20% of the arriving waste emerges. These residues are sent lo landfill. For example, if one ton waste arrives at the composting facility, 200 kg residues would emerge and be sent to landfill. Thus, it is possible to say that essentially 80% of the arriving waste to incineration facility is equal to incineration rate.



Actual sporceSep/Desired source sep	source seperation effect
0.000	0.000
0.100	0.012
0.200	0.035
0.300	0.092
0.400	0.186
0.500	0.329
0.600	0.407
0.700	0.437
0.800	0.453
0.900	0.458
1.000	0.460

Data Points: 11

Figure 6.3. Source Separation Effect on Composting.



Actual sporceSep/Desired source sep	source seperation effect Recycling
0.000	0.000
0.100	0.009
0.200	0.042
0.300	0.089
0.400	0.186
0.500	0.329
0.600	0.500
0.700	0.688
0.800	0.781
0.900	0.812
1.000	0.820

Data Points: 11

Figure 6.4. Source Separation Effect on Recycling.

While constructing this part of the model, the assumptions on waste composition, private recycling fraction were made. Compostable (organic) waste constitutes 54% of the composed waste whereas the percentage of recyclables is determined as 32 [13]. In order to identify private recycling fraction, nine district municipalities were contacted. Private recycling quantities of Beşiktaş, Kağıthane, Küçükçekmece, Pendik, Ümraniye, Sultangazi, Gaziosmanpaşa, Bağcılar and Kadıköy are used to forecast the total private recycling quantity, and consequently private recycling fraction in Istanbul. These districts were chosen because the number of people living in these districts constitutes 1 in 3 of the total population and these districts have people from different socio-economic backgrounds which can influence source separation habits. Furthermore, it was assumed that Istanbul's population will increase up to 20 million, and it will saturate at that point. Waste generation per person will also be stabilized after a slight incraese [11].

6.2. Capacity Addition Sub-model

Composting capacity increases with capacity additions whereas decreases due to depreciation. Every year the capacity is added as much as the depreciation of composting facility if its budget is adequate. Otherwise, capacity is added to the extent that the budget permits. However, large capacity investments (i.e. possible composting addition) can be done after a delay period, since building new facilities and acquiring necessary equipment take time (see Figure 6.5). Moreover, these kinds of investments are done after a certain threshold is passed in terms of capacity.

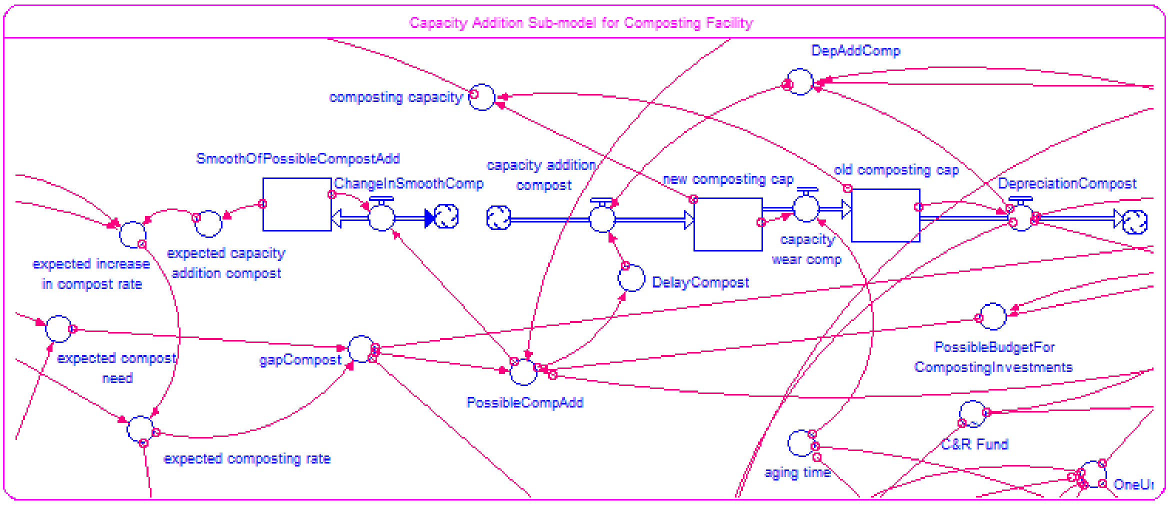


Figure 6.5. Capacity Addition Sub-model for Composting.

In this model, while determining the amount of capacity addition (i.e. capacity addition compost), composting depreciation and possible composting addition are considered. Possible composting addition is equal to either composting gap or affordable capacity addition (i.e. amount of composting capacity that can be purchased with the existing budget). While determining the possible composting addition, the model initially checks whether a certain amount of money exists in the composting budget. If it does, then the amount of possible capacity addition is determined as follows: If the composting budget is greater than the money needed to cover composting gap, then possible composting addition would be equal to composting gap. Otherwise, possible composting addition would be equal to affordable capacity addition. Composting gap is the difference between expected composting need and expected composting rate. Expected composting need represents the forecasted need of five years later. Expected composting rate is the sum of current rate and expected increase in composting rate in the next five years. Expected increase in composting rate is determined according to expected capacity addition to composting. Expected capacity addition to composting is calculated according to the average capacity additions for the composting facility during the past five years.

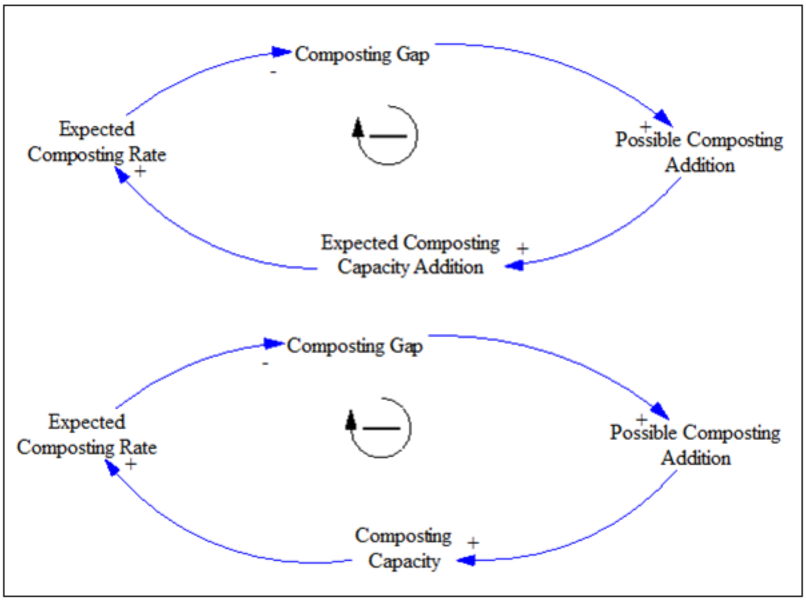


Figure 6.6. Composting Negative Loops.

The negative loops showing these causal relations for composting are given in Figure 6.6. As composting gap increases, possible composting addition increases. Possible composting addition has a positive impact on expected capacity addition to composting and composting capacity. Expected composting rate is positively affected by expected capacity addition to composting since expected composting rate is the sum of current composting rate and expected increase in the composting rate. Lastly, as expected composting rate increases, composting gap decreases, since composting gap is the difference between expected composting need and expected composting rate.

Recycling and incineration capacity additions follow essentially the same procedure.

While constructing this part of the model, the assumptions on depreciations, delay time of capacity investment and thresholds were made. In the model, it was assumed that total capacity of a facility consists of new and old capacity. Newly added capacities to a facility are considered old after six years, and the facility only depreciates from its old capacity. Composting and incineration facilities lose 1 in 20 of their old capacities every year whereas recycling capacity loses 1 in 15 of its old capacity [33–35]. When an investment decision is made, the required money is immediately withdrawn from the budget but capacity additon is observed five years later. As stated the reason behind is that building new facilities and acquiring necessary equipment take time. Thus, delay time of the capacity investments was specified as five years [13]. Investment thresholds for composting, recycling and incineration were assumed to be 40 million TL, 120 million TL and 480 million TL, respectively. The reason for having a different investment threshold for each operation is that each facility has a different unit capital cost.

6.3. Budget Allocation Sub-model

Incineration budget increases with incineration fund and decreases with incineration investments and depreciation expenses. Since as the facility loses some of its capacity with depreciation, the model tries to replace the lost capacity. Thus, if the incineration budget is greater than the money needed to replace all of the lost capacity, then all of the lost capacity is replaced. Otherwise, the capacity is added as much as the incineration budget allows.

Possible budget for incineration investments represents the money left for the incineration investments after depreciation expenses of the incineration facility are deducted. If the possible budget for incineration investments is greater than the money needed to cover incineration gap, then only enough money would be withdrawn from the budget to close the incineration gap. Otherwise, all of the budget for incineration investments would be withdrawn. Budget allocation sub-model for incineration is given in Figure 6.7.

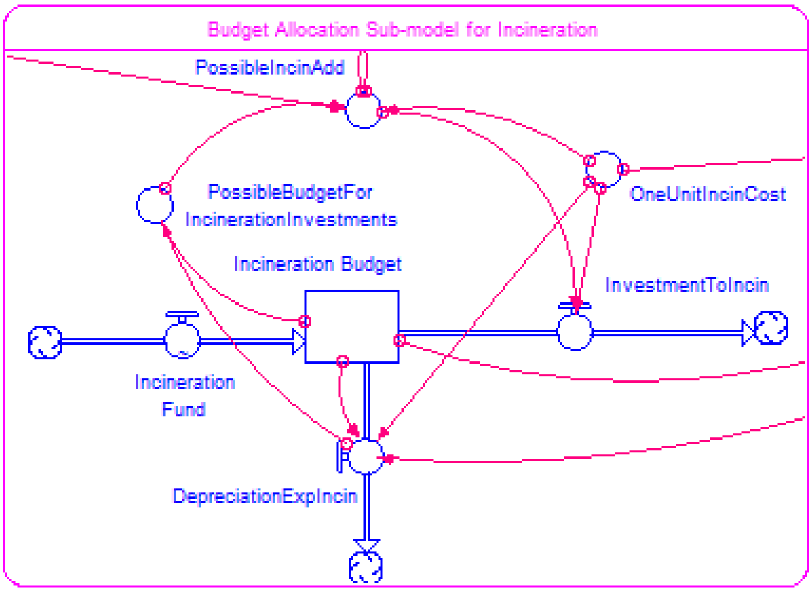


Figure 6.7. Budget Allocation Sub-model For Incineration.

Recycling and composting budget allocation follows essentially the same procedure. The only difference is that since there is a common fund for composting and recycling operations, the fund directed to composting and recycling budgets is proportional to the composting and recycling gaps.Budget allocation sub-model for composting and recycling is given in Figure 6.8.

Since the money directed to composting and recycling budgets is proportional to the composting and recycling gaps; as composting gap increases, money directed to composting budget increases as well. Thus, money directed to recycling budget and consequently possible recycling addition decrease. As possible recycling addition de-

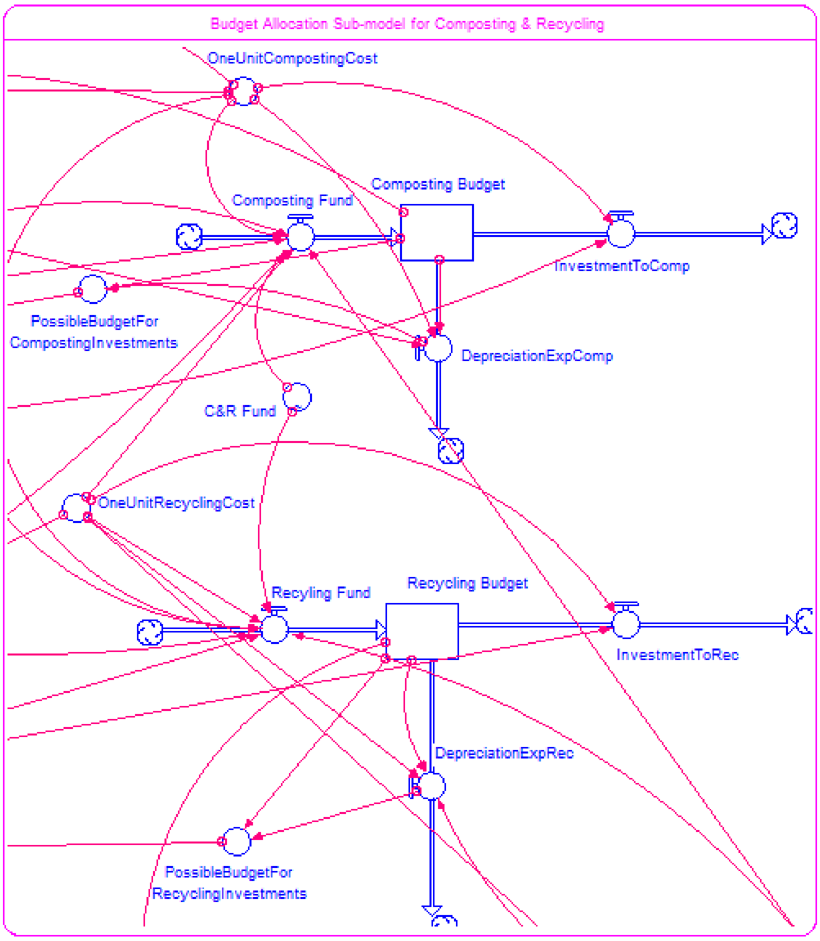


Figure 6.8. Budget Allocation Sub-model For Composting and Recycling.

creases, expected recycling rate decreases. This yields an increase in recycling gap since recycling gap is the difference between expected recycling need and expected recycling rate. As recycling gap increases, money directed to recycling budget increases as well. Thus, money directed to composting budget and consequently possible composting addition decrease. As possible composting addition decreases, expected composting rate decreases. It thus leads to an increase in composting gap. The positive loop showing these causal relations between composting and recycling is given in Figure 6.9.

While constructing this part of the model, the assumptions on one unit capital costs of composting, recycling, incineration and distribution of the fund to these operations were made. One unit (kt) capital costs of composting, recycling and incineration were assumed to be 175,000 TL, 525,000 TL and 1,875,500 TL, respectively [33–35].

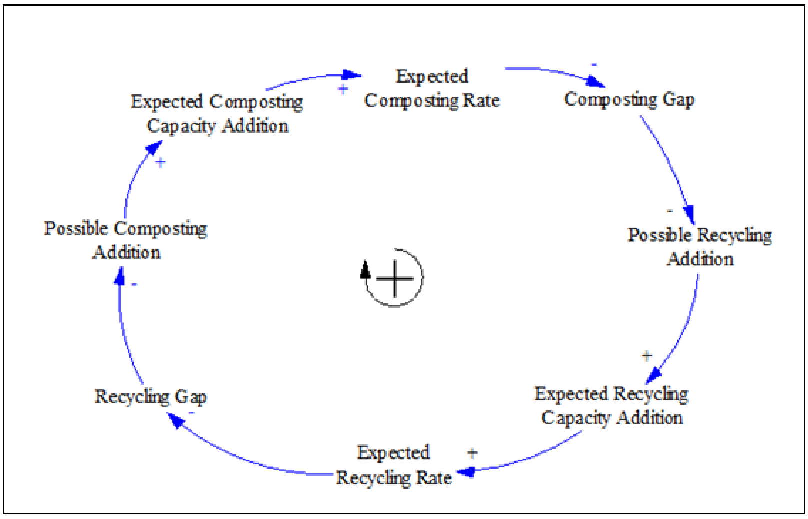


Figure 6.9. Composting-Recycling Positive Loop.

Moreover, it was assumed that fund is distributed to composting, recycling and incineration as follows: 1/3 of the fund is directed to incineration budget and rest of the fund is directed to composting and recycling budgets as proportional to composting and recycling gaps, respectively.

7. ANALYSIS AND VALIDATION OF THE MODEL

Stella 9.0.3 software is employed to build the model and to make the simulation experiments. Time unit is years whereas time step is determined as 1/4 year. Time horizon in most runs is 40 years starting from 2016. The horizon is suitable to be able to observe the direct, indirect, and delayed effects of the variables and feedback loops.

In the first part, dynamics in the base run are examined. Then, in the validation part, the experiments carried out to test the validity of the model are analysed.

7.1. Analysis of Base Behaviour

To simulate the base scenario starting from 2006, initial landfill waste was taken 32822 kt [13]. It was assumed that population increases from 12.44 million to 20 million between 2006 and 2056 whereas waste generation per person increases from 1,20 to 1,30 [11, 12]. Since both waste generation per person and population increase, waste generation rate increases.

It was assumed that capacity addition is only made to the composting facility as much as the depreciation rate of composting facility. In other words, investment is made just to keep the capacity of the composting facility constant.

Source separation rate linearly increases from 0,03 to 0,23 between 2006 and 2056. Since composting rate increases as source separation increases, composting rate becomes 77 kt/year from 70 kt/year with the increasing source separation rate.

Waste generation rate reaches to 9526,5 kt/year whereas the capacity of composting facility is still 260 kt/year in 2056. Since waste generation rate increases more than the composting rate, landfill waste increasingly grows and reaches to 424039 kt in 2056. Dynamics of landfill waste, waste generation rate and composting rate are given in Figure 7.1 and 7.2.

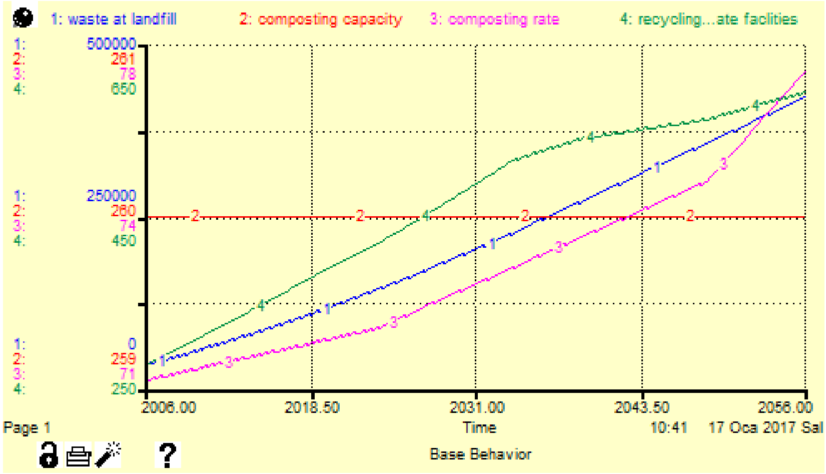


Figure 7.1. Landfill Waste, Capacity and Rates - Model's Base Behaviour Between 2006 and 2056.

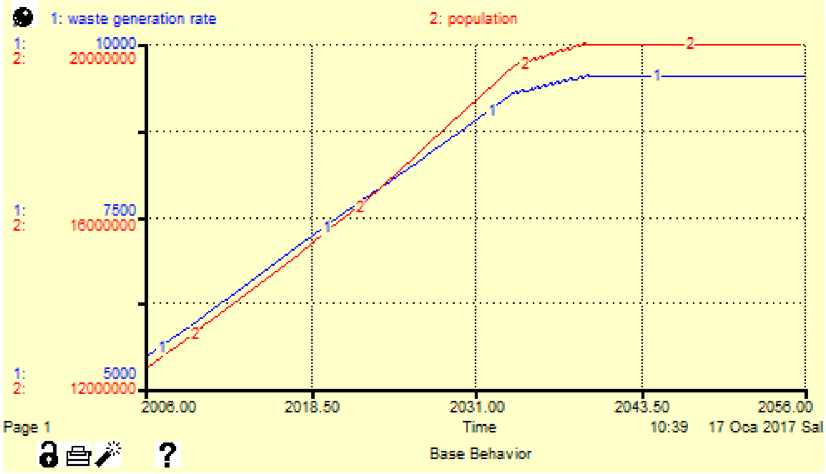


Figure 7.2. Waste Generation Rate and Population - Model's Base Behaviour Between 2006 and 2056.

When the base scenario is simulated for the years 2006-2016, it is possible to see that the base behaviour obtained through this model is compatible with the behaviour of the real system. The dynamics of the real system and the model for 2006-2016 can be seen from Figure 7.19-7.22 in validation section.

7.2. Validation of the Model

The objective of model validation is to ensure that the model is a reasonable description of the real system with respect to the dynamic problem [36]. Model validation consists of structure and behaviour validity.

7.2.1. Structure Validity

Structure test is used to confirm whether the structure of a model is a meaningful and valid description of the actual relations that exists in the dynamic problem. Two types of structure tests exist: direct structure tests and indirect structure tests [36].

Direct structure tests examine the validity of the model equations through direct comparison with real system structure. Main direct structure tests are parameter and variable confirmation, dimensional consistency and meaningfulness of equations testing [36]. Applying these tests, all variables and parameters in the model have counterparts in real life. No dimensional inconsistency exists in the equations. Dimensions of all the parameters and variables are given in Table 1. All equations in the model satisfy extreme condition tests.

Extreme condition test via simulation is one of the most important indirect structure tests. Extreme values are assigned to chosen variables and observed behavior is compared to expected behavior of the real system under extreme conditions [36]. Extreme condition test with variables, population and source separation, are carried out.

7.2.1.1. Extreme Condition 1. Population is set to increase from 15 million to 50 million. Total fund is arranged by ensuring that net fund increases as proportional to the population growth. Net fund, the money left after depreciation expenses are deducted, increases from 30 to 660 million TL. Increase in the budget makes more capacity addition to composting, recycling and incineration facilities possible.

Figure 7.3. Landfill Waste and Capacities under Extreme Condition 1.

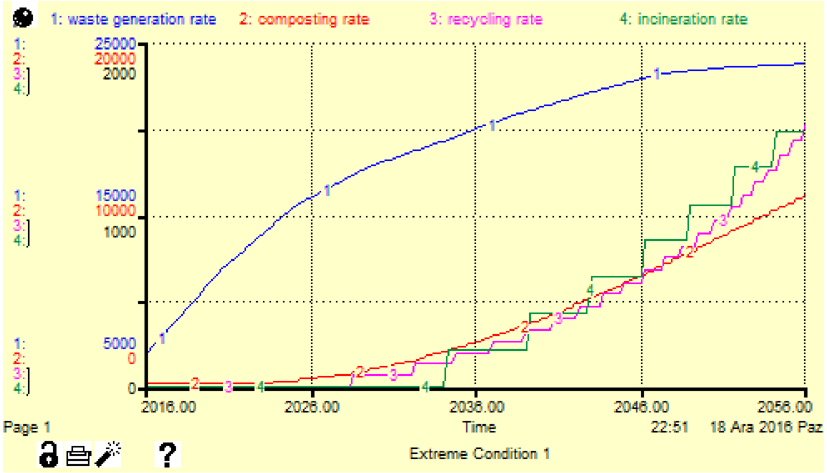


Figure 7.4. Rates under Extreme Condition 1.

