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ORIGINAL ARTICLE

The effects of external costs on the system selection for treatment and disposal of municipal solid wastes: a deterministic case study for a pre-assessment

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Abstract Selecting a system for treatment and disposal of municipal solid wastes (i.e., selection of the capacity, location and type of the processes and management programs) is the key factor which determines the cost of the municipal solid waste management applications. In these applications, every process and management program is an individual economic activity, and they cause not only private costs and benefits but also external costs and benefits in different levels. In the current decision making applications, however, the final decisions for the system selection are mostly taken by the decision makers without considering external costs and/or benefits. In this paper, a new cost optimization model approach which theoretically has to give same decision results at every run under the same model conditions was used to determine an appropriate system for treatment and disposal of municipal solid wastes in a large region. Firstly the solutions were obtained for the case that the objective function included only private (internal) costs and benefits. Then, different scenarios that include external costs obtained from the literature were applied and the solutions were compared with the previous ones. Results showed that different final decisions could be obtained for some scenarios at the same model conditions. These differences were analyzed in terms of the total cost of the system, and it was observed that an annual reduction between 1 and 8 Euro/person could be obtained with respect to the first decision. The effect of these external cost-related reductions in the annual total cost of the system was calculated as earnings in the range of 2–13 %. On the other hand, a Monte Carlo simulation which was applied for the range of the external costs indicated some meaningful inconsistency between the values of the study and the literature. All these findings refer to need for a new comprehensive decision making application for real external costs of the study area before final decision. In conclusion, it can be said that this deterministic approach might be useful for environmental managers and decision makers in terms of reduction the total cost and the external costs of the system before final decisions.

Keywords Decision making · Treatment and disposal · External costs · Linear optimization model · Municipal solid wastes

Introduction

Integrated municipal solid waste management (MSWM) can be defined as the selection and application of suitable treatment and disposal processes (i.e., techniques, methods and technologies such as separator, composting, incineration, land filling, etc.) and management programs (i.e., generation, storage, collection and transportation policies) to achieve waste management objectives and goals [1]. Selecting a system (i.e., selection of the capacity, location and type of the processes and the programs) to be used in treatment, disposal and management of wastes is the first stage of the municipal solid waste (MSW) management. The final decision of this first stage is the basic element that will determine total cost of the all management applications.

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In MSWM applications, every process and management program is an individual economic activity. In environmental economics, total cost of an economic activity can be defined as the sum of the net private costs and the net external costs associated with the activity. The net cost represents the sum of the costs minus the sum of the benefits [2]. Accordingly, the net private cost (the net internal cost) of a social or economic activity is defined as the sum of the costs (the internal costs) minus the sum of the benefits (the internal benefits) of the effects of the activity, carried out by a group, on the group itself. And the net external cost of a social or economic activity is defined as the sum of the costs (the external costs) minus the sum of the benefits (the external benefits) of the effects of the activity, carried out by a group, on another group [3]. Internal costs and benefit types to be considered in the selection of the treatment and disposal system are as follows: up-front costs, building-operation-maintenance costs, back-end costs, transportation costs, and revenues [4]. The external costs and benefits (the externalities) can result from the various processes (e.g., raw material extraction, manufacture, transportation, use of the product and disposal of it after turning into waste material) which a product undergoes during its life cycle [5]. As for the waste management, it is possible to group these processes in six items: generation, storage, collection, transportation, treatment and disposal of the waste. Each of these processes absolutely causes some external costs and benefits in various levels [6]. The externalities are affected from the variables such as legal restrictions and features including waste composition and the type, technology, location and age of the process [7]. Based on this information, it can be said that the basic element defining the amount of external costs and benefits in the MSWM is the waste treatment and disposal system to be used. On the other hand, the external costs and benefits are generally not taken into consideration during the system selection stage [8]. However, even the external costs solely resulting from disamenities, a negative influence on perceptions of environmental quality, can constitute an important part of the total cost of the system. For example, Jamasb et al. [9] states that the role of the external costs resulting from disamenities in the total cost is about 10 % for the incineration and 25 % for the landfilling. Therefore, it is clear that omission of the external costs may lead to some misjudgments related to the waste management application.