However, landfill waste increases as well since waste generation rate increases along with population. If population shows such a dramatic increase, landfill waste is expected to reach 625878 kt in 2056. In other words, landfill area become 1425,7 ha in 2056.

Capacities of composting, recycling and incineration facilities would be 20288 kt/year, 5556 kt/year and 1859 kt/year in 2056, respectively. Waste generation rate becomes 23805 kt/year at the end of the simulation whereas composting, recycling and

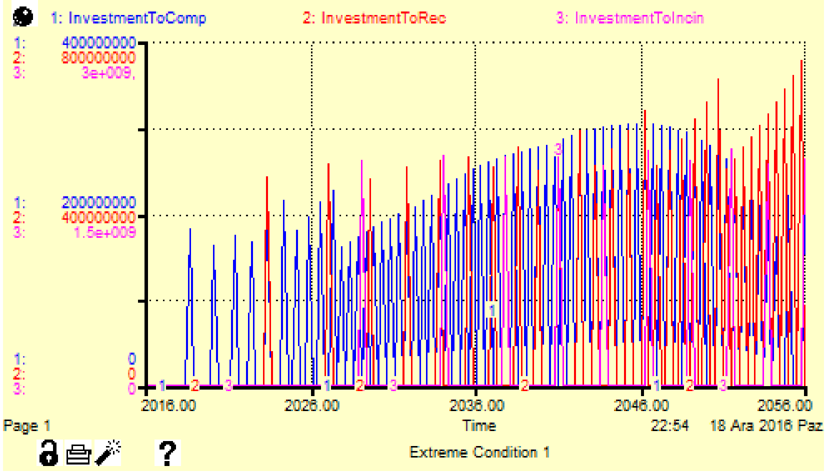


Figure 7.5. Investment to Facilities under Extreme Condition 1.

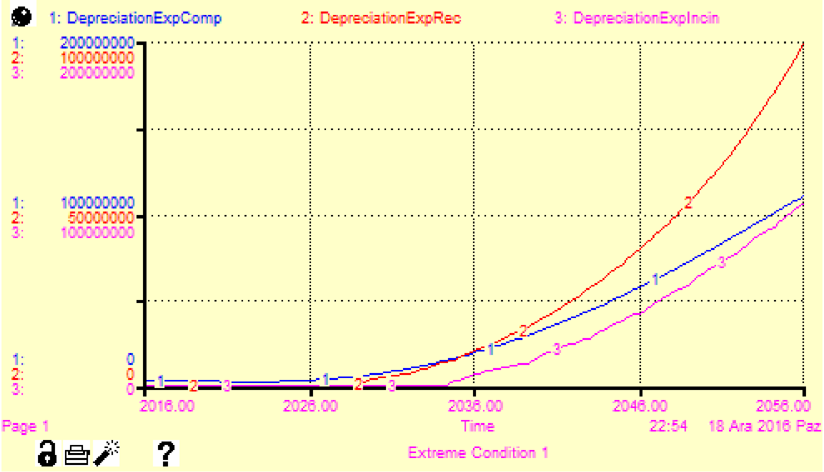


Figure 7.6. Depreciation Expenses under Extreme Condition 1.

incineration rates reach to 10906 kt/year, 1431 kt/year and 1488 kt/year, respectively. Figure 7.3-7.5 indicate that capacity investments are quite frequent. The reason behind is that budget drastically increases over time along with the population growth. As the budget increases, money directed to capacity investments goes up, and consequently more capacity investments occur. Depreciation expenses increase with an increasing rate along with the capacities. In conclusion, dynamics of the model under this extreme condition are logical and acceptable.

7.2.1.2. Extreme Condition 2. Population is set to decrease from 15 million to 5 million. Total fund allocated to capacity investments and expenses decreases from 30 million TL to 15 million TL, since population and budget have a positive causal link. Decrease in the budget makes less capacity addition to composting, recycling and incineration facilities possible. Landfill waste decreasingly grows since waste generation rate decreases dramatically along with population. If population shows such a dramatic decrease, landfill waste is expected to be 221713 kt in 2056, corresponding to 505 ha.

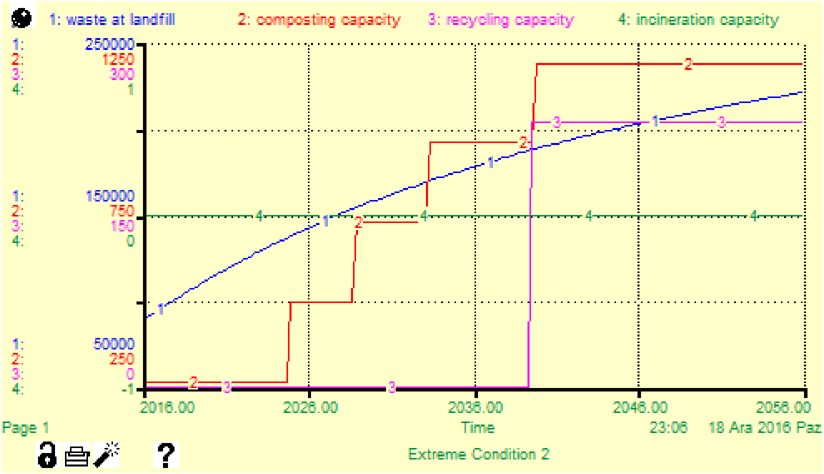


Figure 7.7. Landfill Waste and Capacities under Extreme Condition 2.

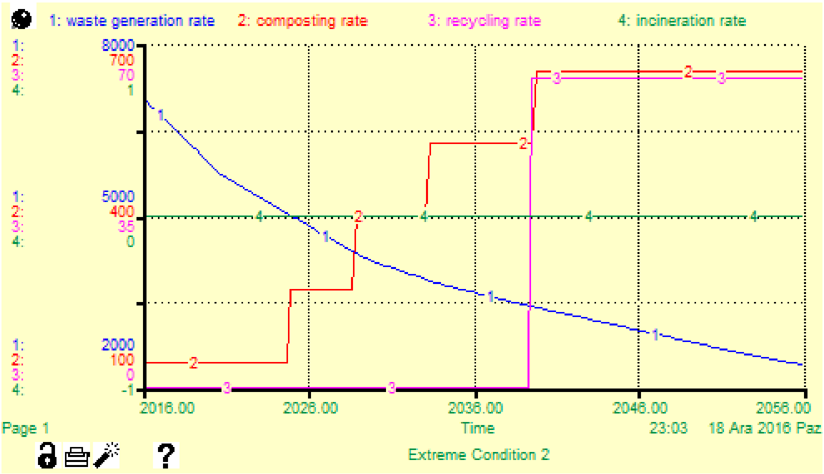


Figure 7.8. Rates under Extreme Condition 2.

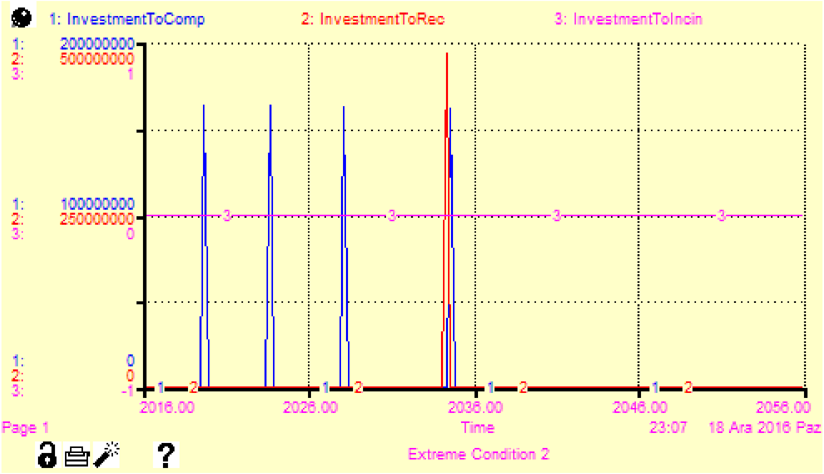


Figure 7.9. Investment to Facilities under Extreme Condition 2.

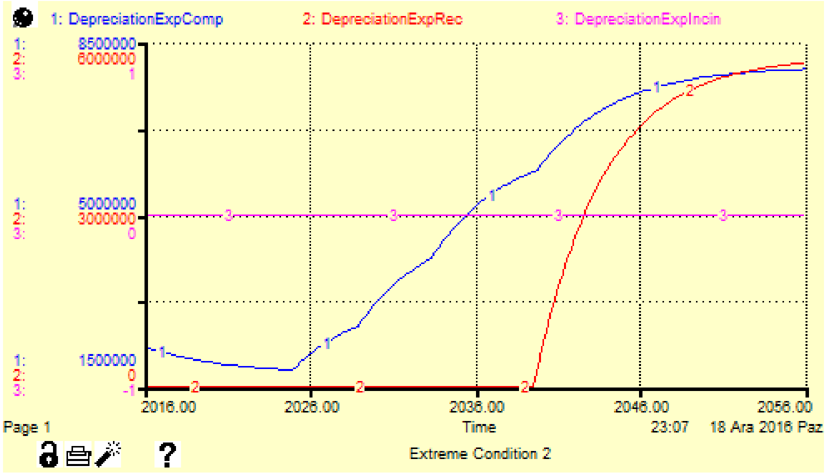


Figure 7.10. Depreciation Expenses under Extreme Condition 2.

Capacities of composting, recycling and incineration facilities would be 1193 kt/year, 231 kt/year and 0 kt/year, respectively. Waste generation rate becomes 2396 kt/year at the end of the simulation whereas composting, recycling and incineration rates become 654 kt/year, 63 kt/year, 0 kt/year, respectively. As it can be seen from the Figure 7.7-7.10, elapsed time between capacity additions increases as time goes by since budget decreases each year along with the population. In fact, composting and recycling investments end in the first 20 years of the time horizon. No incineration investment is made during 40 years because investment threshold for incineration, much higher than the investment thresholds for composting and recycling, could not be reached due to decreasing budget. Therefore, dynamics of the model under this extreme condition are reasonable as well.

7.2.1.3. Extreme Condition 3. Source separation rate is set to 1 (100%) in this test. Total money directed to capacity investments and expenses increases from 30 million TL to 210 million TL over the 40 years along with the population. Total fund is arranged by ensuring that increase of the net fund is proportional to the population growth. As stated, net fund is the money left after depreciation expenses are deducted. In this case, net fund increases from 30 to 120 million TL over 40 years.

Since composting and recycling facilities would receive separated waste instead of mixed waste and no resources would be allocated to separate the waste, facilities would be able to utilize all of their capacities. Thus, capacities of composting and recycling facilities can become equal to their rates.

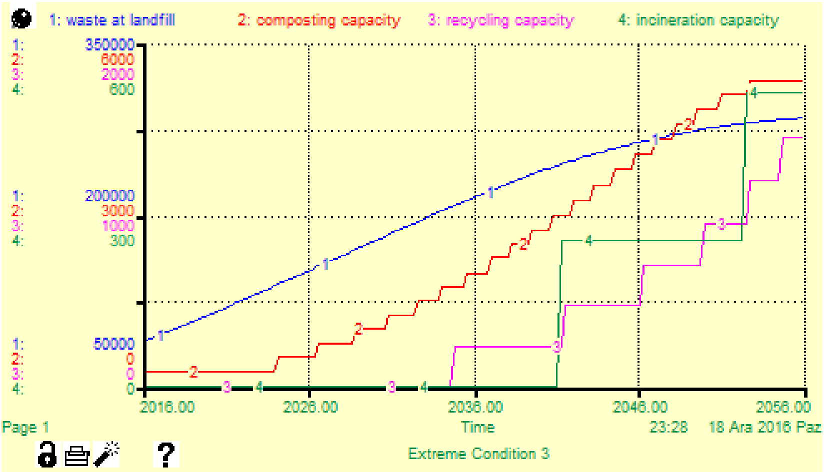


Figure 7.11. Landfill Waste and Capacities under Extreme Condition 3.

Source separation also positively affects recycling by private facilities, so as source separation increases, recyclable fraction of the waste collected by municipality can decrease. If source separation was 1, landfill waste would be expected to reach 285589

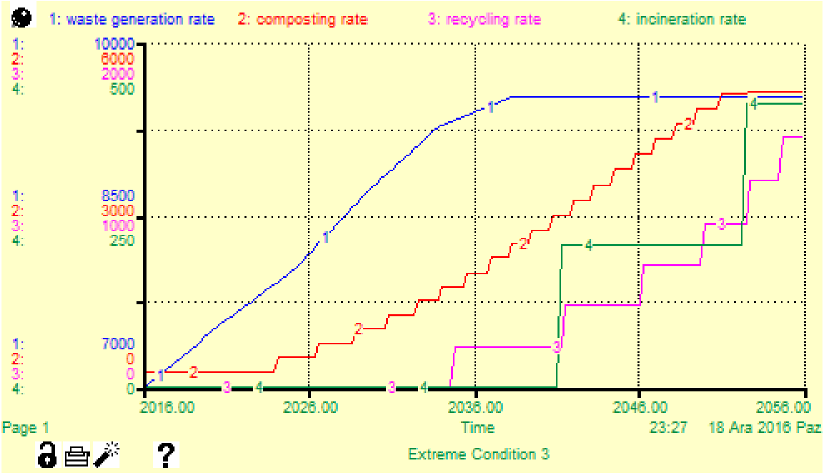


Figure 7.12. Rates under Extreme Condition 3.

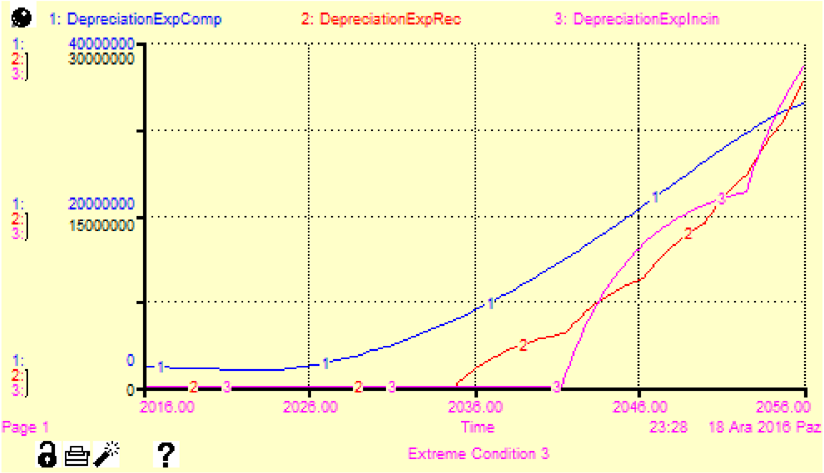


Figure 7.13. Investment to Facilities under Extreme Condition 3.

kt in 2056 and capacities of composting, recycling and incineration facilities would reach to 5362 kt/year, 1457 kt/year and 515 kt/year, respectively. Waste generation rate becomes 9526.5 kt/year at the end of the simulation, recycling rate becomes equal to recycling capacity. However, composting rate becomes 5144 kt/year which is lower than composting capacity. The reason behind it is that although composting facility is able to process 5362 kt organic waste per year in 2056, only 5144 kt organic waste will be generated. Incineration rate becomes equal to 80% of its capacity since 20% of the waste received by incineration facility is sent back to landfill because 20% of the waste is left as residue after incineration processes.

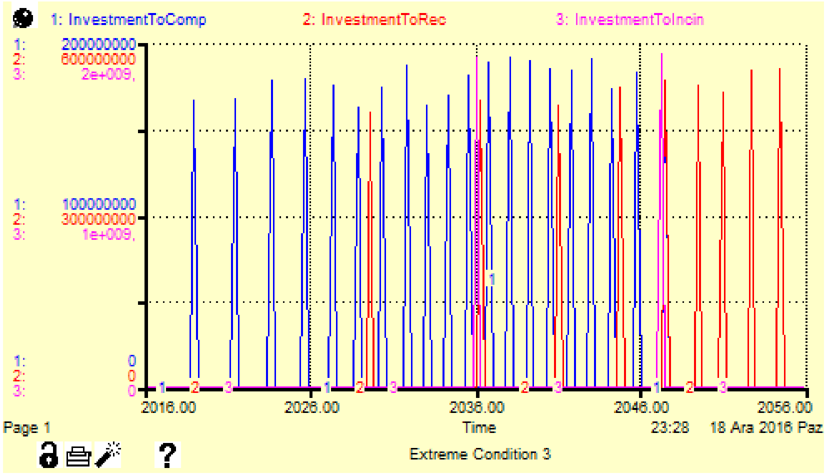


Figure 7.14. Depreciation Expenses under Extreme Condition 3.

As it can be seen from the Figure 7.11-7.14, capacities of composting, recycling and incineration facilities increase stepwise. Around 2040, investment frequency for composting starts to decrease whereas frequency for recycling starts to increase because gap recycling becomes much greater than composting gap, consequently most of the composting & recycling fund is directed to recycling budget and the rest is directed to composting budget to cover depreciation expenses. Moreover, since investment threshold for composting is much smaller than the investment thresholds for recycling and incineration, depreciation expenses of composting exhibit smoother behaviour than the others. To conclude, dynamics of the model under this extreme condition are logical.

7.2.1.4. Extreme Condition 4. In this test, source separation rate is set to 0,0001. Since composting and recycling facilities would receive mixed waste, composting and recycling rate would be equal to compostable and recyclable fraction of the waste they receive, respectively. It also negatively affects recycling by private facilities because private facilities mainly collect source separated waste. When source separated waste is very low, they would have to separate the waste themselves and it would decrease their performance.

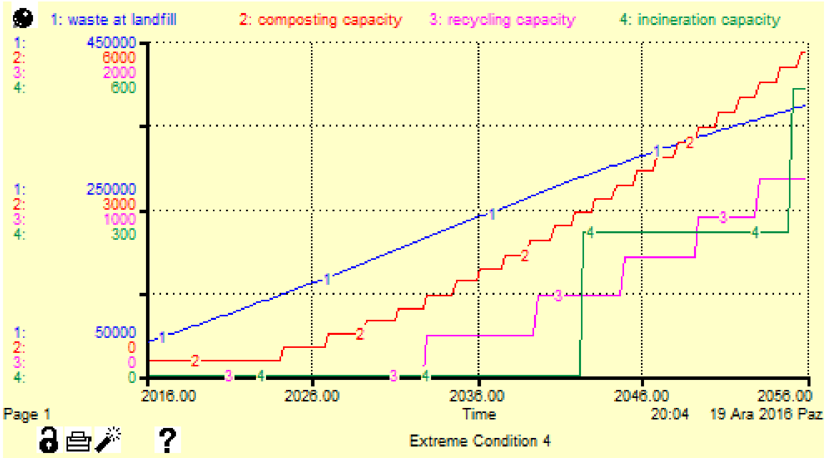


Figure 7.15. Landfill Waste and Capacities under Extreme Condition 4.

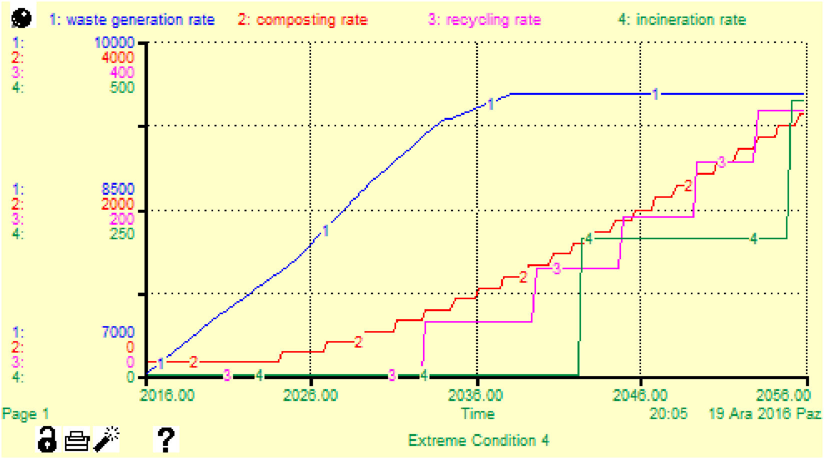


Figure 7.16. Rates under Extreme Condition 4.

Landfill waste would be expected to reach 373434 kt in 2056 and capacities of composting, recycling and incineration facilities would reach to 5812 kt/year, 1178 kt/year and 514 kt/year, respectively. Composting, recycling and incineration rates would be 3139 kt/year, 318 kt/year and 412 kt/year, respectively whereas waste generation rate would be 9526.5 kt/year at the end of the simulation. As it is expected, although capacities of the facilities are quite similar, rates obtained in this run are much lower than the ones obtained in extreme condition 3 (see Figure 7.15-7.18). Therefore, it is possible to say that dynamics of the model under this extreme condition are rational.

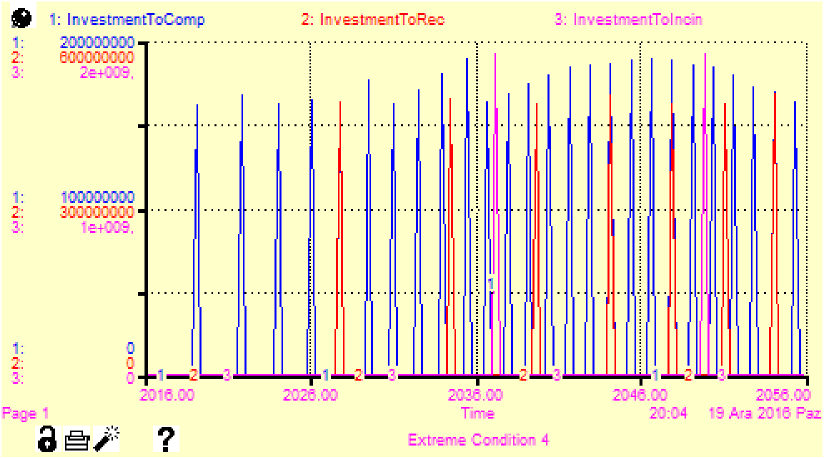


Figure 7.17. Investment to Facilities under Extreme Condition 4.

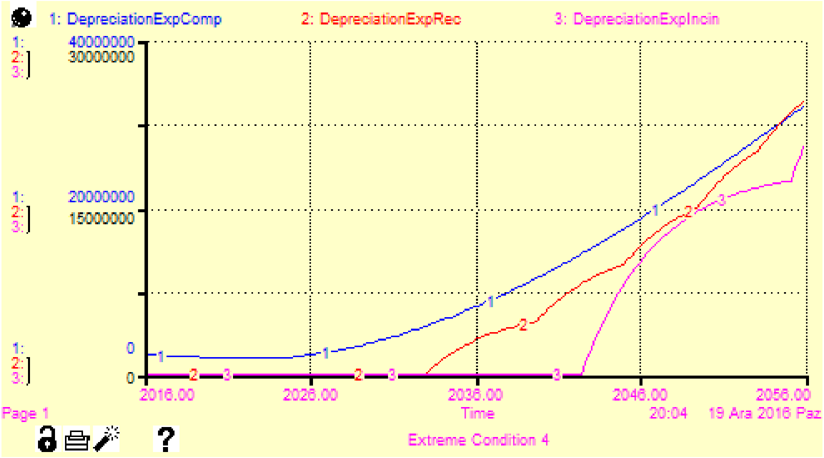


Figure 7.18. Depreciation Expenses under Extreme Condition 4.

7.2.2. Behaviour Validity

After the model passes the structural tests, behaviour validity of the model is tested. Behaviour validity tests are performed to check whether the model generates similar dynamics to the real system in similar input conditions. Behaviour validity test for system dynamics models is about pattern prediction rather than point prediction [36].

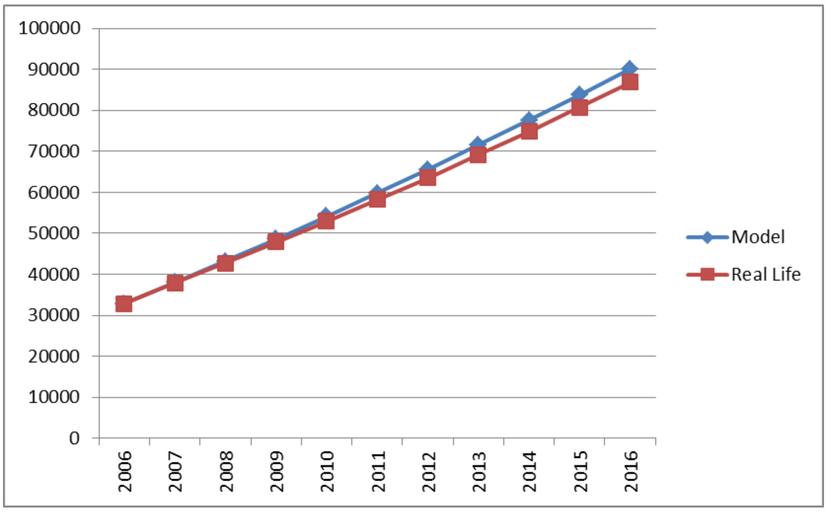


Figure 7.19. Landfill Waste Patterns of the Model and Real Life for 2006-2016.

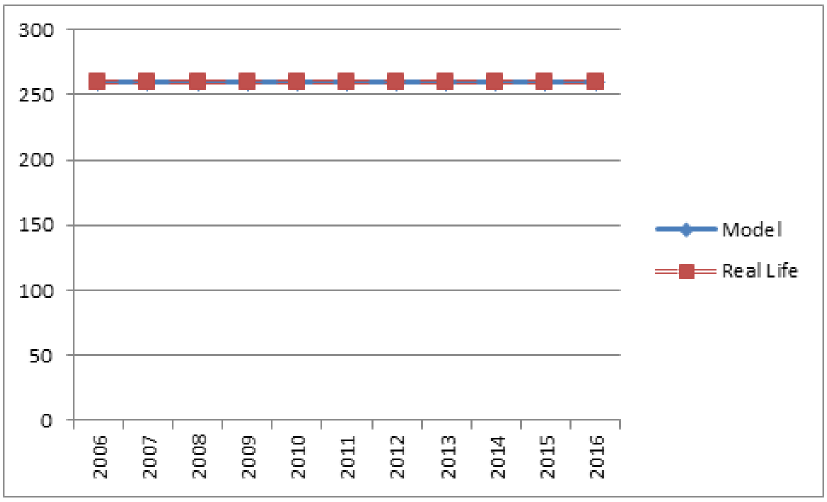


Figure 7.20. Composting Capacity in Real Life and the Model for 2006-2016.

Pattern of the data obtained for the years 2006-2016 is compared with the pattern produced by the model. As it can be seen through Figure 7.19 -7.22, model generates quite similar dynamics to the real system.

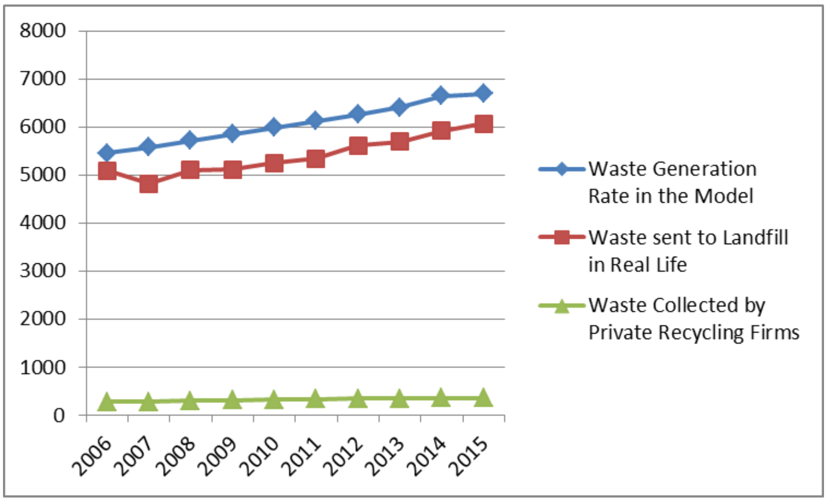


Figure 7.21. Waste Rates in Real Life and the Model for 2006-2016.

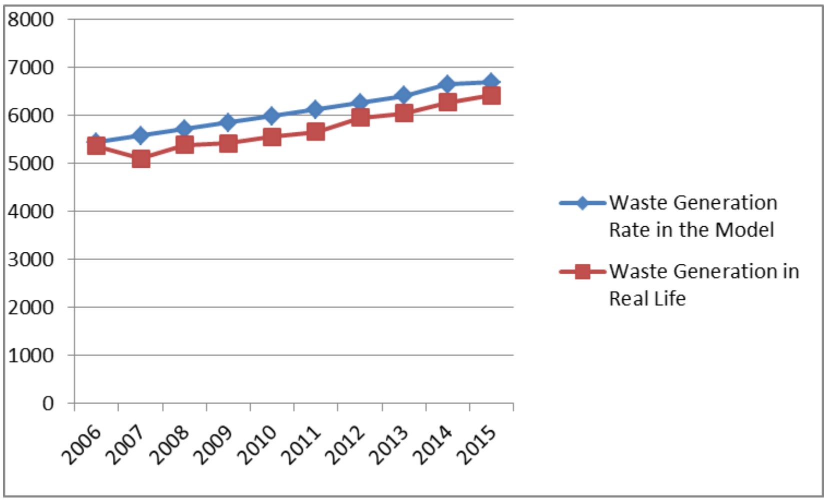


Figure 7.22. Waste Generation Rate in Real Life and the Model for 2006-2016.

8. SENSITIVITY ANALYSIS

Behaviour sensitivity test enables its users to find those parameters to which the model is highly sensitive and investigating if the real system would show such a high sensitivity to these parameters [36]. Summary of sensitivity analysis is given in this section. Sensitivities of the four variables, population, waste generation per person, source separation and budget, are examined because these variables are expected to be responsible for the system's behaviour.

8.1. Population

In the base run, population was set to increase from 15 million to 20 million over 40 years. In sensitivity runs, population starts from 15 million and reaches to 25, 30 and 40 million.

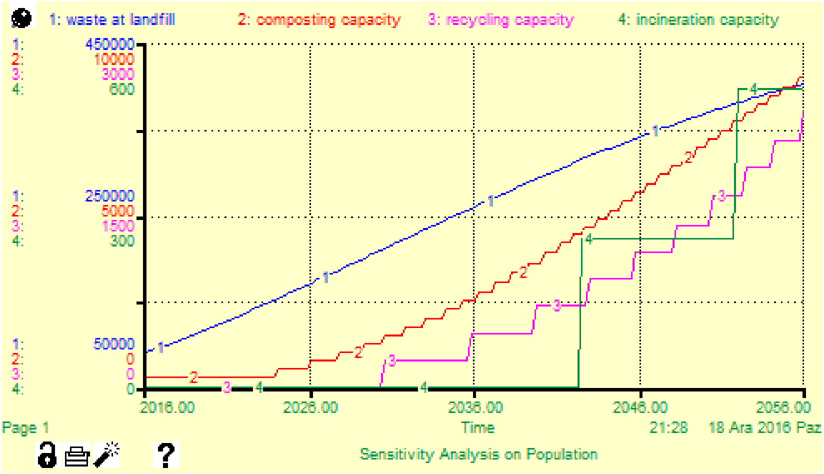


Figure 8.1. Landfill Waste and Capacities-Population Sensitivity Analysis 1.

When population increases to 25 million over 40 years, dynamics of landfill waste, capacities and rates of composting, recycling and incineration facilities can be seen from Figure 8.1 and 8.2. Along with the population growth, total fund increases from 30 million to 340 million TL, and net fund increases from 30 million to 210 million TL. Landfill waste reaches to 403391 kt in 2056 whereas the capacities of composting, recycling and incineration become 9008 kt/year, 2414 kt/year and 521 kt/year, respectively. Waste generation rate becomes 11749 kt/year at the end of this run whereas composting, recycling and incineration rates become 4937 kt/year, 591 kt/year and 417 kt/year, respectively.

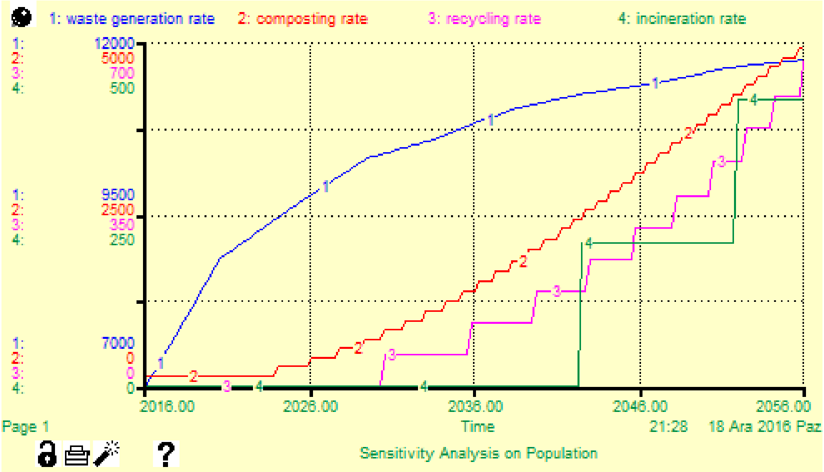


Figure 8.2. Rates-Population Sensitivity Analysis 1.

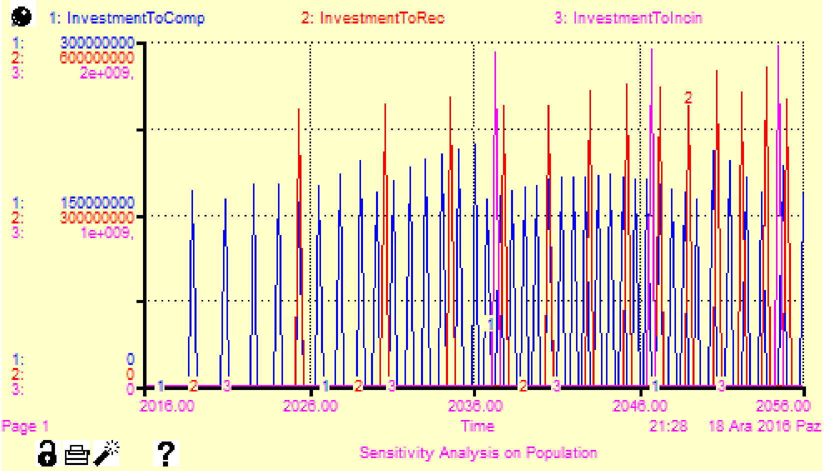


Figure 8.3. Investment to Facilities-Population Sensitivity Analysis 1.

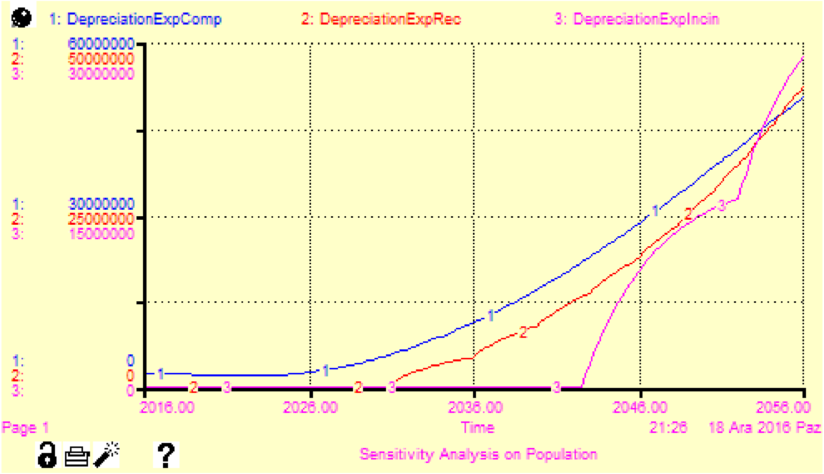


Figure 8.4. Depreciation Expenses-Population Sensitivity Analysis 1.

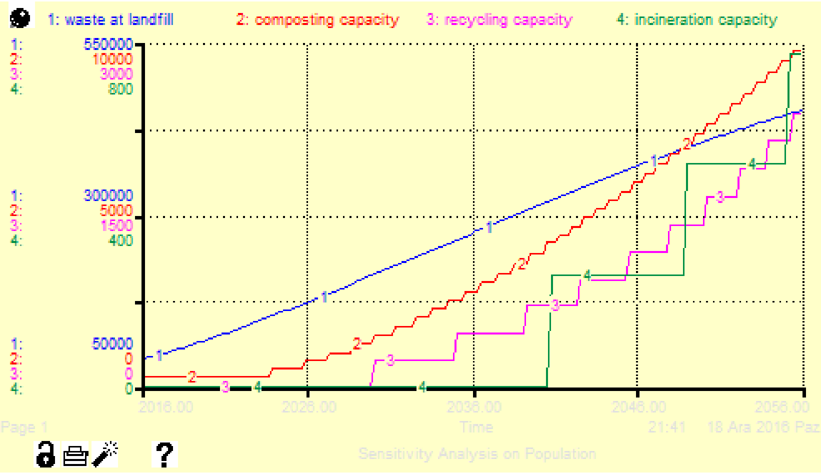


Figure 8.5. Landfill Waste and Capacities-Population Sensitivity Analysis 2.

When population increases to 30 million, changes in landfill waste, capacities and rates of composting, recycling and incineration facilities are presented in Figure 8.5 and 8.6. Along with the population growth, total fund increases from 30 million to 430 million TL, and net fund increases from 30 million to 300 million TL. Landfill waste reaches to 452986 kt in 2056 whereas the capacities of composting, recycling and incineration become 9822 kt/year, 2386 kt/year and 776 kt/year, respectively. Waste generation rate becomes 14276 kt/year at the end of this run whereas composting, recycling and incineration rates become 5383 kt/year, 655 kt/year and 621 kt/year, respectively.

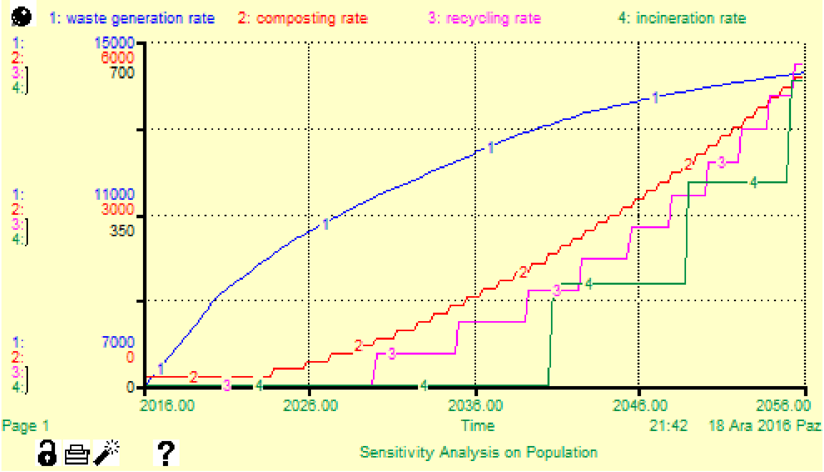


Figure 8.6. Rates-Population Sensitivity Analysis 2.

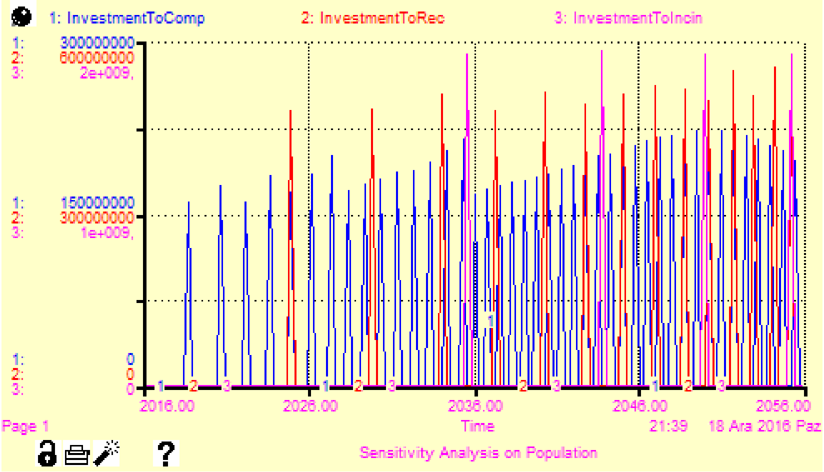


Figure 8.7. Investment to Facilities-Population Sensitivity Analysis 2.

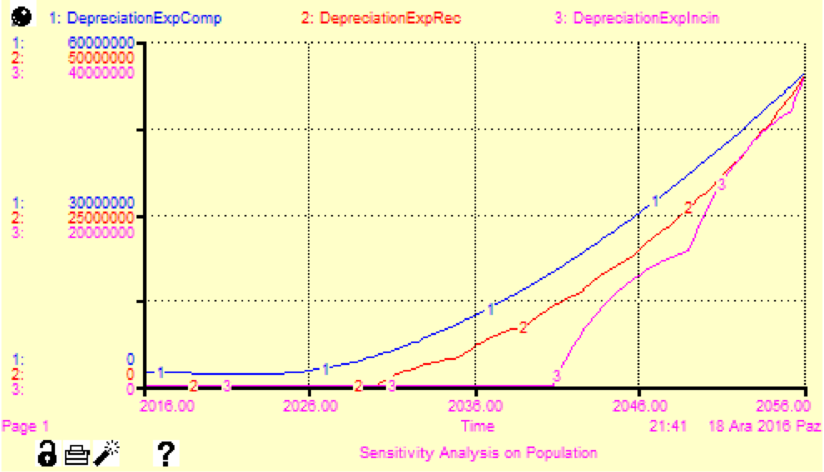


Figure 8.8. Depreciation Expenses-Population Sensitivity Analysis 2.

When population increases to 40 million, dynamics of landfill waste, capacities and rates of composting, recycling and incineration facilities are provided in Figure 8.9 and 8.10. Along with the population growth, total fund increases from 30 million to approximately 645 million TL, and net fund increases from 30 million to 480 million TL. Landfill waste reaches to 552658 kt in 2056 whereas the capacities of composting, recycling and incineration become 12899 kt/year, 3014 kt/year and 780 kt/year, respectively. Waste generation rate becomes 19024 kt/year at the end of this run whereas composting, recycling and incineration rates are 7070 kt/year, 827 kt/year and 624 kt/year, respectively.

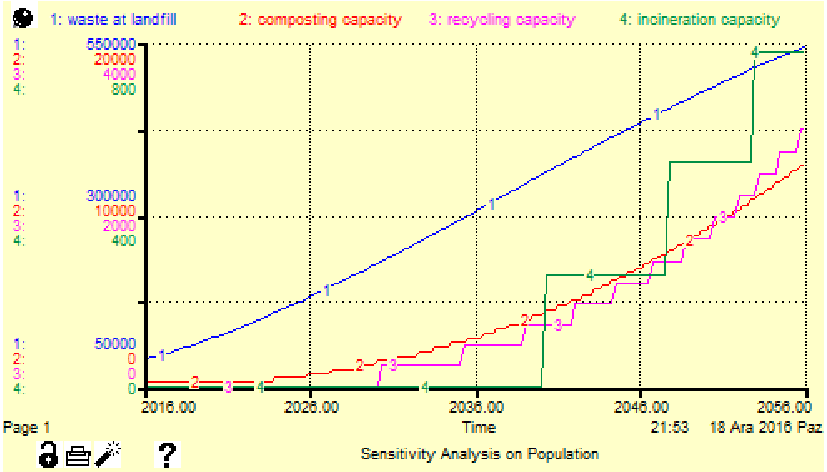


Figure 8.9. Landfill Waste and Capacities-Population Sensitivity Analysis 3.

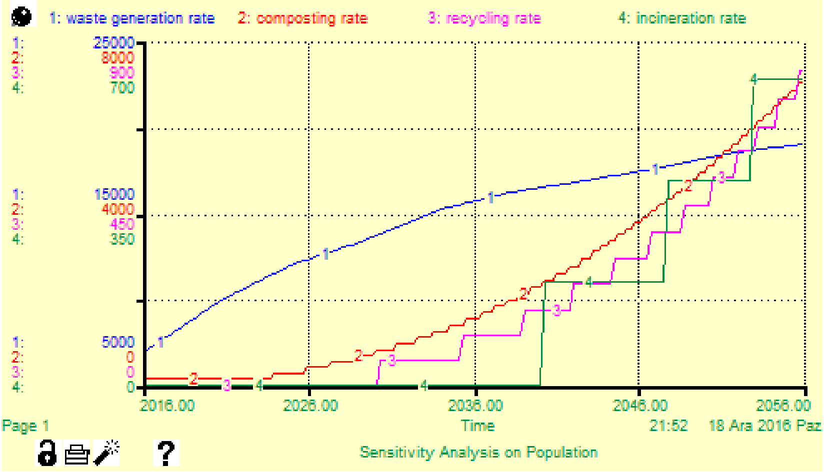


Figure 8.10. Rates-Population Sensitivity Analysis 3.