The amount of external costs can be determined with different valuation approaches [10], and the external costs of MSWM processes (i.e., the process-based external costs) have been estimated by many existing studies [3, 5–7, 9]. Moreover, the amount of the process-based external costs can be used for an economic decision making process [11]. An example of using economic valuation studies to support decision making are "externality adder" studies completed by several states of America in the 1990s to guide selection of new electricity generation capacity. According to Matthews et al. [11], states explicitly sought estimates of the social damage from different types of power generation processes in these studies. These states recognized that utilities made investment decisions on the basis of their cost per kilowatt-hour. The state regulatory commissions saw that a utility might choose a polluting plant because it was cheaper to the utility, even though emissions would impose large social costs. This hypothesis has also been separately confirmed for some part of the MSWM applications (for examples, please see Korucu et al. [12] on determination of the location for a disposal process which is only a small part of the system selection, and Kinnaman et al. [13] on a determination attempt of a socially optimal rate in terms of recycling process) and some other environmental issues so far (e.g., Travisi et al. [14] on an agricultural pesticide issue). On the other hand, possible final decision differences caused by the omission or consideration of the process-based external costs in a decision making procedure of a system to be used in the MSWM have not been shown before. The novelty of this study is to provide an examination of the aforementioned hypothesis for the whole system selection stage of MSWM for the first time analytically. In this study, possible differences caused by the consideration of the all process-based external costs in the system selection step of the MSWM were examined. For this, the final decisions proposed by a new cost optimization model taking into account only the internal costs and benefits were taken as a reference point for a case study. The model was run again for different constraint types and various scenarios representing different levels of external costs, and new final decisions were obtained. The decisions obtained in the two stages were compared, and differences were assessed. Finally, a simulation study was performed to evaluate inconsistencies between external costs of the study and the related literature, and results were discussed.

Materials and methods

The main question of this study is whether there is a meaningful difference between taking or not taking the external costs and benefits into consideration in terms of the final decision in system selection applications carried out for the treatment and disposal of MSWs. Under nonlinear cost optimization model conditions, this question could not be answered definitely because of the possibility of different results for different solution methods under the same model conditions. For this reason, firstly a new mixed integer linear cost optimization model which theoretically has to give same results under the same model conditions because of its linearity was developed. The details of the model and its application in Kocaeli region for only the internal costs and benefits were presented by Korucu et al. [15]. In this paper, the same optimization model was used for some different scenarios including the external costs in addition to the internal costs and benefits to evaluate the effect of external costs on the final decision. Unfortunately, the scenarios do not include the external benefits because of the lack of data (please see "External costs"). All the methodology of this study can be summarized as follows:

- Collection of the required data (e.g., constraints, variables and parameters of the model, waste production and characterization, cost and benefit values etc.),
- configuration of the linear cost optimization model for the study area (*),
- application of the model for only internal costs and benefits in terms of different constraints (i.e., maximum transportation distance, allowable number of landfills) (*),
- determination of the process-based external costs with the help of the literature,
- development of some external cost scenarios to lower the uncertainty of the study,
- re-application of the model for the internal costs and benefits and the external costs together to evaluate the effect of external costs on final decision,
- performing of a simulation study to evaluate inconsistencies between external costs of the study and related literature,
- discussion of the results.

Here, "*" refers to the steps of the methodology which were detailed and shown in Korucu et al. [15]. Please see both of Korucu et al. [15] and the "Cost Optimization Model" part of this study for further details of these steps and the general algorithm of our mathematical model, if required. In Korucu et al. [15], the model was applied by taking into consideration only the internal costs and benefits for Kocaeli, and final decisions were obtained for the different transportation distances and the different landfill area number constraints. Those final decisions were called "Decision_1" in this paper. The same optimization model was applied by adding the external costs to the internal costs and benefits in this paper and the new final decisions obtained here were called "Decision_2".