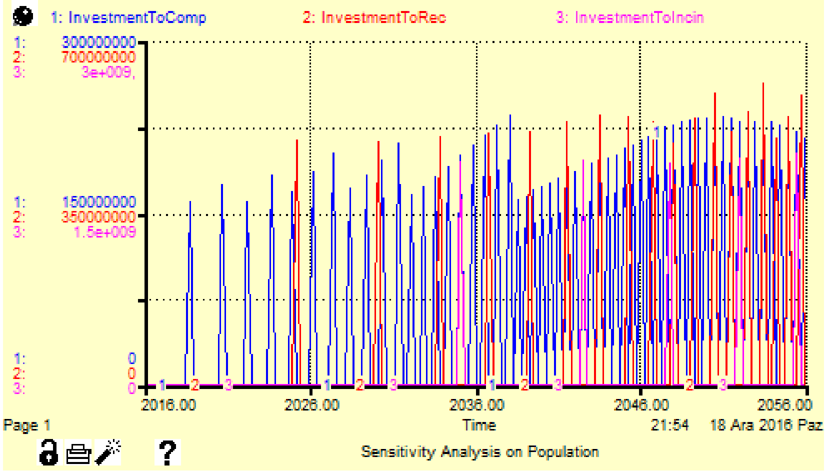


Figure 8.11. Investment to Facilities-Population Sensitivity Analysis 3.

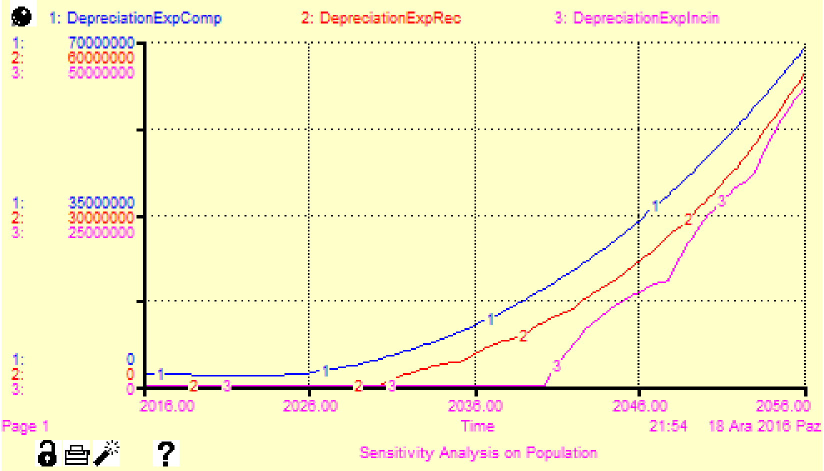


Figure 8.12. Depreciation Expenses-Population Sensitivity Analysis 3.

From the results, it can be seen that as population increases, waste generation rate, money directed to capacity investments, and consequently total capacity additions to facilities increase. However, since there is a common fund proportionally directed to both composting and recycling budgets according to composting and recycling gaps, capacities of both composting and recycling might not increase (see Table 8.1). If one of the gaps is much higher than the other, most of the common fund will be directed to the one with the higher gap. Thus, the capacity of the one with the lower gap might not increase. Moreover, landfill waste obviously increases together with the increasing population growth.

Table 8.1. Results of Population Sensitivity Runs.

Population (million)	**Landfill Waste(kt)**	**Composting Capacity (kt/year)**	**Recycling Capacity (kt/year)**	**Incineration Capacity (kt/year)**
15 to 25	403391	9008	2414	521
15 to 30	452986	9822	2386	776
15 to 40	552658	12899	3014	780

8.2. Source Separation

In the base run, source separation rate increases to 0,23. In sensitivity runs, source separation rate changes between 0,2 and 0,8.

When source separation rate is set to 0,2, changes in landfill waste, composting, recycling and incineration rates are given in Figure 8.13 and 8.14. In this run, net fund increases from 30 to 120 million TL together with growing population. Landfill waste reaches to 360121 kt in 2056 whereas the capacities of composting, recycling and incineration become 6155 kt/year, 1412 kt/year and 256 kt/year, respectively.

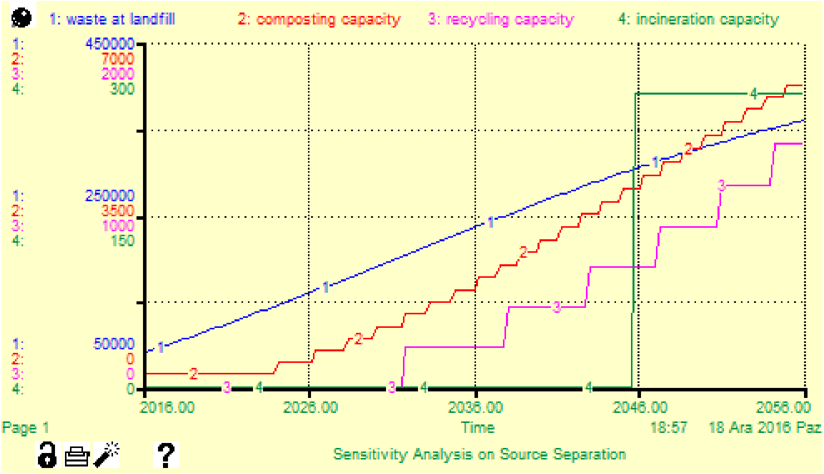


Figure 8.13. Landfill Waste and Capacities-Source Separation Sensitivity Analysis 1.

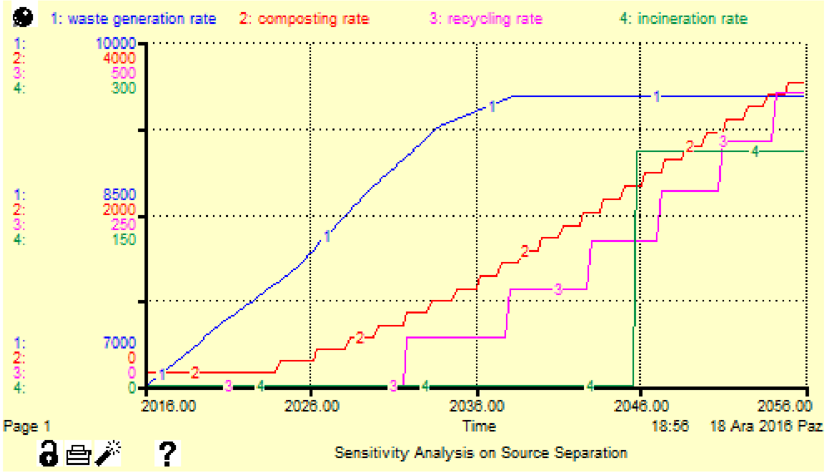


Figure 8.14. Rates-Source Separation Sensitivity Analysis 1.

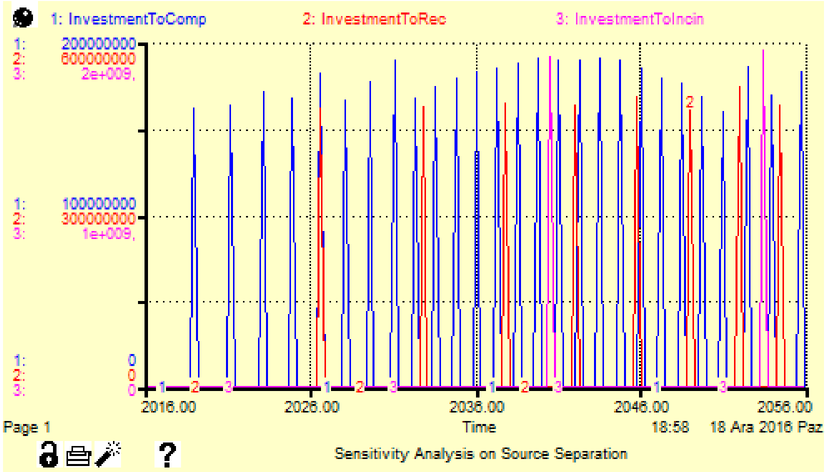


Figure 8.15. Investment to Facilities-Source Separation Sensitivity Analysis 1.

Waste generation rate becomes 9526.5 kt/year at the end of this run whereas composting, recycling and incineration rates are 3536 kt/year, 427.5 kt/year and 205 kt/year, respectively.

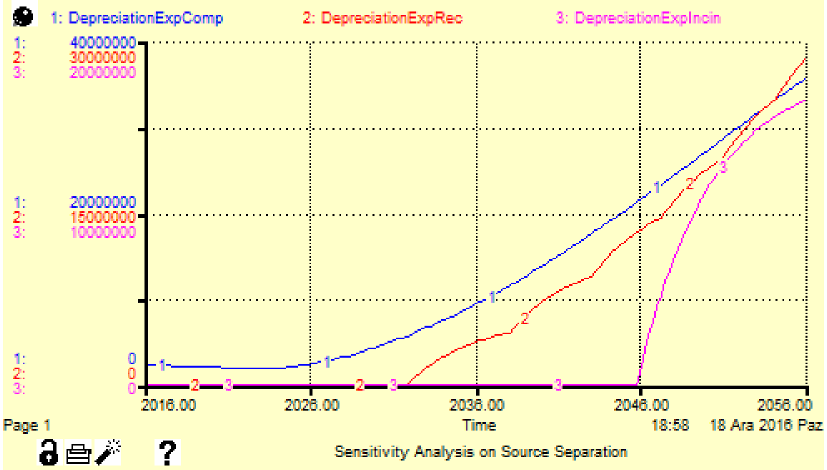


Figure 8.16. Depreciation Expenses-Source Separation Sensitivity Analysis 1.

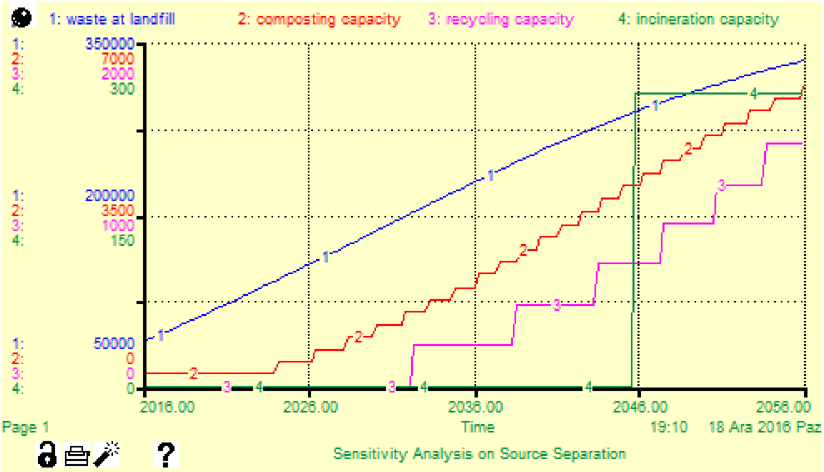


Figure 8.17. Landfill Waste and Capacities-Source Separation Sensitivity Analysis 2.

When source separation rate is set to 0,4, dynamics of landfill waste, composting, recycling and incineration rates can be seen from Figure 8.17 and 8.18. Landfill waste reaches to 334910 kt in 2056 whereas the capacities of composting, recycling and incineration become 6109, 1420 and 256 kt/year, respectively. Waste generation rate becomes 9526.5 kt/year at the end of this run whereas composting, recycling and incineration rates become 4260 kt/year, 602 kt/year and 205 kt/year, respectively.

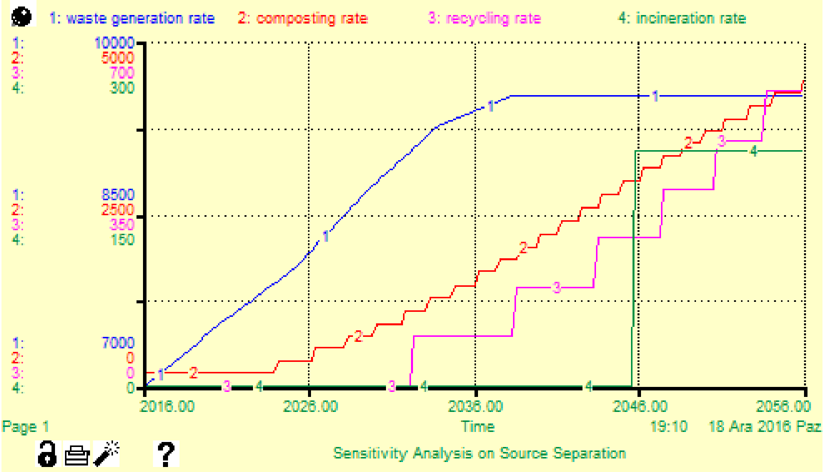


Figure 8.18. Rates-Source Separation Sensitivity Analysis 2.

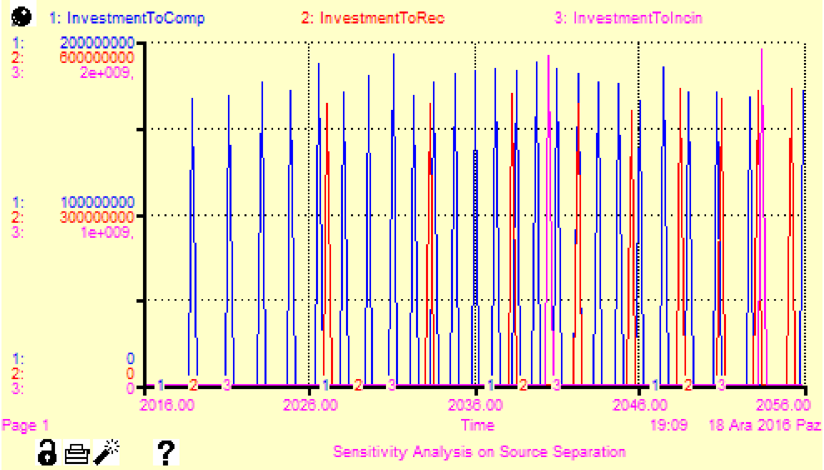


Figure 8.19. Investment to Facilities-Source Separation Sensitivity Analysis 2.

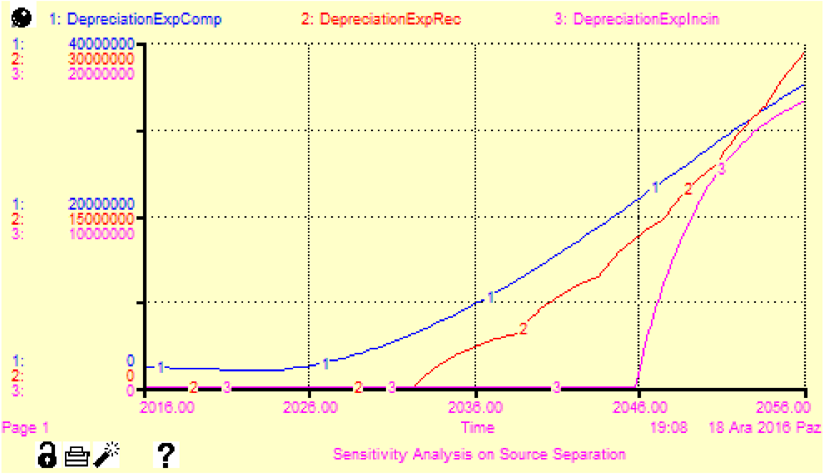


Figure 8.20. Depreciation Expenses-Source Separation Sensitivity Analysis 2.

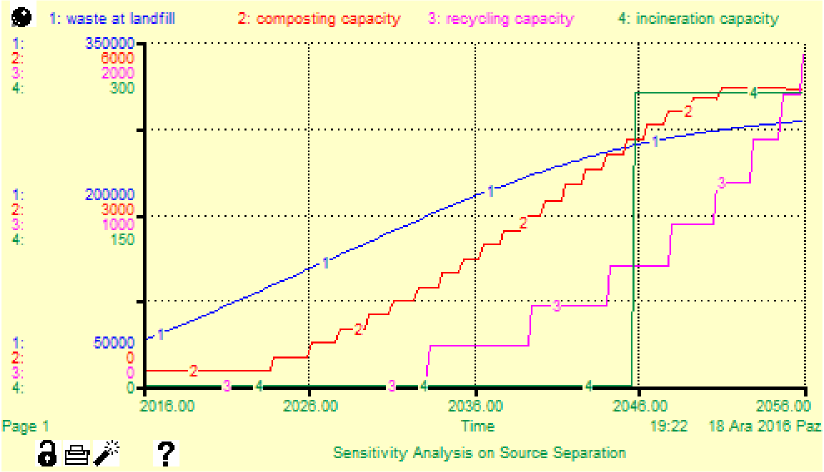


Figure 8.21. Landfill Waste and Capacities-Source Separation Sensitivity Analysis 3.

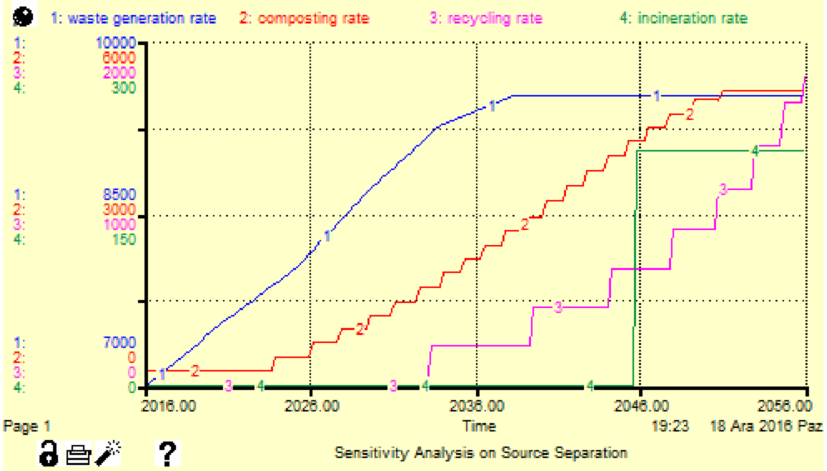


Figure 8.22. Rates-Source Separation Sensitivity Analysis 3.

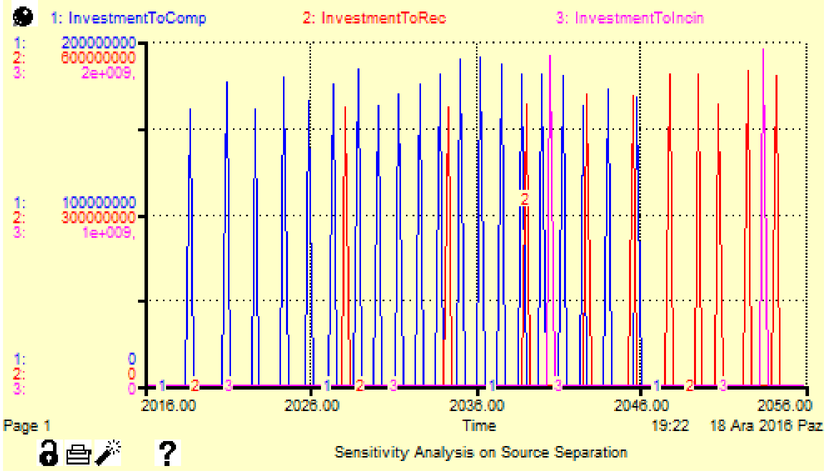


Figure 8.23. Investment to Facilities-Source Separation Sensitivity Analysis 3.

When source separation rate is set to 0,8, changes in landfill waste, composting, recycling and incineration rates are presented in Figure 8.21 and 8.22. Landfill waste reaches to 281517 kt in 2056 whereas the capacities of composting, recycling and incineration are 5196, 1934 and 256 kt/year, respectively. Waste generation rate becomes 9526.5 kt/year at the end of this run whereas composting, recycling and incineration rates become 5144 kt/year, 1646 kt/year and 205 kt/year, respectively.

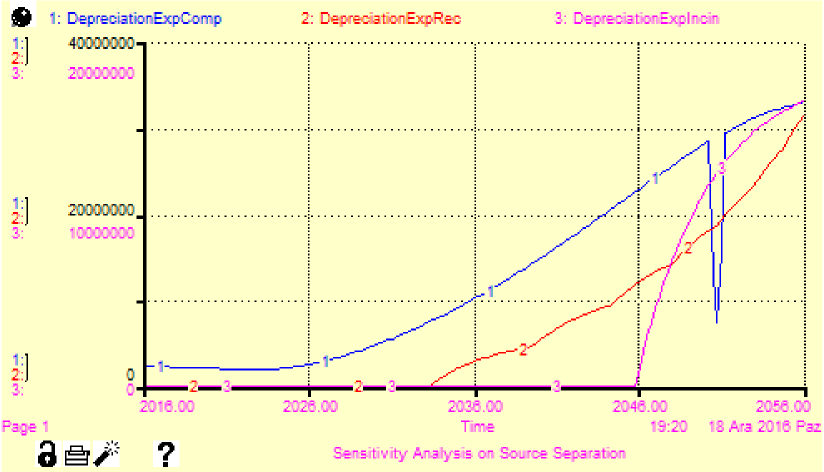


Figure 8.24. Depreciation Expenses-Source Separation Sensitivity Analysis 3.

It can be seen that composting and recycling rates increase along with source separation rate, however incineration rate stays the same (see Table 8.2). Incineration rate actually can be negatively affected by source separation rate because incineration rate is proportional to the minimum of incineration capacity and waste left after composting and recycling rates have been removed. In these runs, incineration rate did not decrease because incinerable (combustible) waste is much more than the incineration capacity for all source separation rates, thus even if incinerable waste decreases along with the increasing source separation, it is still higher than the incineration capacity. In other words, waste left after composting and recycling rates have been removed (incinerable waste) is greater than incineration capacity and incineration facility can receive waste up to its capacity, so incineration rate is not affected by source separation in these cases, since its rate is proportional to capacity of the plant.

Table 8.2. Results of Source Separation Sensitivity Runs.

Source Separation Rate	**Landfill Waste(kt)**	**Composting Rate (kt/year)**	**Recycling Rate (kt/year)**	**Incineration Rate (kt/year)**
0,2	360121	3536	427,5	205
0,4	334910	4260	602	205
0,8	281517	5144	1646	205

8.3. Waste Generation per Person

In the base run, waste generation per person was set to increase from 1,2 to 1,3 kg/day between 2006 and 2056. In sensitivity runs, waste generation per capita starts from 1,27 in 2016 and reaches to 1,4, 1,7 and 2 kg/day over 40 years.

When waste generation per person is set to increase from 1,27 to 1,4 kg/day over 40 years, changes in landfill waste, capacities and rates of composting, recycling and incineration are given in Figure 8.25 and 8.26. Landfill waste reaches to 386843 kt

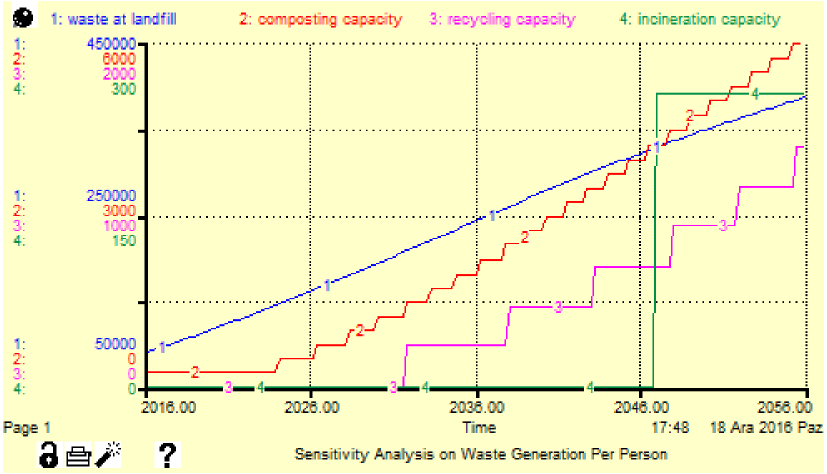


Figure 8.25. Landfill Waste and Capacities-Waste Generation per Person Sensitivity Analysis 1.

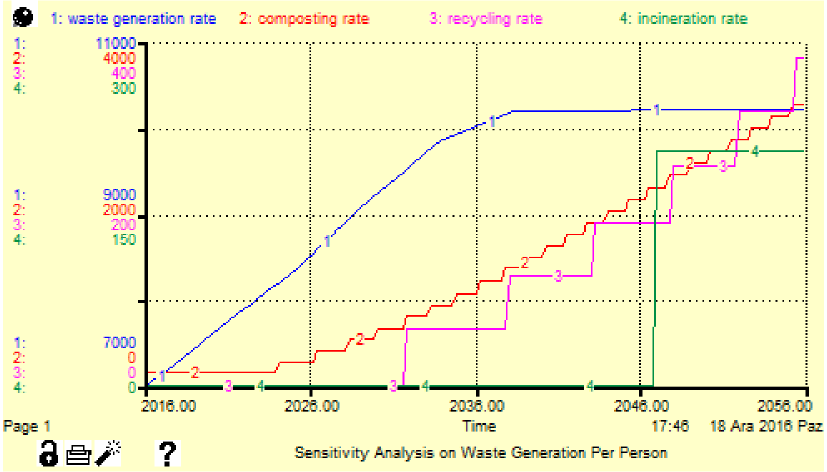


Figure 8.26. Rates-Waste Generation per Person Sensitivity Analysis 1.

in 2056 whereas the capacities of composting, recycling and incineration become 5996 kt/year, 1397 kt/year and 256 kt/year, respectively. Waste generation rate becomes 10220 kt/year at the end of this run whereas composting, recycling and incineration rates become 3286 kt/year, 383 kt/year and 205 kt/year, respectively.

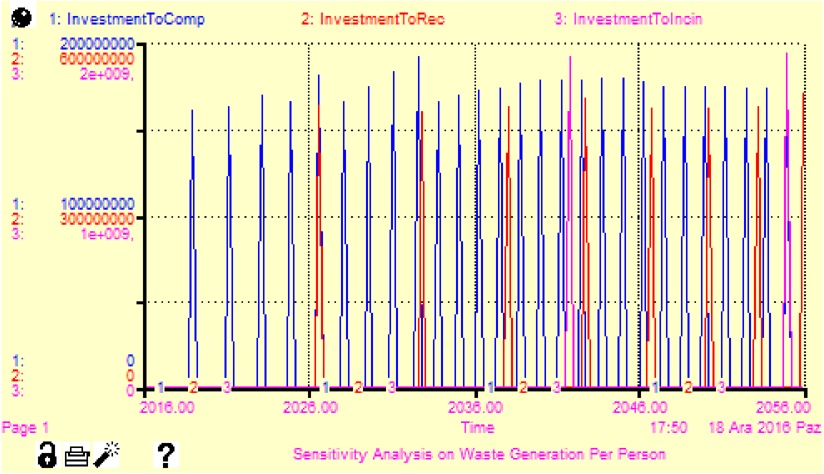


Figure 8.27. Investment to Facilities-Waste Generation per Person Sensitivity Analysis 1.

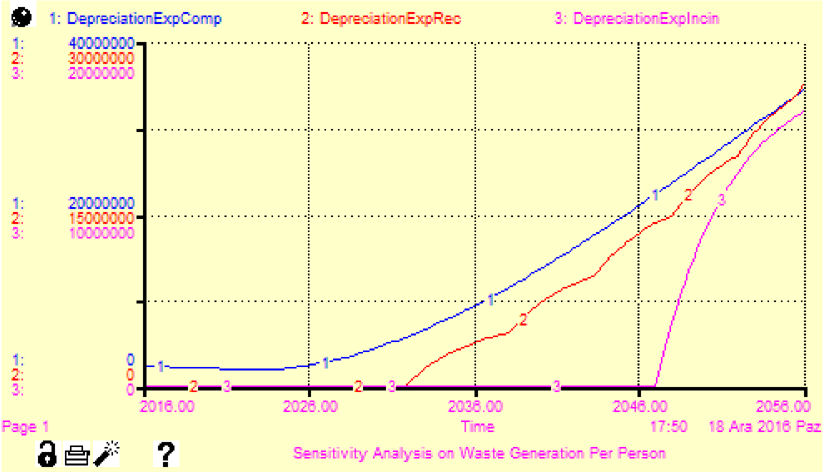


Figure 8.28. Depreciation Expenses-Waste Generation per Person Sensitivity Analysis 1.

When waste generation per capita is set to increase from 1,27 to 1,7 kg/day over 40 years, dynamics of landfill waste, capacities and rates of composting, recycling and incineration can be seen from Figure 8.29 and 8.30. Landfill waste reaches to 437919 kt in 2056 whereas the capacities of composting, recycling and incineration become 6099 kt/year, 1177 kt/year and 256 kt/year, respectively. Waste generation rate becomes 12410 kt/year at the end of this run whereas composting, recycling and incineration rates are 3342 kt/year, 323 kt/year and 205 kt/year, respectively.

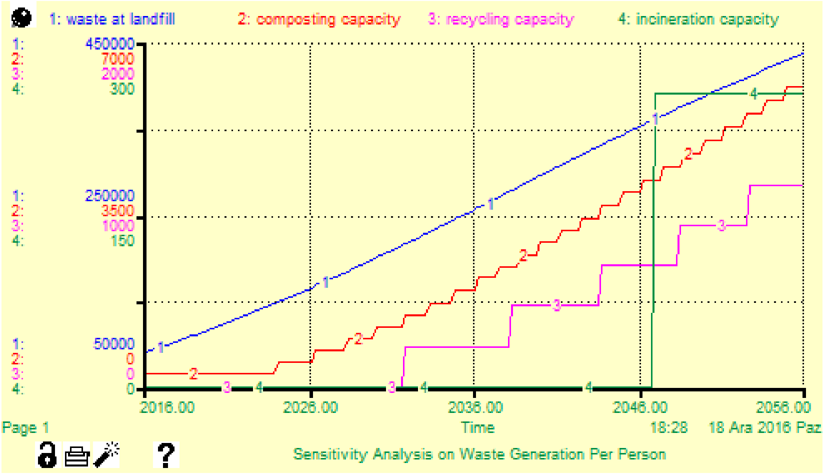


Figure 8.29. Landfill Waste and Capacities-Waste Generation per Person Sensitivity Analysis 2.

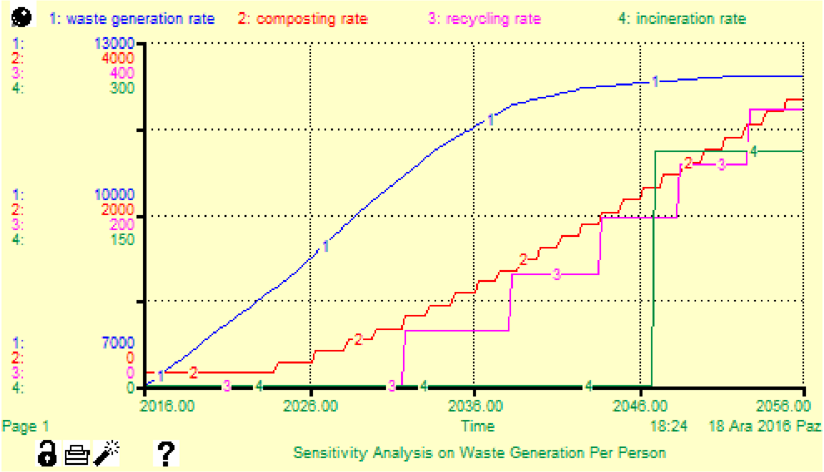


Figure 8.30. Rates-Waste Generation per Person Sensitivity Analysis 2.

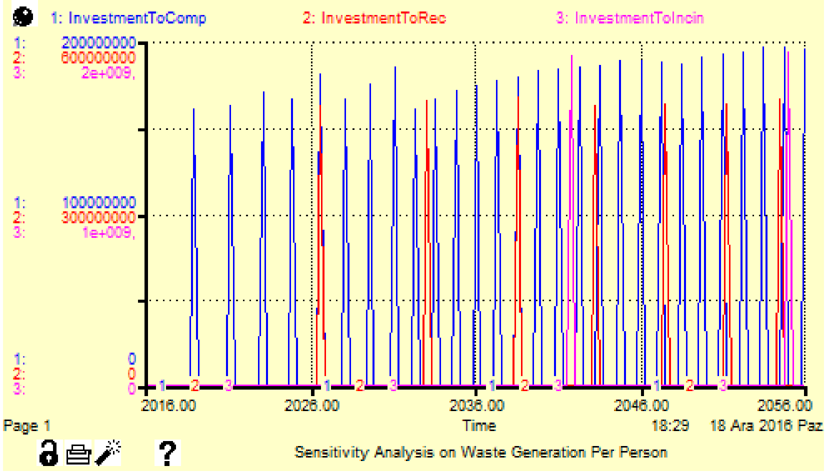


Figure 8.31. Investment to Facilities-Waste Generation per Person Sensitivity Analysis 2.

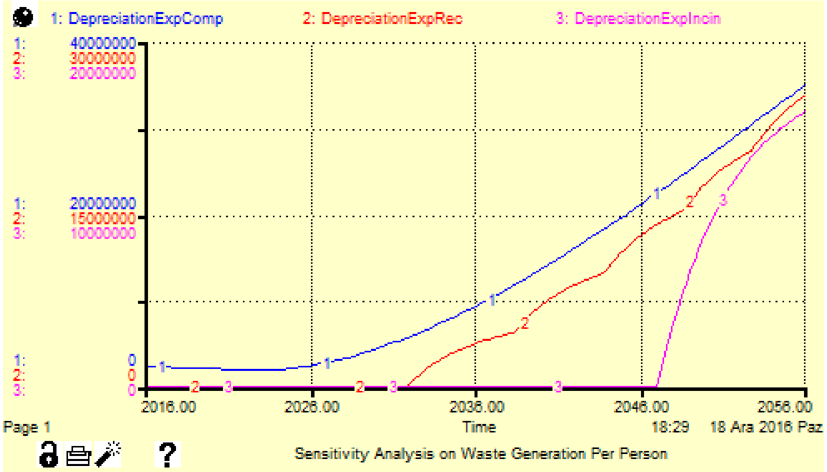


Figure 8.32. Depreciation Expenses-Waste Generation per Person Sensitivity Analysis 2.

When waste generation per capita is set to increase from 1,27 to 2 kg/day over 40 years, changes in landfill waste, capacities and rates of composting, recycling and incineration are presented in Figure 8.33 and 8.34. Landfill waste reaches to 506447 kt in 2056 whereas the capacities of composting, recycling and incineration become 6436 kt/year, 1178 kt/year and 256 kt/year, respectively. Waste generation rate reaches to 14600 kt/year at the end of this run whereas composting, recycling and incineration rates become 3400 kt/year, 323 kt/year and 205 kt/year, respectively.

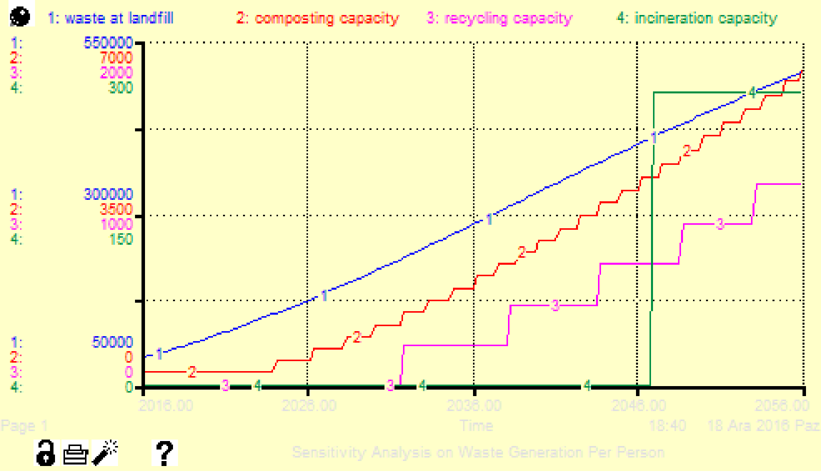


Figure 8.33. Landfill Waste and Capacities-Waste Generation per Person Sensitivity Analysis 3.

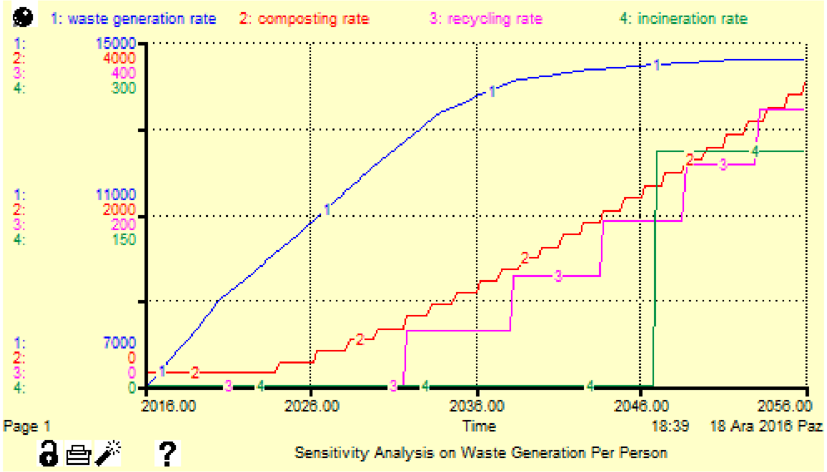


Figure 8.34. Rates-Waste Generation per Person Sensitivity Analysis 3.

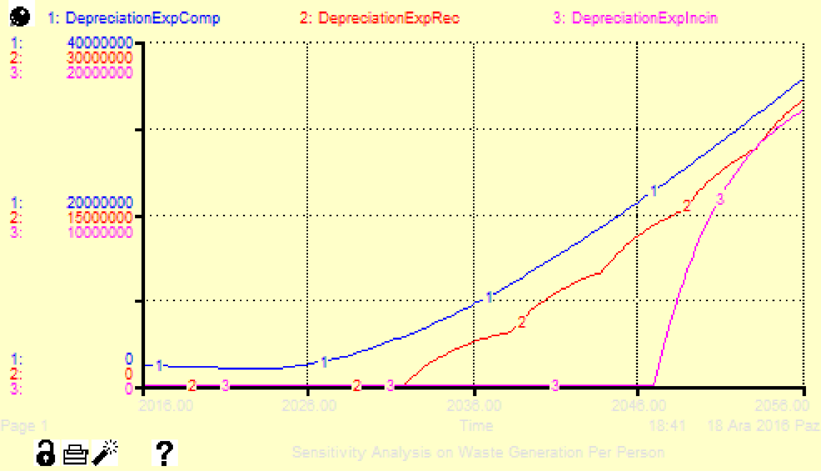


Figure 8.35. Investment to Facilities-Waste Generation per Person Sensitivity Analysis 3.

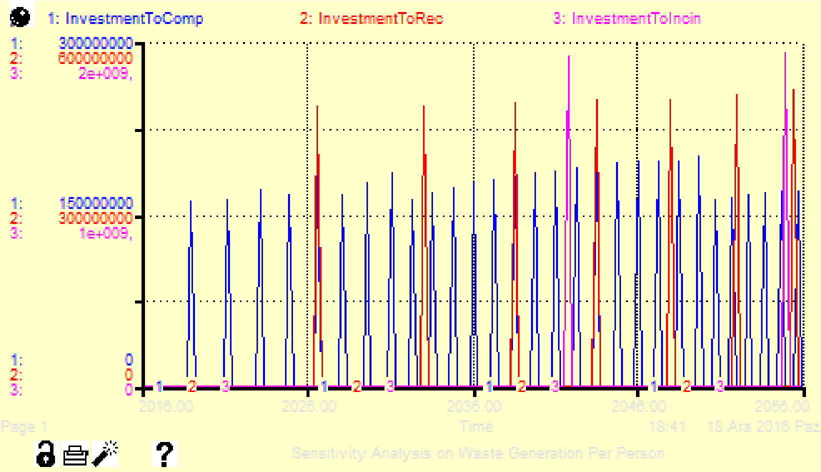


Figure 8.36. Depreciation Expenses-Waste Generation per Person Sensitivity Analysis 3.

It can be seen from Table 8.3 that landfill waste increases together with the waste generation per person. As it was stated, fund is distributed to composting, recycling and incineration as follows: 1/3 of the fund is directed to incineration budget and rest of the fund is directed to composting and recycling budgets as proportional to composting and recycling gaps, respectively. In all of these runs, net fund increases 30 to 120 million TL, since population dynamics are the same. However, as waste generation rate increases, composting, recycling and incineration gaps change. Since composting and recycling budgets increase as proportional to their gaps, money directed to composting and recycling budgets can exhibit a different pattern for different waste generation per person values. It explains the different composting and recycling capacities for different waste generation per person scenarios in Table 8.3 although the fund directed to capacity investments is the same.

Table 8.3. Results of Waste Generation per Person Sensitivity Runs.

Waste Generation per Person (kg/day)	**Landfill Waste (kt)**	**Composting Capacity (kt/year)**	**Recycling Capacity (kt/year)**	**Incineration Capacity (kt/year)**
1,4	386843	5996	1397	256
1,7	437919	6099	1177	256
2	506447	6436	1178	256

8.4. Budget

In the base run, net fund was set to increase from 30 to 120 million TL over 40 years. In sensitivity runs, net fund starts from 30 and reaches to approximately 120, 300 and 480 million TL.

When net fund is set to increase from 30 to 120 million TL over 40 years, dynamics of landfill, composting, recycling and incineration capacities and rates are given in Figure 8.37 and 8.38. Landfill waste reaches to 365110 kt in 2056 whereas the capacities of composting, recycling and incineration become 6315 kt/year, 1413 kt/year and 259 kt/year, respectively. Waste generation rate reaches to 9526.5 kt/year, composting, recycling and incineration rates are 3461 kt/year, 388 kt/year and 207 kt/year respectively.

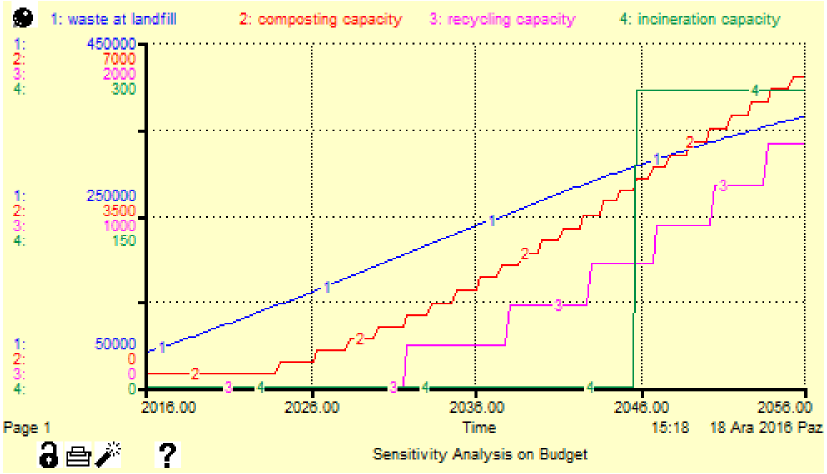


Figure 8.37. Landfill Waste and Capacities-Budget Sensitivity Analysis 1.

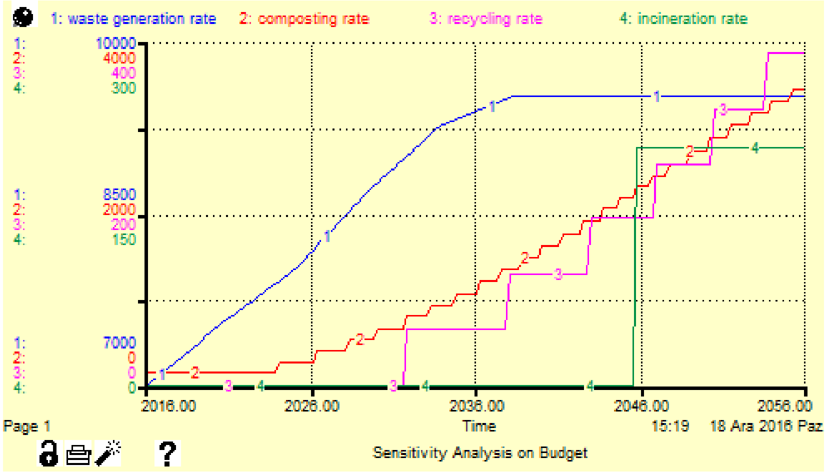


Figure 8.38. Rates-Budget Sensitivity Analysis 1.

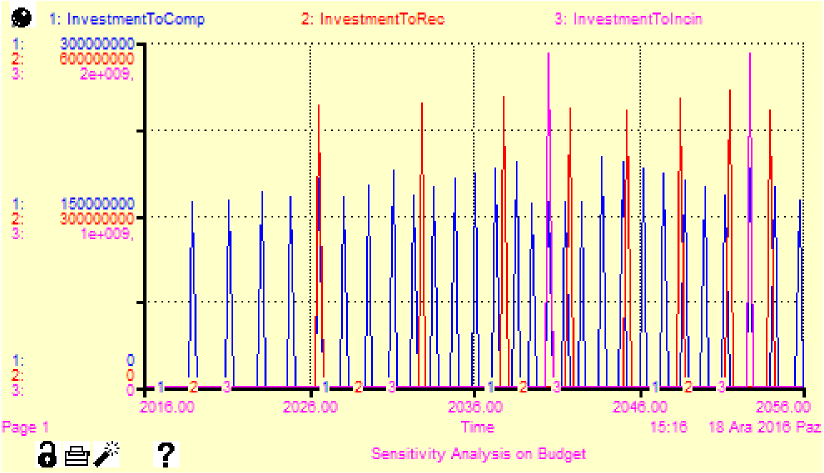


Figure 8.39. Investment to Facilities-Budget Sensitivity Analysis 1.