Study area

Figure 1 shows the study area (Kocaeli region) in details. As one of the most densely industrialized regions of Turkey, the province of Kocaeli has a population of 1,634,691 for the year 2012. An average of 0.99 kg of MSW per person per day has been generated in the city [16]. In this study, information on how the component compositions of sub-regions may change over the project range (2015–2040) was defined according to the projection studies of Kocaeli Metropolitan Municipality and University of Kocaeli (average waste composition: organic wastes 42 %, recycled wastes 30 %, hazardous wastes 2 %, combustible wastes 21 %, others 5 %) [15, 16]. In the present situation, the MSWs generated across the city are being collected at four existing transfer stations (F1, F2, F4, F6) and disposed of in two landfill areas (Dilovası landfill area and Solaklar landfill area) after the transportation. Additional two hypothetical stations (F3, F5) were defined in the optimization model for the study area (see Fig. 1). Since capacity of the landfills is expected to be exhausted by 2015, the city needs a new system for the treatment and disposal of MSWs. Accordingly, this study will be a pre-assessment to see potential variations for Kocaeli before the final decision.

Cost optimization model

Since MSW mass is a mixed composition of various types of waste components with different physical and chemical properties, the optimization model was designed to include all possible treatments and disposal processes for these different waste components. For some processes which are used in current MSWM applications, it is possible to have multiple waste inputs coming from different treatment and/or disposal processes. For example, the wastes to be sent to an 'Aerobic Biological Treatment Plant' like composting may be the sum of the organic wastes separately collected at the source and those coming from a 'Material Recovery Facility' (MRF). These two inputs have different waste contents practically. In an optimization model, these different inputs mean different variables at one model node. If the model needs to predict the output value of this node, as in this study, this situation means non-linearity. This problem was first described and resolved in a linear way by Solana et al. [17, 18]. On the other hand, their mathematical model which did not include the building cost of the used processes in the model could not ensure the most efficient system alternative because they were not able to ask the model the best system alternative; they just tried to find the best system alternative among a few system alternatives which were given to the model by themselves.

Our mixed integer linear cost optimization model aims to eliminate the aforementioned problem using a 'divided process approach'. First, an integrated MSWM model consisting of all the possible processes that can be used in the treatment and disposal of MSWs was formulated in the model. In this integrated management model, two different treatment and disposal processes, i.e., composting and

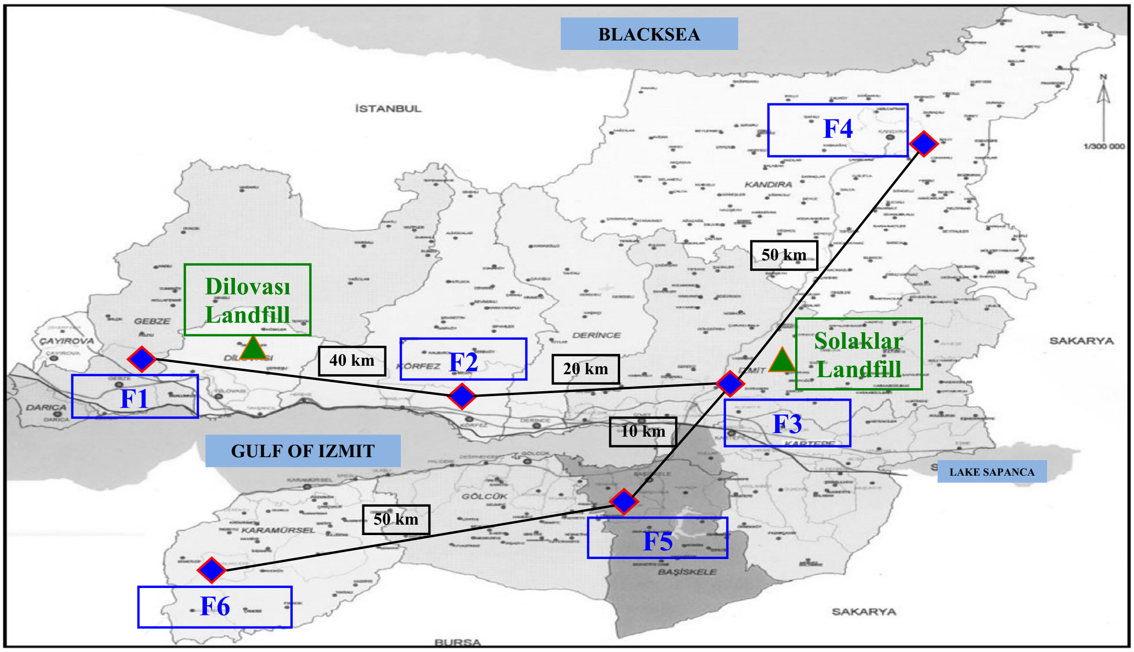

Fig. 1 Study area (F1, F2, F3, F4, F5 and F6 refer the transfer stations used in the optimization model)