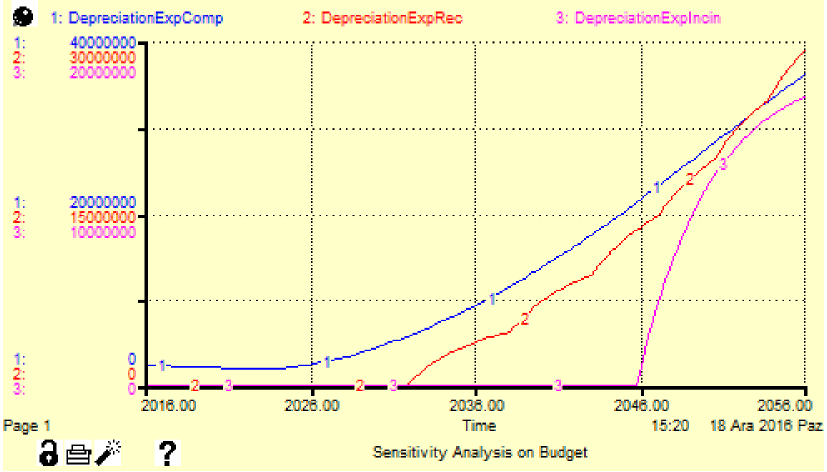


Figure 8.40. Depreciation Expenses-Budget Sensitivity Analysis 1.

When net fund is set to increase from 30 to 300 million TL over 40 years, changes in landfill waste, composting, recycling and incineration capacities and rates can be seen from Figure 8.41 and 8.42. Landfill waste reaches to 336109 kt in 2056 whereas the capacities of composting, recycling and incineration become 9042 kt/year, 3238 kt/year and 521 kt/year, respectively. Waste generation rate becomes to 9526.5 kt/year, composting, recycling and incineration rates are 4968 kt/year, 817 kt/year and 416 kt/year respectively.

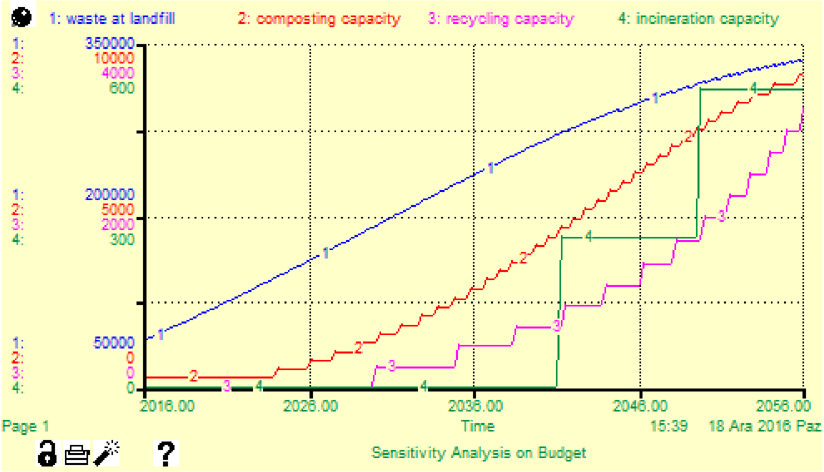


Figure 8.41. Landfill Waste and Capacities-Budget Sensitivity Analysis 2.

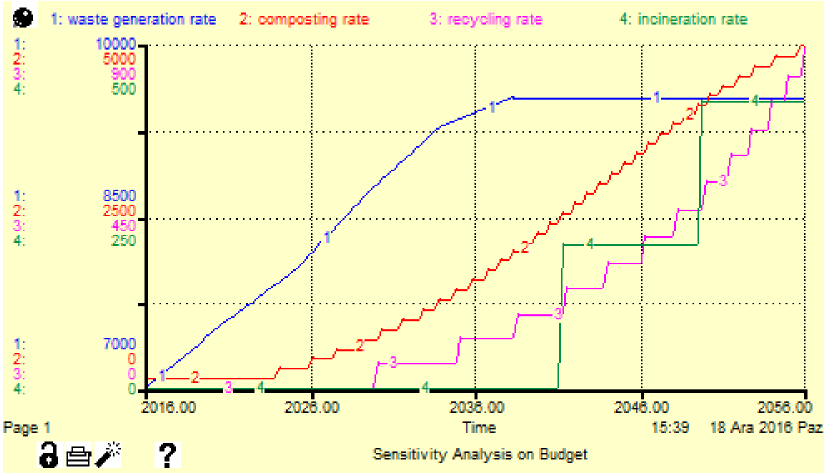


Figure 8.42. Rates-Budget Sensitivity Analysis 2.

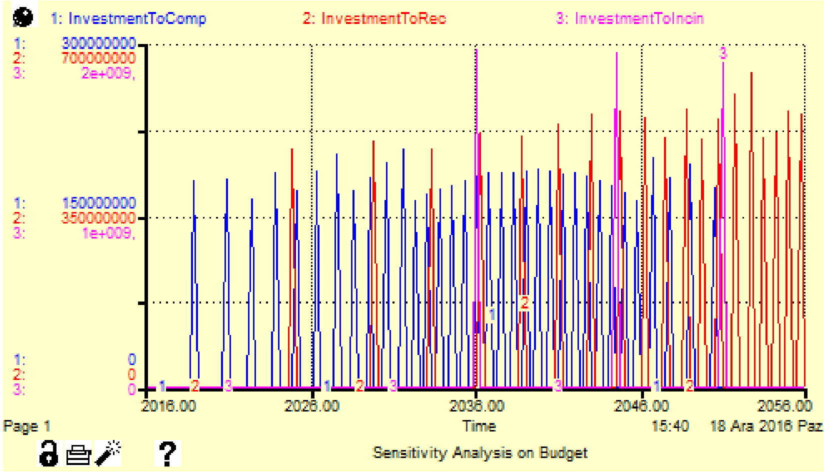


Figure 8.43. Investment to Facilities-Budget Sensitivity Analysis 2.

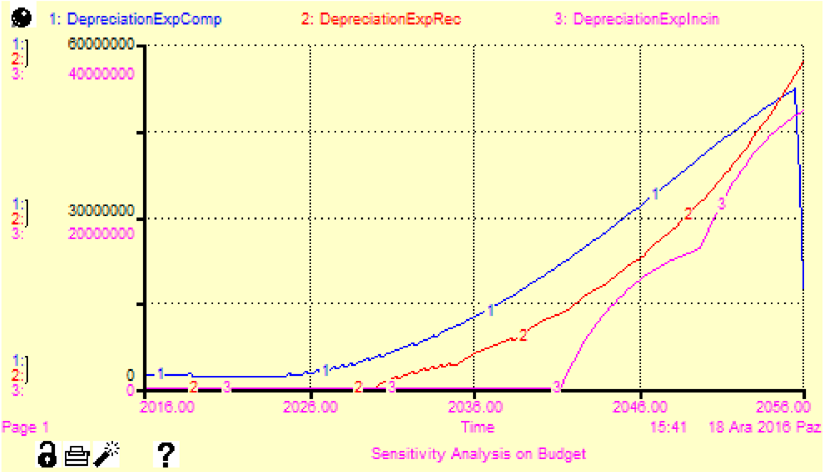


Figure 8.44. Depreciation Expenses-Budget Sensitivity Analysis 2.

When net fund is set to increase from 30 to 480 million TL over 40 years, dynamics of landfill waste, composting, recycling and incineration capacities and rates are presented in Figure 8.45 and 8.46. Landfill waste reaches to 330736 kt in 2056 whereas the capacities of composting, recycling and incineration become 8952 kt/year, 3846 kt/year, 783 kt/year, respectively. Waste generation rate reaches to 9526.5 kt/year, composting, recycling and incineration rates become 4921 kt/year, 1055 kt/year, 626 kt/year respectively.

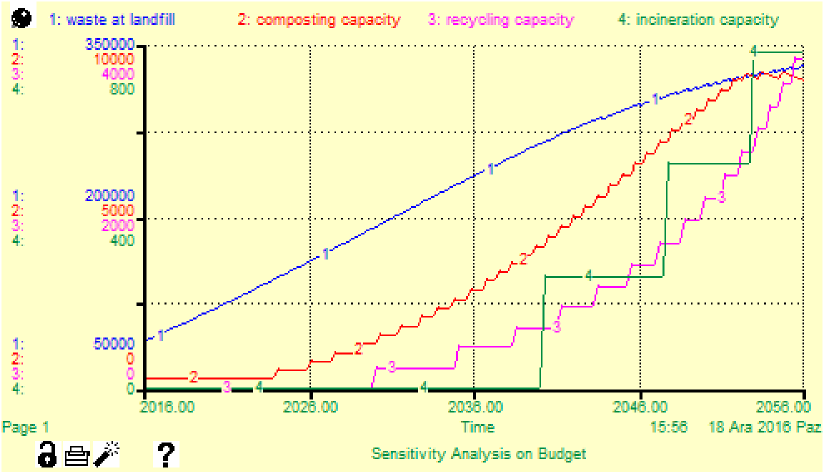


Figure 8.45. Landfill Waste and Capacities-Budget Sensitivity Analysis 3.

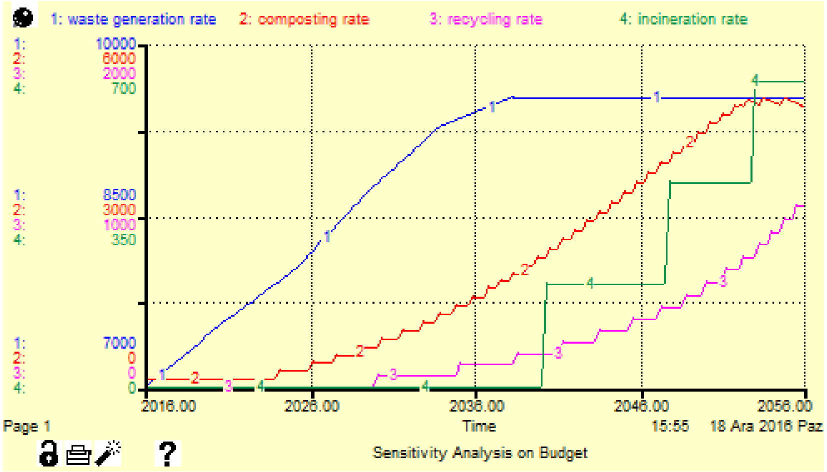


Figure 8.46. Rates-Budget Sensitivity Analysis 3.

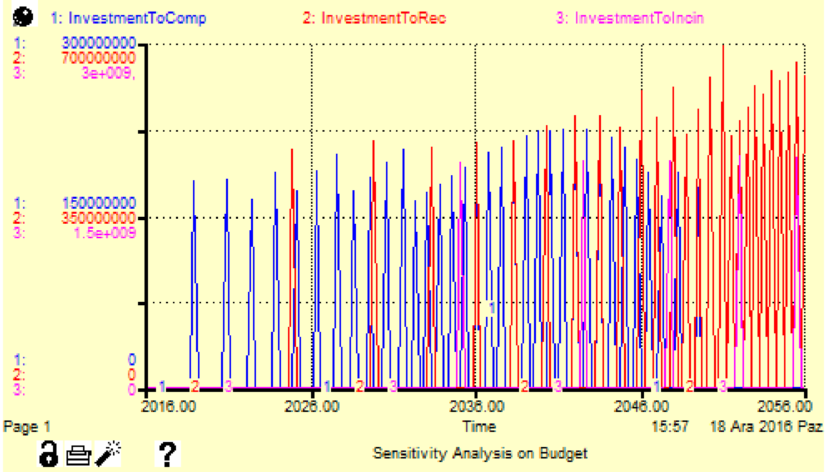


Figure 8.47. Investment to Facilities-Budget Sensitivity Analysis 3.

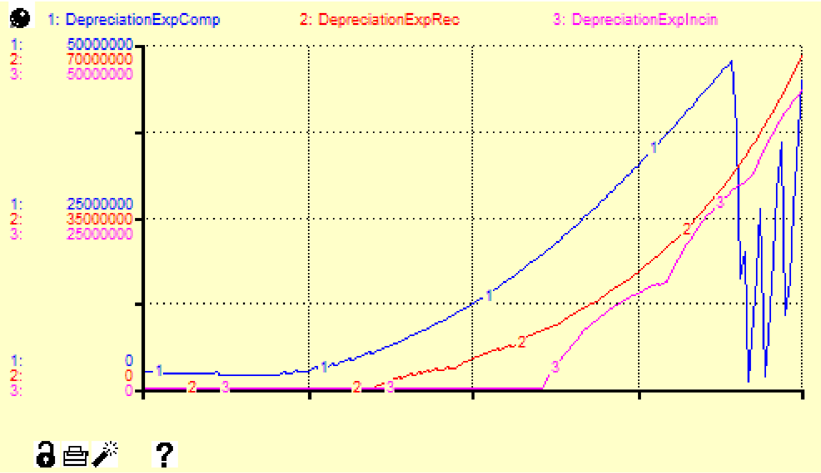


Figure 8.48. Depreciation Expenses-Budget Sensitivity Analysis 3.

It can be clearly seen from Table 8.4 that as the budget growth increases, landfill waste in 2056 decreases. Capacities tend to increase as well along with the increase in the budget growth. However, when the net fund is set to increase from 30 to 300, composting capacity reaches to 9042 kt/year whereas it becomes 8952 kt/year when the net fund is set to increase from 30 to 480. The reason behind this decrease is that when such an increase in the money directed to investment budgets occurs, capacity of the composting facility can increase faster than recycling facility, since the threshold for recycling investment is higher. Composting gap decreases faster than recycling gap, and consequently most of the money is directed to recycling budget. Capacity of composting facility starts to decrease as the money directed to composting budget decreases, because composting budget becomes insufficient to meet the depreciation expenses of composting.

Table 8.4. Results of Budget Sensitivity Runs.

Net Fund(million TL)	**Landfill Waste (kt)**	**Composting Capacity (kt/year)**	**Recycling Capacity (kt/year)**	**Incineration Capacity (kt/year)**
30 to 120	365110	6315	1413	259
30 to 300	336109	9042	3238	521
30 to 480	330736	8952	3846	783

9. SCENARIO ANALYSIS

In this part, seven different scenarios are analysed to identify meaningful improvements in the dynamics. The scenarios differ from each other with respect to mainly fund directed to capacity investments and source separation rate. To draw more clear conclusions from the analysis, the results of these seven scenarios are compared with the base run and some other scenarios. Brief descriptions of these scenarios are given in Table 9.1.

Table 9.1. Scenario Descriptions.

Scenario#	**Scenario Description**
Scenario 1	Business as usual, no new investment to facilities. Just depreciation of the composting facility is compensated. Source separation increases linearly to 0,23 in 40 years.
Scenario 2	Capacity investments to facilities with net fund 30 to 120 million TL and source separation increases linearly to 0,23 in 40 years.
Scenario 3	Capacity investments to facilities with net fund 30 to 300 million TL and source separation increases linearly to 0,23 in 40 years.
Scenario 4	Capacity investments to facilities with net fund 30 to 120 million TL and source separation increases to 0,5 in 40 years.
Scenario 5	Capacity investments to facilities with net fund 30 to 300 million TL and source separation increases to 0,5 in 40 years.
Scenario 6	Capacity investments to facilities with net fund 30 to 300 million TL and source separation increases to 0,8 in 40 years.
Modified Scenario 6	Capacity investments to facilities with net fund 30 to 240 million TL and source separation increases to 0,8 in 40 years.
Scenario 7	What could have been if these capacity investments started in 2006 with net fund 30 to 120 million TL and source separation increases linearly to 0,23 in 50 years.

9.1. Scenario 1

It is assumed that no new investment to composting, recycling and incineration is made (i.e. business as usual). Since there is not any recycling and incineration facility in the city, just composting facility keeps working over the next 40 years. Just depreciation of the composting facility is compensated to maintain capacity of composting facility constant.

Only in this scenario, capacity utilization is set to 0,5, because composting facility does not work with its full capacity in real life. Therefore, composting capacity becomes equal to 130 kt throughout the next 40 years. However, waste generation rate grows with the increasing population and waste generation per person. Therefore, landfill waste increasingly grows and reaches to 424039 kt in 2056. Landfilled waste at 2016 was 90000 kt, so 334039 kt waste is sent to landfill in the next 40 years. 334039 kt waste corresponds to 760,94 ha area. The dynamics of landfill waste, composting capacity and rates under scenario 1 are given in Figure 9.1 and 9.2. Waste generation rate becomes 9526.5 kt/year in 2056 and composting rate is 77 kt/year, so just 7% of the generated waste is treated, rest of them is disposed to landfills.

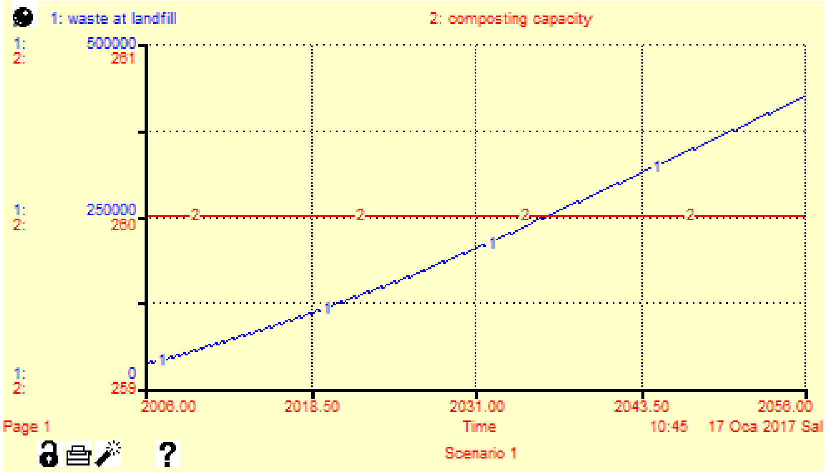


Figure 9.1. Landfill Waste and Composting Capacity-Scenario 1.

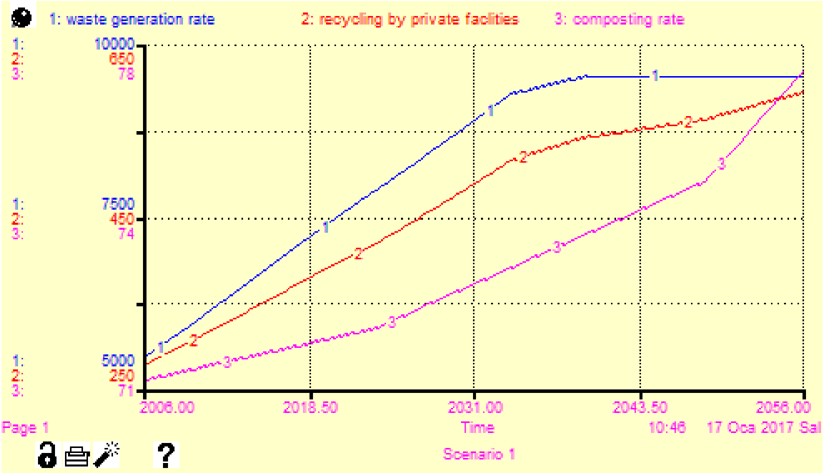


Figure 9.2. Rates-Scenario 1.

9.2. Scenario 2

It is assumed that new investments are made to composting, recycling and incineration with a net fund increasing from 30 to 120 million TL between 2016 and 2056. Source separation linearly increases to 0,23 throughout the simulation. Thanks to this fund, composting, recycling and incineration capacities increase over these years, but these capacity investments are insufficient against increasing waste generation rate. Although waste sent to landfill over 40 years decreases with respect to scenario 1, landfill waste reaches to 363922 kt in 2056. It means that 60117 kt less waste is sent to landfill and 136,95 ha more area is saved via scenario 2 with respect to scenario 1. Thus, scenario 2 achieves 18% improvement over scenario 1 in terms of landfill expansion.

The dynamics of landfill waste, capacities of composting, recycling and incineration facilities under scenario 2 are presented in Figure 9.3 and 9.4. Capacities of composting, recycling and incineration facilities become 5859 kt/year, 1420 kt/year and 256 kt/year, respectively at the end of the simulation whereas composting, recycling and incineration rates become 3464 kt/year, 445 kt/year and 205 kt/year. In 2056, 49% of the generated waste can be treated and 51% of the generated waste will be disposed to landfills.

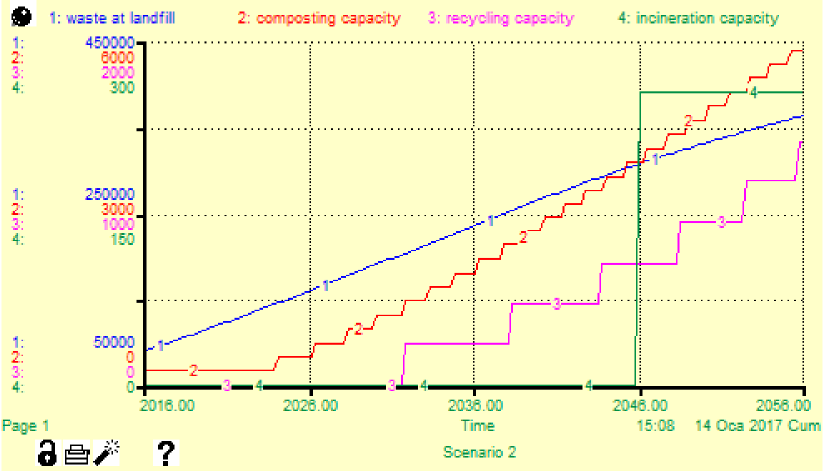


Figure 9.3. Landfill Waste and Capacities-Scenario 2.