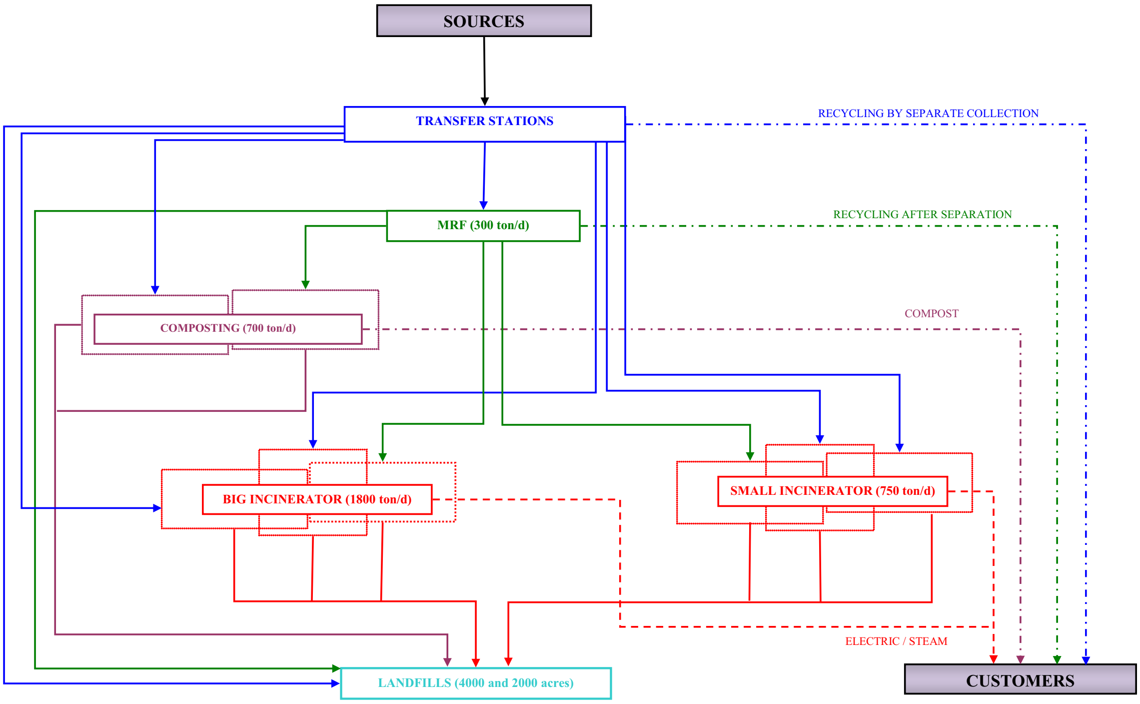

Fig. 2 Flow scheme used in the optimization model (the *dotted squares* refer the parts of divided processes in the model)

incineration, which deliver waste to the next point and have multiple waste inputs with different component compositions were defined as divided parts. This means that they were divided into the number of input flow (please see the dotted squares in Fig. 2). Our mathematical model made it possible to define waste outputs of all the treatment and disposal processes as a linear way in connection with the input compositions.

Flow scheme of the cost optimization model used in this study is shown in Fig. 2. It was decided by a local

30-member decision team to eliminate some treatment and disposal processes from general flow scheme of a MSWM application because of the lack of local real-time data for the processes such as RDF, anaerobic biological treatment, some thermal processes like pyrolysis, etc. However, the eliminated processes can easily be integrated into the model if required. The model was designed via a freely available GNU Linear Programming Kit (GLPK) editor, and solved using 'glpsol' command via Windows command prompt. All parameters, constraints and variables used in the mass balance and the structure of the model were determined by the decision team.

The model has two general types of modeling constraints like normative process constraints (e.g., legislative biodegradable waste constraint for landfills; heating value constraint for thermal processes) and technical process constraints (e.g., modeling nodes like transfer stations, separators, composting, incinerator; organic material flows after separate collection; waste outputs of the processes in terms of the linearity of the model). The component-based transportation costs of the model just include the internal costs (please see Table 1). Transportation costs of the products separated and sold to the customers at the MRF areas were not included in the model as the products would be directly picked up by the customers themselves. The incineration plants proposed by the model will be built and operated by a contract firm on the basis of a build-operate-transfer model. The municipal administration will pay a tipping fee per each unit of waste to the contract firm. Revenues generated through the use of the plant, such as energy sale, will be collectible by the firm. The minimum calorific value requirement for any waste to be incinerated was fixed at 8000 kj/kg. Incineration as an alternative thermal treatment process was entered into the model with 2 different options, one being big capacity (1800 t/day) and the other, small capacity (750 t/day). In a similar way, the model offers two options for landfill size: large (4000 acre) and small (2000 acre). The capacity of MRF and composting processes in the model are 300 and 700 t/day, respectively. All technical and economical data for the processes used in the model are formulated based on the up-to-date local data taken from the operational reports [19] of the public waste management organization of Kocaeli (IZAYDAS).

Costs and benefits

Internal costs and benefits

The internal cost types of the objective function in the model are as follows: up-front costs (Q_U), building, operation, maintenance, and back-end costs (Q_B), transportation

Table 1 Internal costs and benefits used in the cost optimization model

Costs/waste components	Other waste types (e.g. scrap)	Biodegradable kitchen, park and garden wastes	Paper, carton and bulky carton	Plastic	Glass	Metal and bulky metal	Other combustibles and other bulky combustibles
Transportation Costs (Euro/ton waste/km)	0.015	0.043	0.036	0.013	0.004	0.004	0.010
Building, operation, maintenance costs for big OR small incinerators—tipping fee (Euro/ton waste)	17 OR 20						
Building, operation, maintenance costs for landfills (Euro/ton waste)	32.62						
Back-end costs for landfills (Euro/ton waste)	7.62						
Revenues from recycled materials for MRF (Euro/ton waste)	250	0	100	225	0	200	0
Revenues from compost for composting (Euro/ton waste)	0	14	0	0	0	0	0
Revenues from landfill gas (Euro/ton waste)	2.4						

Up-front costs: 1000 Euro/year for 0.25 acre for all process type (except incinerators due to the tipping fee)

Building, operation, maintenance costs: 645,000 Euro/year for a MRF and 3,750,000 Euro/year for a compost process

Revenues from process scrap sale: 15,000,000 Euro/25 years for big incinerators and 10,000,000 Euro/25 years for small incinerators (nearly 1 Euro per ton waste)

Incineration tipping fee offsets the up-front costs, the building, operation, maintenance costs, capital costs, disposal costs of any unusable residues and all the possible revenues along 25 years for contractor firm

Table 2 Net internal cost and the external costs for municipal solid waste treatment and disposal processes

Processes	Net internal cost of process (Euro per tone waste)	External costs of process (Euro per tone waste)	External costs of process/net internal cost of process (process-based *E*/*I*)
Incinerator (only energy recovery)	51.23[a] 103[c]	60.55–69.67[a] 3.89[e] 22[f]	1.18–1.36[a]
Incinerator (heat and energy recovery)	68.18[a] 79[c] 40–135[h] 16 or 19[i]	38.73–48.21[a] 17.64[c] 5[f] 3.7–23.68[h] 15–90[i]	0.57–0.71[a] 0.22[c] 0.09–0.18[h] 0.79–4.74[i]
Landfill	9.12[a] 40[c] 5.92–40[h]	21.63–29.54[a] 1.92–2.75[b] 14[f] 11.84[g] 1.48–10.36[h]	2.37–3.24[a] 0.25–0.26[h]
Landfill (with energy recovery)	7.7[a] 36[c] 45[i]	16.27–21.01[a] 1.52–2.18[b] 22.14[c] 3.99–6.48[d] 11[f] 2.96–6.66[g] 7–42[i]	2.11–2.73[a] 0.62[c] 0.16–0.93[i]
Composting and MRF together	19.7[a] 20[i]	0.47–2.65[a] 1–6[i]	0.02–0.14[a] 0.1–0.6[i]

[a] Jamasb and Nepal [9]

[b] Defra [22]

[c] Dijkgraaf and Vollebergh [23]

[d] Kinnaman [21]

[e] Isely and Lowen [20]

[f] Rabl, Spadaro, and Zoughaib [24]

[g] Nahman [25]

[h] Miranda and Hale [26]

[i] This study

costs (Q_T). Similarly, the internal benefit types of the objective function in the model are as follows: revenues from recycled materials (J_R), revenues from compost sale (J_C), revenues from energy sale (J_E) and revenues from scrap sale (J_s). Internal cost and benefit values used in the model for the case study are shown in Table 1.