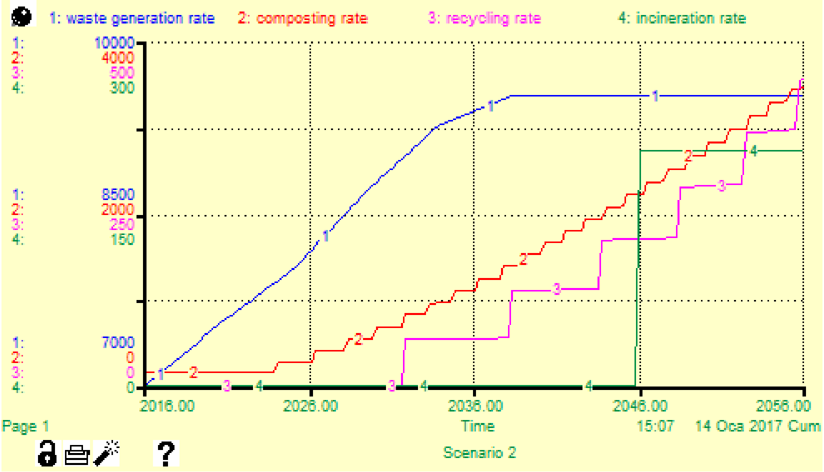


Figure 9.4. Rates-Scenario 2.

9.3. Scenario 3

It is assumed that new investments are made to composting, recycling and incineration with a net fund increasing from 30 to 300 million TL between 2016 and 2056. Source separation linearly increases to 0,23 throughout the simulation. Although this fund is much higher than the one in scenario 2, capacity investments are still insufficient against increasing waste generation rate. Waste sent to landfill over 40 years decreases with respect to scenario 1 and 2. Landfill waste reaches to 330556 kt in 2056, it means that 93483 kt less waste is sent to landfill and 212,95 ha more area is saved via scenario 3 with respect to scenario 1. Therefore, Scenario 3 achieves 28% improvement over scenario 1 in terms of landfill expansion. More capacity investments can be made thanks to this scenario. However, as the capacities of the facilities increase, their depreciation expenses increase as well.

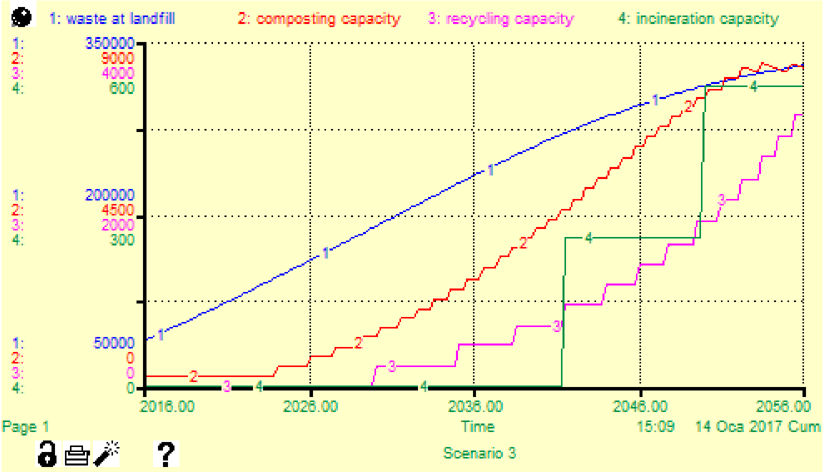


Figure 9.5. Landfill Waste and Capacities-Scenario 3.

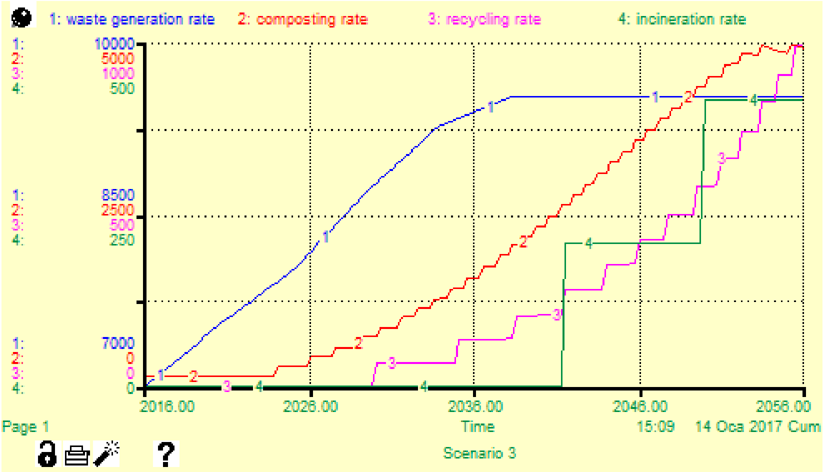


Figure 9.6. Rates-Scenario 3.

The dynamics of landfill waste, capacities of composting, recycling and incineration facilities under scenario 3 are provided in Figure 9.5 and 9.6. Capacities of composting, recycling and incineration facilities are 8337,5 kt/year, 3170,5 kt/year, 523 kt/year in 2056 whereas composting, recycling and incineration rates become 4956 kt/year, 993 kt/year and 418 kt/year, respectively. In 2056, 73% of the generated waste can be treated and the rest of the generated waste will be disposed to landfills.

9.4. Scenario 4

In this scenario, it is assumed that new investments are made to composting, recycling and incineration with a net fund increasing from 30 to 120 million TL over the next 40 years. Source separation increases to 0,5 from 0,07 between 2016 and 2056.

Although waste sent to landfill over 40 years decreases with respect to scenario 1 and 2, landfill waste still reaches to 338474 kt in 2056. Scenario 4 achieves 26% improvement over scenario 1 in terms of landfill expansion since 194,92 ha area is saved via scenario 4 with respect to scenario 1. It can be seen by comparing scenario 4 with scenario 3 that their landfill waste values in 2056 and their improvement rates in terms of landfill expansion are quite close even though there is a huge difference between the budgets of these scenarios.

Furthermore, although the only difference between the scenario 4 and 2 is source separation rate, there is a significant difference between their improvement rates. 57,97 ha more area can be saved by just increasing source separation to 0,5 instead of 0,23.

The dynamics of landfill waste, capacities of composting, recycling and incineration facilities under scenario 4 are presented in Figure 9.7 and 9.8. Capacities of the composting, recycling and incineration facilities are 5636 kt/year, 1420 kt/year and 256 kt/year in 2056 whereas composting, recycling and incineration rates are 4892 kt/year, 782 kt/year and 205 kt/year, respectively. 71% of the generated waste can be treated in 2056 and 29% of the generated waste will be disposed to landfills.

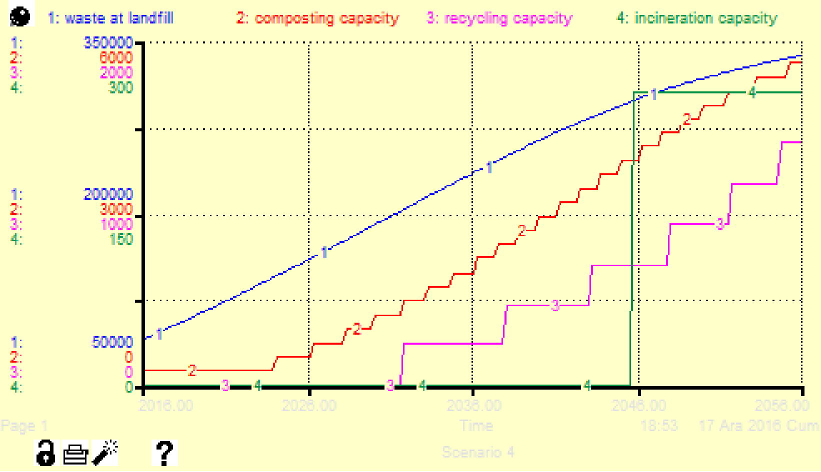


Figure 9.7. Landfill Waste and Capacities-Scenario 4.

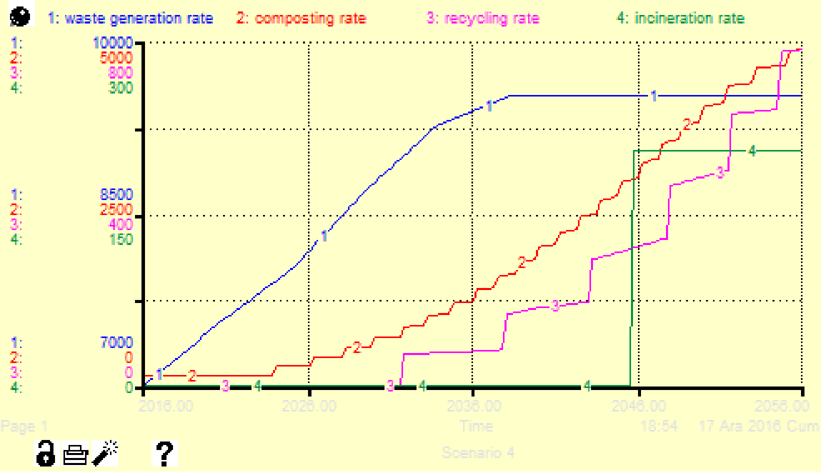


Figure 9.8. Rates-Scenario 4.

9.5. Scenario 5

In scenario 5, it is assumed that new investments are made to composting, recycling and incineration with a net fund increasing from 30 to 300 million TL over the next 40 years. Source separation increases to 0,5 from 0,07 between 2016 and 2056. In this scenario, landfill waste reaches to 304633 kt in 2056. It means that 272,01 ha more area is saved via scenario 5 with respect to scenario 1. Thus, scenario 5 achieves 36% improvement over scenario 1 in terms of landfill expansion. Moreover, scenario 5 saves 59,06 ha more area than scenario 3 even though the only difference between the scenario 5 and 3 is source separation rate. Thus, increasing source separation rate to 0,5 instead of 0,23 makes improvement rate increase from 28% to 36%.

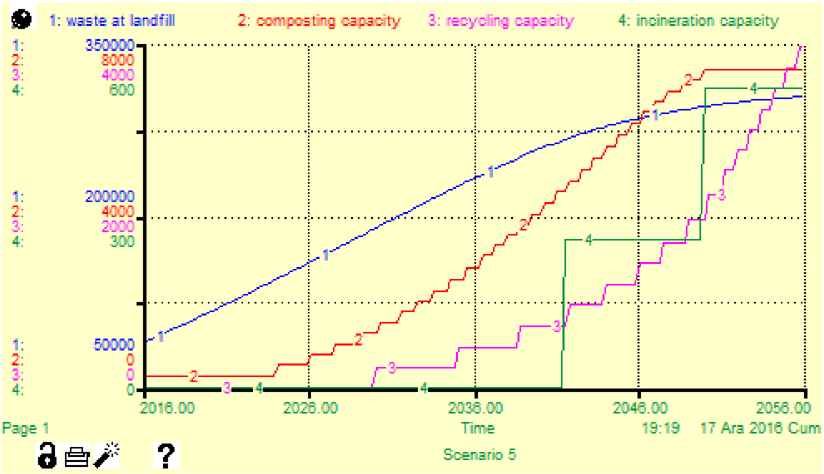


Figure 9.9. Landfill Waste and Capacities-Scenario 5.

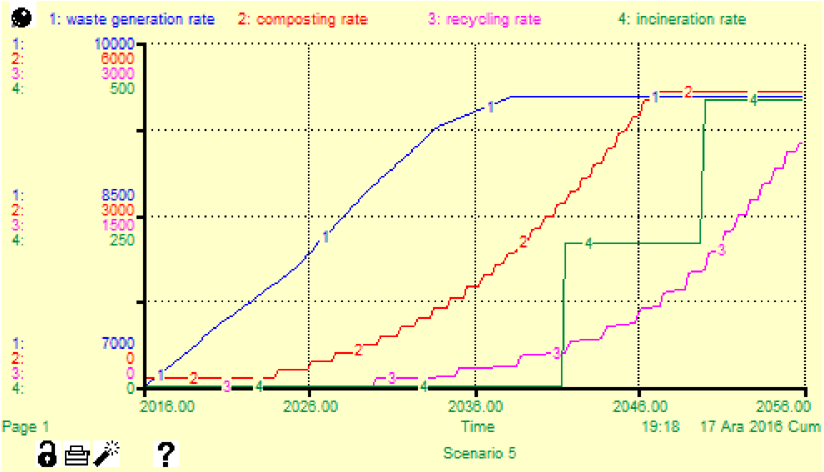


Figure 9.10. Rates-Scenario 5.

The dynamics of landfill waste, capacities of composting, recycling and incineration facilities under scenario 5 are given in Figure 9.9 and 9.10. Capacities of composting, recycling and incineration facilities in 2056 are 7415 kt/year, 3983,5 kt/year and 523 kt/year whereas composting, recycling and incineration rates become 5144 kt/year, 2125 kt/year and 418 kt/year, respectively. 90% of the generated waste can be treated in 2056 and the rest of the generated waste will be disposed to landfills. Composting and recycling rates reach to the required levels by 2056.

9.6. Scenario 6

In this scenario, the money directed to composting, recycling and incineration investments increases from 30 to 300 million TL between 2016 and 2056. Source separation increases to 0,8 from 0,07 over the next 40 years. In this scenario, landfill waste reaches to 280786 kt in 2056. 326,33 ha more area is saved via scenario 6 with respect to scenario 1, so scenario 6 achieves 43% improvement over scenario 1 in terms of landfill expansion.

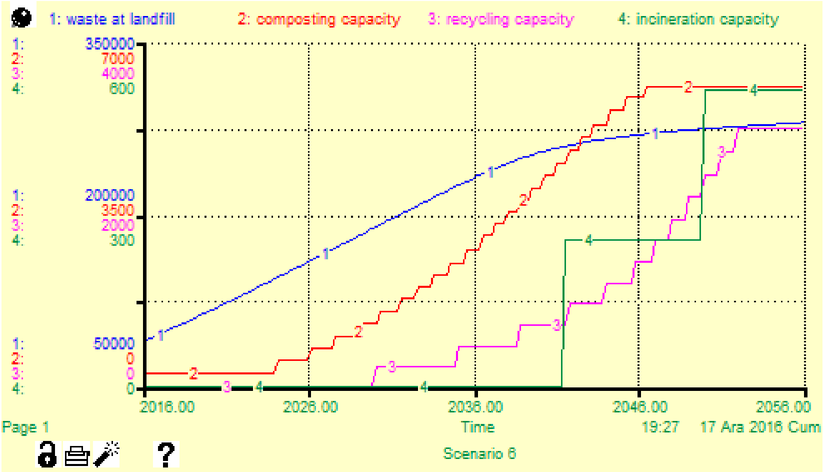


Figure 9.11. Landfill Waste and Capacities-Scenario 6.

Moreover, when scenario 6 is compared to scenario 5, it can be seen that scenario 6 saves 54,32 ha more area than scenario 5 thanks to more rapidly increasing source separation rate. In other words, scenario 6 provides 7% more improvement than scenario 5.

Figure 9.11 and 9.12 which demonstrate the dynamics of landfill waste, capacities and rates of composting, recycling and incineration facilities under scenario 6 is presented below. Capacities of composting, recycling and incineration facilities in 2056

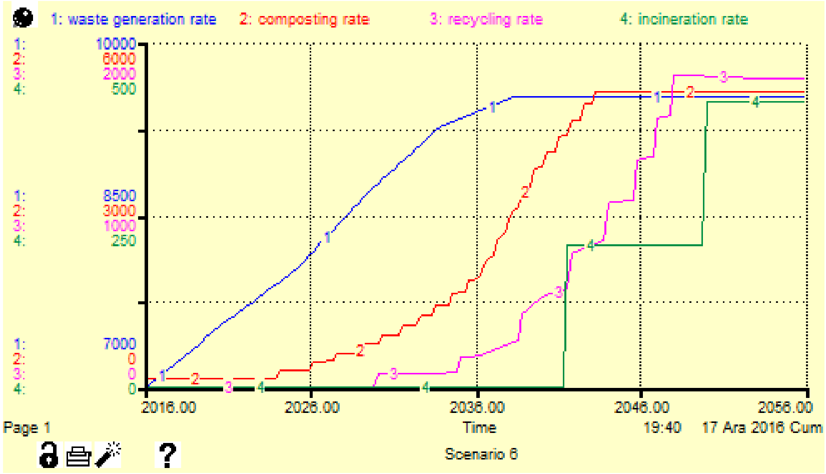


Figure 9.12. Rates-Scenario 6.

are 6131 kt/year, 3009 kt/year, 518 kt/year, composting, recycling and incineration rates become 5144 kt/year, 1792 kt/year and 414 kt/year, respectively. In 2056, 90% of the generated waste can be treated and 10% of the generated waste will be disposed to landfills. Composting and recycling rate reaches to the required level around 2043 and 2048, respectively.

9.7. Modified Scenario 6

In scenario 6, composting and recycling rates reached the required level around 2043 and 2048, respectively. It indicates that no capacity investment to composting is made between 2043 and 2056. After 2043, composting facility just preserves its capacity by covering their depreciation. In other words, there will be no need to save money for capacity addition. Only depreciation expenses are withdrawn from composting budget. The same situation is valid for recycling after 2048. Thus, scenario 6 is modified to see if lesser fund is allocated to composting and recycling, how it would affect the dynamics of the system.

Figure 9.13 and 9.14 which demonstrate the dynamics of landfill waste, capacities and rates of composting, recycling and incineration facilities for modified scenario 6 are presented below. Net fund is set to increase 30 to 240 million TL during 40

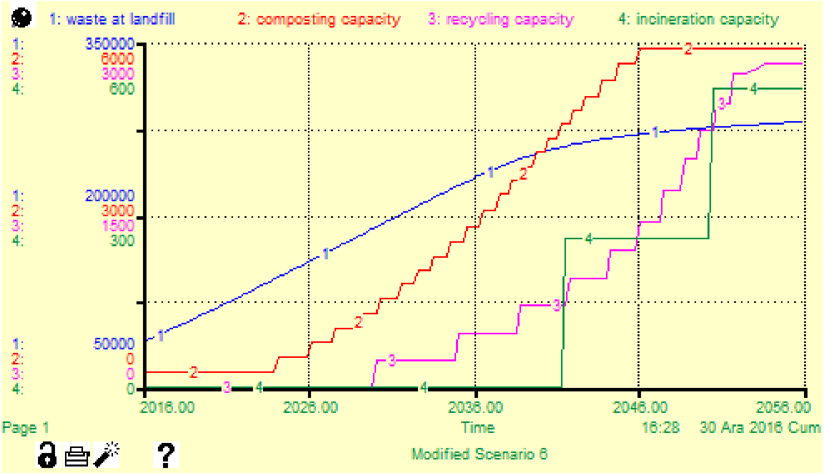


Figure 9.13. Landfill Waste and Capacities-Modified Scenario 6.

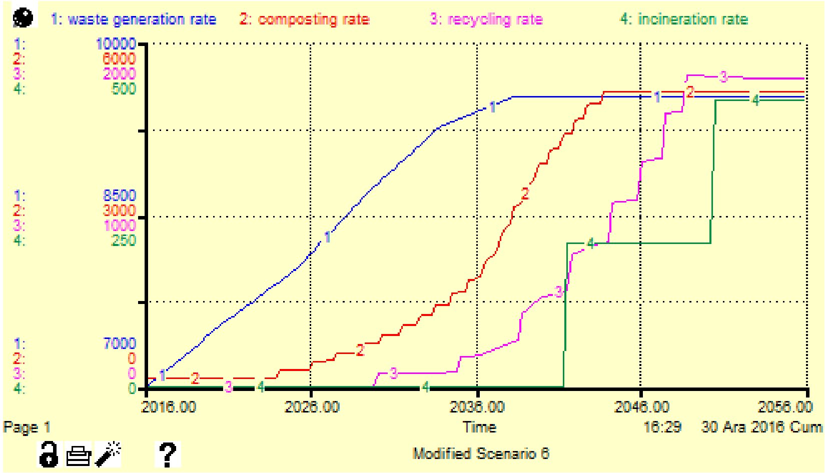


Figure 9.14. Rates-Modified Scenario 6.

years. Landfill waste reaches to 281673 kt in 2056 and it corresponds to 436,63 ha area expansion. It means 43% improvement is achieved in terms of landfill expansion, which is equal to the improvement rate of scenario 6.

Capacities of composting, recycling and incineration facilities in 2056 are 5904 kt/year, 2826 kt/year and 522 kt/year whereas composting, recycling and incineration rates become 5144 kt/year, 1792 kt/year and 418 kt/year, respectively. In 2056, 90% of the generated waste can be treated and rest of the generated waste will be disposed to landfills. Therefore, it is possible to say that similar results to scenario 6 are obtained with less fund.

9.8. Scenario 7

In scenario 7, what could have been if the capacity investments had started in 2006 was analysed. In this scenario, it is assumed that net fund increases from 30 million to 300 million TL between 2006 and 2056, and source separation linearly increases to 0,23.

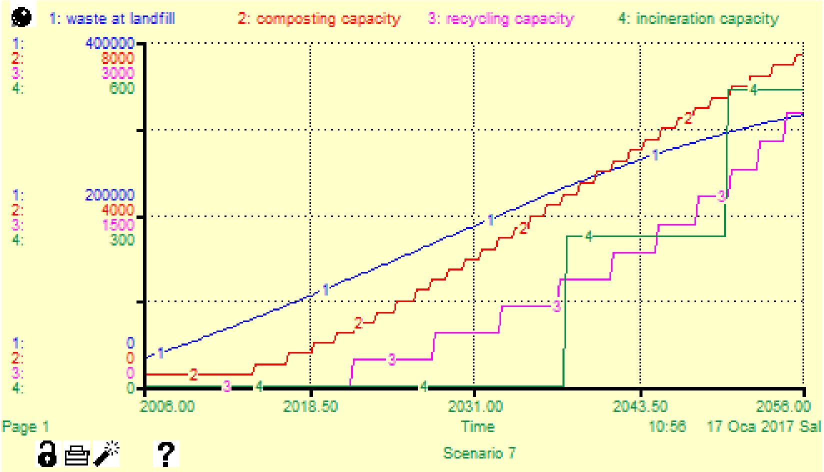


Figure 9.15. Landfill Waste and Capacities-Scenario 7.

Landfill waste reaches to 316827 kt in 2056, and landfilled waste at 2006 was 32822 kt, so 284005 kt waste is sent to landfill between 2006 and 2056. In other words, 244,23 ha more area could have been saved with respect to scenario 1 if these investments had started in 2006. Thus, scenario 7 would achieve 25% improvement over scenario 1 in terms of landfill waste values in 2056.

Figure 9.15 and 9.16 which show the dynamics of landfill waste, capacities of composting, recycling and incineration facilities under scenario 7 are presented below. Capacities of composting, recycling and incineration facilities in 2056 are 7721 kt/year, 2390 kt/year and 519 kt/year whereas composting, recycling and incineration rates

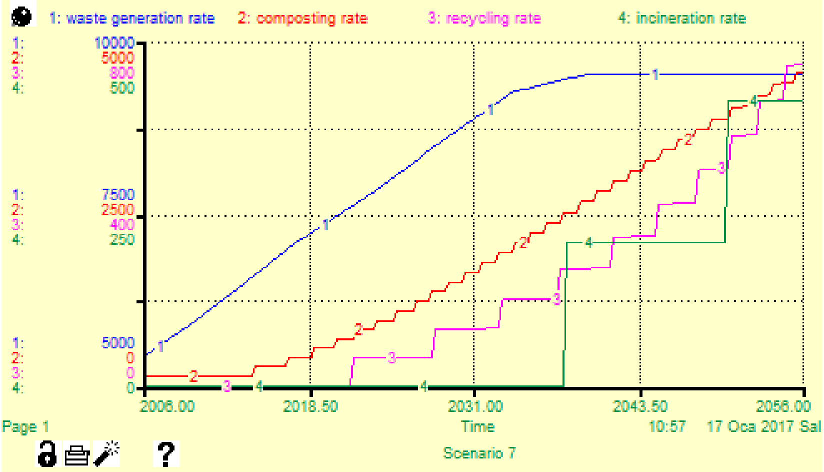


Figure 9.16. Rates-Scenario 7.

become 4565 kt/year, 745 kt/year and 415 kt/year, respectively. In 2056, 66% of the generated waste can be treated and rest of the generated waste will be disposed to landfills.

10. ANALYSIS OF THE RESULTS

205 ha of the 691 ha area allocated to be used as sanitary landfills in Istanbul are full by 2016. The remaining 486 ha are will be full by 2042 in scenario 1, 2045 in scenario 2, 2047 in scenario 3, 2046 in scenario 4, and 2055 in scenario 5. 0,925 and 0,928 of the allocated area will be full by 2056 with scenario 6 and modified scenario 6, respectively. It means existing landfills can be more efficiently utilized with scenario 6 and modified scenario 6. Table 10.1 shows waste sent to landfill over 40 years and landfill expansions under different scenarios whereas improvement rates of the scenarios are given in Table 10.2. Table 10.3 and 10.4 present composting, recycling, incineration rates, recycling by private facilities and percentage of treated waste in 2056.

Table 10.1. Landfill Expansions over 40 Years.

Scenario#	**Landfill Waste in 2056 (kt)**	**Waste Sent to Landfill over 40 years**	**Landfill Expansion (ha)**
Scenario 1	424039	334039	760,94
Scenario 2	363922	273922	623,99
Scenario 3	330556	240556	547,99
Scenario 4	338474	248474	566,02
Scenario 5	304633	214633	488,93
Scenario 6	280741	190741	434,51
Modified Scenario 6	281673	191673	436,63

When scenario 3 and 4 are examined, it is observed that landfill areas in 2056 are quite close. Scenario 3, in which capacity investments to composting, recycling and incineration facilities are made with a net fund increasing from 30 to 300 million TL and source separation linearly increases over 40 years, slightly outperforms the scenario

Table 10.2. Improvement Rates of Scenarios in 40 Years.

Scenario#	**Improvement**	
	Area (ha)	**Percentage**
Scenario 2	136,95	0,18
Scenario 3	212,95	0,28
Scenario 4	194,92	0,26
Scenario 5	272,01	0,36
Scenario 6	326,32	0,43
Modified Scenario 6	324,30	0,43

4, in which investments to composting, recycling and incineration facilities are made with a net fund increasing from 30 to 120 million TL and source separation reaches to 0,5 over 40 years. It is thus possible to say that making efforts to increase source separation rate is as significant as allocating funds for capacity investments.

The effect of the source separation on dynamics of landfill areas can also be seen by comparing scenario 3 and 5. The only difference between these two scenarios is that source separation linearly increases to 0,23 over the time horizon in scenario 3 whereas source separation rate increases to 0,5 in scenario 5. When these two scenarios are compared, it is seen that source separation provides 8% more improvement in terms of landfill expansion.

The comparison of scenario 5 and 6 can be another example of this situation. The only difference between scenario 5 and 6 is the increase in the source separation rates over 40 years. Scenario 6 provides 7% more improvement than scenario 5 in terms of landfill expansion. On the other hand, percentage of treated waste in 2056 is the same for both scenario 5 and 6. The reason behind is that composting and recycling rates reach the required levels in both scenarios. Furthermore, although the capacities in scenario 5 are much higher than the capacities in scenario 6, they both reach the required levels of composting and recycling rates. It means as source separation increases, the need for capacity investments decreases.

Table 10.3. Processing Rates in 2056 for All Scenarios.

Scenario #	**Composting Rate**	**Reycling Rate**	**Incineration Rate**	**Private Recycling Rate**
Scenario 1	77	0	0	592
Scenario 2	3464	445	205	592
Scenario 3	4956	993	418	592
Scenario 4	4892	782	205	924
Scenario 5	5144	2125	418	924
Scenario 6	5144	1792	418	1257
Modified Scenario 6	5144	1792	418	1257
Scenario 7	4565	749	415	592

Table 10.4. Treated Waste Percentage for All Scenarios.

Scenario #	**Waste Generation Rate**	**Treated Waste**	**Percentage of Treated Waste**
Scenario 1	9526,5	669	0,07
Scenario 2	9526,5	4706	0,49
Scenario 3	9526,5	6959	0,73
Scenario 4	9526,5	6803	0,71
Scenario 5	9526,5	8611	0,90
Scenario 6	9526,5	8611	0,90
Modified Scenario 6	9526,5	8611	0,90
Scenario 7	9526,5	6321	0,66

Moreover, examining composting, recycling and incineration rates is 2056 is useful to evaluate how much of the generated waste can be treated and how much of the generated waste is sent to landfills. It is important because treating all of the generated means that waste sent to landfills is kept at its required minimum. It can be seen that treated waste ratio in 2056 in scenario 1 is 0,07 (i.e. business as usual), which is very low. Treated waste ratio in 2056 in scenario 5 and 6 is 0,9. It means most of the generated waste is disposed via composting, recycling and incineration processes and much less waste is sent to landfill with respect to 2016.

Scenario 6 is obviously a good strategy, since it has the highest budget and source separation rate with respect to other scenarios. Scenario 6 provides 43% improvement in terms of landfill expansion and treated waste ratio becomes 90% in 2056. However, it is shown that after the required composting and recycling rate is met, most of the money directed to composting and recycling budget is not used; because no capacity investment is made, only deprecation expenses are withdrawn from the budgets. With modified scenario 6, the same improvements can be made with less fund. Therefore modified scenario 6 is selected to be the best strategy.

11. CONCLUSION

Istanbul is the most densely populated city of Turkey. Land scarcity has become a problem with the increasing population and urbanization. Inefficient waste management strategies, largely depending on landfilling, worsen this problem. Waste management strategies gain more importance with the increasing waste generation rate. Reducing landfilling and encouraging other types of waste disposal methods is the primary objective of European environmental policies as well, since landfilling does not provide resource recovery and it occupies too much area. Thus, the aim of this study is to analyse how fast the existing landfills in Istanbul become full and how the existing landfills can be more efficiently utilized via additional investments on waste treatment facilities. The dynamics of the system are examined with different budgets and source separation rates to be able to identify the best waste management strategies for Istanbul.

Scenario 6 was obviously a good strategy by having the highest fund and source separation rate with respect to other scenarios. However, modified scenario 6 is the best strategy since it produces quite similar results to scenario 6 with less fund. A more interesting outcome of this study is that source separation rate is as critical as the budget in waste management strategies. Moreover, it is shown that required facility capacities to meet the waste processing need decrease with the increasing source separation. Since increasing source separation rate mostly involves enhancing public awareness and infrastructure to separate waste at source such as containers and special bags for different kinds of wastes, it is possible to say that source separation is a more cost effective way of reducing waste sent to landfills and it should be integrated to waste management strategies along with the capacity investments. Moreover, design of reusable and longer lasting products can decrease waste generation rate by reducing consumption, since waste generation per person is one the main drivers of waste generation rate. In this way, in addition to resources used for the disposal of these wastes, the resources required to manufacture the related products will be saved.

As future research, consumption patterns and its effect on waste generation rate and consequently composting, recycling and incineration rate can be investigated. Moreover, amounts of energy and resources recovered through waste treatment strategies can be examined.

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APPENDIX A: MODEL EQUATIONS

Composting Budget(t) = Composting Budget(t - dt) + (Composting Fund - InvestmentToComp - DepreciationExpComp) * dt t
INIT Composting Budget = 4000000 {TL}
INFLOWS:
Composting Fund = IF(gapCompost>0) THEN(IF(gapRecycling>0) THEN(CR Fund*gapCompost/(gapCompost+gapRecycling)) ELSE(CR Fund-DepreciationRecycle*OneUnitRecyclingCost)) ELSE(DepreciationCompost*OneUnitCompostingCost) {TL/year}
OUTFLOWS:
InvestmentToComp = PossibleCompAdd*OneUnitCompostingCost/DT {TL/year}
DepreciationExpComp = IF(Composting Budget>=DepreciationCompost * OneUnitCompostingCost * DT) THEN(DepreciationCompost*OneUnitCompostingCost) ELSE(Composting Budget/DT) {TL/year}
Incineration Budget(t) = Incineration Budget(t - dt) + (IncinFund - InvestmentToIncin - DepreciationExpIncin) * dt
INIT Incineration Budget = 4000000 {TL}
INFLOWS:
IncinFund = GRAPH(TIME) (2016, 1e+007), (2020, 1.5e+007), (2024, 2e+007), (2028, 2.5e+007), (2032, 3.3e+007), (2036, 4.3e+007), (2040, 5.6e+007), (2044, 6.8e+007), (2048, 8.1e+007), (2052, 9.7e+007), (2056, 1.1e+008) {TL/year}
OUTFLOWS:
InvestmentToIncin = PossibleIncinAdd*OneUnitIncinCost/DT {TL/year}
DepreciationExpIncin = IF(Incineration Budget>=OneUnitIncinCost * DepreciationIncin * DT) THEN(OneUnitIncinCost*DepreciationIncin) ELSE(Incineration Budget/DT) {TL/year}
new composting cap(t) = new composting cap(t - dt) + (capacity addition

compost - capacity wear comp) * dt

INIT new composting cap = 0 {kt/year}

INFLOWS:

capacity addition compost = DelayCompost/DT+DepAddComp {kt/year^2}

OUTFLOWS:

capacity wear comp = new composting cap/aging time {kt/year^2}

new incineration cap(t) = new incineration cap(t - dt) + (capacity addition incin - capacity wear incin) * dt

INIT new incineration cap = 0 {kt/year}

INFLOWS:

capacity addition incin = DelayInc/DT+DepAddIncin {kt/year^2}

OUTFLOWS:

capacity wear incin = new incineration cap/aging time {kt/year^2}

new recycling cap(t) = new recycling cap(t - dt) + (capacity addition recycle - capacity wear rec) * dt

INIT new recycling cap = 0 {kt/year}

INFLOWS:

capacity addition recycle = DelayRecycle/DT+ DepAddRec {kt/year^2}

OUTFLOWS:

capacity wear rec = new recycling cap/aging time {kt/year^2}

old composting cap(t) = old composting cap(t - dt) + (capacity wear comp - DepreciationCompost) * dt

INIT old composting cap = 260 {kt/year}

INFLOWS:

capacity wear comp = new composting cap/aging time {kt/year^2}

OUTFLOWS:

DepreciationCompost = old composting cap/20 {kt/year^2}

old incineration cap(t) = old incineration cap(t - dt) + (capacity wear incin - DepreciationIncin) * dt

INIT old incineration cap = 0 {kt/year}

INFLOWS:

capacity wear incin = new incineration cap/aging time {kt/year^2}

OUTFLOWS:

DepreciationIncin = old incineration cap/20 {kt/year^2}

old recycling cap(t) = old recycling cap(t - dt) + (capacity wear rec - DepreciationRecycle) * dt

INIT old recycling cap = 0 {kt/year}

INFLOWS:

capacity wear rec = new recycling cap/aging time {kt/year^2}

OUTFLOWS:

DepreciationRecycle = old recycling cap/15 {kt/year^2}

Recycling Budget(t) = Recycling Budget(t - dt) + (Recyling Fund - InvestmentToRec - DepreciationExpRec) * dt

INIT Recycling Budget = 4000000 {TL}

INFLOWS:

Recyling Fund = IF(gapRecycling>0)

THEN(IF(gapCompost>0)

THEN(CR Fund*gapRecycling/(gapCompost+gapRecycling))

ELSE(CR Fund-DepreciationCompost*OneUnitCompostingCost))

ELSE(OneUnitRecyclingCost*DepreciationRecycle) {TL/year}

OUTFLOWS:

InvestmentToRec = PossibleRecAdd*OneUnitRecyclingCost/DT {TL/year}

DepreciationExpRec = IF(Recycling Budget>=DepreciationRecycle * OneUnitRecyclingCost * DT)

THEN(DepreciationRecycle*OneUnitRecyclingCost)

ELSE(Recycling Budget/DT) {TL/year}

SmoothOfPossibleCompostAdd(t) = SmoothOfPossibleCompostAdd(t - dt) + (Change InSmoothComp) * dt

INIT SmoothOfPossibleCompostAdd = 0 {kt/year}

INFLOWS:

ChangeInSmoothComp = (PossibleCompAdd-SmoothOfPossibleCompostAdd)/5 {kt/year^2}

SmoothOfPossibleIncinAdd(t) = SmoothOfPossibleIncinAdd(t - dt) + (ChangeInSmoothIncin) * dt

INIT SmoothOfPossibleIncinAdd = 0 {kt/year}

INFLOWS:

ChangeInSmoothIncin = (PossibleIncinAdd-SmoothOfPossibleIncinAdd)/5 {kt/year^2}

SmoothOfPossibleRecycleAdd(t) = SmoothOfPossibleRecycleAdd(t - dt) + (ChangeIn SmoothRecycle) * dt

INIT SmoothOfPossibleRecycleAdd = 0 {kt/year}

INFLOWS:

ChangeInSmoothRecycle = (PossibleRecAdd-SmoothOfPossibleRecycleAdd)/5 {kt/year^2}

waste at landfill(t) = waste at landfill(t - dt)+(waste generation rate-composting rate - recycling rate - incineration rate - recycling by private faclities) * dt

INIT waste at landfill = 90000 {kt}

INFLOWS:

waste generation rate = population*waste generation per person per day * 365/ 1000000 {kt/year}

OUTFLOWS:

composting rate = MIN(composting capacity*capacity utilization*(composable fr + source seperation effect comp), waste generation rate * composable fr) {kt/year}

recycling rate = MIN(recycling capacity*(recylable fraction+source seperation effectRecycling), waste generation rate*recylable fraction) {kt/year}

incineration rate = MIN(incineration capacity, waste generation rate-composting rate-recycling rate-recycling by private faclities)*0.8 {kt/year}

recycling by private faclities = waste generation rate*fraction of private recycling {kt/year}

aging time = 6 {year}

capacity utilization = 1 {dimensionless}

composable fr = 0.54 {dimensionless}

composting capacity = new composting cap+old composting cap {kt/year}

DelayCompost = DELAY(PossibleCompAdd,5,0) {kt/year^2}

DelayInc = DELAY(PossibleIncinAdd,5,0) {kt/year^2}

DelayRecycle = DELAY(PossibleRecAdd,5,0) {kt/year^2}

DepAddComp = IF(Composting Budge*t* >=DepreciationCompost * OneUnitCompostingCost * DT)

THEN(DepreciationCompost)

ELSE(Composting Budget/(OneUnitCompostingCost*DT)) {kt/year^2}

DepAddIncin = IF(Incineration Budge*t* >=DepreciationIncin * OneUnitIncinCost * DT)

THEN(DepreciationIncin)

ELSE(Incineration Budget/(OneUnitIncinCost*DT)) {kt/year^2}

DepAddRec = IF(Recycling Budget>=DepreciationRecycle* OneUnitRecyclingCost * DT)

THEN(DepreciationRecycle)

ELSE(Recycling Budget/(OneUnitRecyclingCost*DT)) {kt/year^2}

Desired source sep = 1 {dimensionless}

expected capacity addition compost = SmoothOfPossibleCompostAdd*5 {kt/year}

expected capacity addition incin = SmoothOfPossibleIncinAdd*5 {kt/year}

expected capacity addition recycling = SmoothOfPossibleRecycleAdd*5 {kt/year}

expected composting rate = composting rate+expected increase in compost rate {kt/year}

expected compost need = composable fr*ExpWasteGenRate {kt/year}

expected incin need = ExpWasteGenRate-(expected composting rate+expected recycling rate+recycling by private faclities) {kt/year}

expected incin rate = incineration rate+expected increase in incin rate {kt/year}

expected increase in compost rate = expected capacity addition compost* (composable fr+source seperation effect comp) {kt/year}

expected increase in incin rate = expected capacity addition incin*0.8 {kt/year}

expected increase in recycling rate = expected capacity addition recycling* (recylable fraction+source seperation effect Recycling) {kt/year}

expected recycling need = recylable fraction*ExpWasteGenRate {kt/year}

expected recycling rate = expected increase in recycling rate+recycling rate {kt/year}

ExpWasteGenRate = projected population*projected waste generation per person * 365 / 1000000 {kt/year}

gapCompost = IF((expected compost need-expected composting rate)>=0) THEN(expected compost need-expected composting rate) ELSE(0){kt/year}

gapIncin = IF((expected incin need-expected incin rate)>=0) THEN(expected incin need-expected incin rate) ELSE(0) {kt/year}

gapRecycling = IF((expected recycling need-expected recycling rate)>= 0) THEN(expected recycling need-expected recycling rate) ELSE(0) {kt/year}

incineration capacity = new incineration cap+old incineration cap {kt/year}

OneUnitCompostingCost = 175*1000 {TL/kt}

OneUnitIncinCost = 1875.5*1000 {TL/kt}

OneUnitRecyclingCost = 525*1000 {TL/kt}

PossibleBudgetFor CompInvestments = Composting Budget - DepreciationExpComp * DT {TL}

PossibleBudgetFor IncinerationInvestments = Incineration Budget - DepreciationExpIncin * DT {TL}

PossibleBudgetFor RecyclingInvestments = Recycling Budget - DepreciationExpRec * DT {TL}

PossibleCompAdd = IF(PossibleBudgetFor CompInvestments>=40000000) THEN(IF(gapCompost * OneUnitCompostingCost<=PossibleBudgetFor CompInvestments) THEN(gapCompost) ELSE(PossibleBudgetFor CompInvestments/OneUnitCompostingCost)) ELSE(0) {kt/year}

PossibleIncinAdd = IF((PossibleBudgetFor IncinerationInvestments)>=480000000) THEN(IF(gapIncin*OneUnitIncinCost<=PossibleBudgetFor IncinerationInvestments) THEN(gapIncin) ELSE(PossibleBudgetFor IncinerationInvestments/OneUnitIncinCost))

ELSE(0) {kt/year}

PossibleRecAdd = IF((PossibleBudgetFor RecyclingInvestments)>=120000000) THEN(IF(gapRecycling*OneUnitRecyclingCost<=PossibleBudgetForRecycling Investments) THEN(gapRecycling) ELSE(PossibleBudgetFor RecyclingInvestments/OneUnitRecyclingCost)) ELSE(0) {kt/year}

recycling capacity = new recycling cap+old recycling cap {kt/year}

Actual sporceSep = GRAPH(TIME) (2016, 0.07), (2020, 0.105), (2024, 0.135), (2028, 0.175), (2032, 0.245), (2036, 0.345), (2040, 0.615), (2044, 0.71), (2048, 0.76), (2052, 0.785), (2056, 0.8) {dimensionless}

CR Fund = GRAPH(TIME) (2016, 2e+007), (2020, 3.9e+007), (2024, 5.4e+007), (2028, 7.3e+007), (2032, 9.8e+007), (2036, 1.2e+008), (2040, 1.4e+008), (2044 1.7e+008), (2048, 2e+008), (2052, 2.3e+008), (2056, 2.6e+008) {TL/year}

fraction of private recycling = GRAPH(Actual sporceSep/Desired source sep) (0.00, 0.05), (0.1, 0.053), (0.2, 0.059), (0.3, 0.07), (0.4, 0.082), (0.5, 0.097), (0.6, 0.112), (0.7, 0.125), (0.8, 0.132), (0.9, 0.138), (1, 0.14) {dimensionless}

population = GRAPH(TIME) (2016, 1.5e+007), (2020, 1.6e+007), (2025, 1.7e+007), (2029, 1.8e+007), (2034, 1.9e+007), (2038, 2e+007), (2043, 2e+007), (2047, 2e+007), (2052, 2e+007), (2056, 2e+007) {person}

projected population = GRAPH(TIME) (2016, 1.6e+007), (2020, 1.7e+007), (2024, 1.8e+007), (2028, 1.9e+007), (2032, 2e+007), (2036, 2e+007), (2040, 2e+007), (2044, 2e+007), (2048, 2e+007),(2052, 2e+007), (2056, 2e+007) {person}

projected waste generation per person = GRAPH(TIME) (2016, 1.30), (2020, 1.30), (2025, 1.30), (2029, 1.30), (2034, 1.30), (2038, 1.30), (2043, 1.30), (2047, 1.30), (2052, 1.30), (2056, 1.30) {kg/(day*person)}

recylable fraction = GRAPH(fraction of private recycling) (0.05, 0.27), (0.059, 0.261), (0.068, 0.252), (0.077, 0.243), (0.086, 0.234), (0.095, 0.225), (0.104, 0.216), (0.113, 0.207), (0.122, 0.198), (0.131, 0.189), (0.14, 0.18) {dimensionless}

source seperation effect comp = GRAPH(Actual sporceSep/Desired source sep) (0.00, 0.00), (0.1, 0.0115), (0.2, 0.0345), (0.3, 0.092), (0.4, 0.186), (0.5, 0.329), (0.6, 0.407), (0.7, 0.437), (0.8, 0.453), (0.9, 0.458), (1, 0.46) {dimensionless} source seperation effect Recycling = GRAPH(Actual sporceSep/Desired source sep) (0.00, 0.00), (0.1, 0.00927), (0.2, 0.0417), (0.3, 0.089), (0.4, 0.186), (0.5, 0.329), (0.6, 0.5), (0.7, 0.688), (0.8, 0.781), (0.9, 0.812), (1, 0.82) {dimensionless}

waste generation per person per day = GRAPH(TIME) (2016, 1.29), (2020, 1.30), (2025, 1.30), (2029, 1.30), (2034, 1.30), (2038, 1.30), (2043, 1.30), (2047, 1.30), (2052, 1.30), (2056, 1.30) {kg/(day*person)}