External costs

In literature, it is unfortunately not possible to find process-based external costs and the process-based external benefits for MSWM separately. In general, the external costs and benefits of a process are given in one single value which is equal to just the external costs of the process. The external benefits of processes are generally neglected. There are various studies conducted to assess external costs for the waste treatment and disposal processes, in particular incineration and landfilling. Some of the data obtained in the literature studies are summarized in Table 2. The information presented in Table 2 includes the findings of the studies conducted in different regions by different researchers. As the data given in Table 2 show, the external costs and the external costs/net internal cost ratios of the processes (process-based *E*/*I* value for this study) considerably vary from region to region [20, 21]. According to Eshet et al. [5], for example, the ranges given in literature of the total estimates on external costs originating from emission are 1.3–171 US$/ton waste for incinerator and 0.91–44 US$/ton waste for landfills.

In this study, compatibly with the literature, only the external costs were used for external economic effects of the processes. The process-based external costs of our model just include external costs for the damages and the disamenities originating from waste treatment and disposal processes corresponding with the used literature data in this study. Since the studies performed to determine the external costs are quite expensive and have a complicated structure, it is often not possible to conduct a separate study for each region. For the regions where no study is carried out such as Turkey, it is common to apply various econometric transformation models to the literature information to determine the external costs for the region [3, 27]. In some applications, values from the literature can be transferred to the region in question. According to Prokofieva et al. [28], on the other hand, value transfer applications have been the subject of considerable controversy, as they are often used inappropriately. The consensus seems to be that it can provide valid and reliable estimates under certain conditions. The conditions are: (a) the commodity or the service being valued is very similar to the ones on which the estimates were made; (b) the estimates must have very similar characteristics; (c) the market conditions at both sites are similar; and (d) the similar proposed changes in provision between sites. If the conditions stated above are not adhered to, this can lead to error and restrict the robustness of the transfer process [28].

In this study, any econometric transformation model for external costs was not implemented because of the lack of both national and local econometric values for the study area. Instead, it was preferred to create some external cost scenarios by directly transferring some suitable values given in literature as a reference. Our optimization model is required to be Euro-based and up-to-date external costs for each of the treatment and disposal processes that took place in our study with different capacities and types are given. These basic requirements are only fulfilled by Jamasb et al. [9], if the studies obtained in Table 2 are taken into consideration. The main reason for the preference of the Euro-based and up-to-date values given by Jamasb et al. [9] in this study was the fact that net internal costs and benefits, and external costs have been given together by the authors for each of the waste treatment and disposal processes that took place in the linear model used in our study. When relevant literature is reviewed, it could be understood that it is not easy to reach studies presenting amount of cost values separately for each of the waste treatment and/or disposal processes at the same time.

External cost scenarios

The waste treatment and disposal processes that took place in this study are: (1) MRF, (2) composting, (3) small capacity incinerator with energy and heat recovery, (4) big capacity incinerator with energy and heat recovery, and (5) landfills with energy recovery (small and/or large). The maximum amounts of the external costs of these processes per unit waste given by Jamasb et al. [9] are as follows; 2.65 Euros for MRF, 2.65 Euros for Composting, 48.21 Euros for small incinerator with heat and energy recovery, 48.21 Euros for big incinerator with heat and energy recovery and 21.01 Euros for landfills with energy recovery (see Table 2). To provide convenience in our scenario-based assessments, these values were rounded off to 3, 3, 45, 45, and 21, respectively. The scenario where these values were used in our model was assumed to reflect the current situation for Kocaeli, and it was named as “Middle External Costs” in this paper.

Since it is probable that the amounts of current external costs per unit waste used for Kocaeli in this study would be higher or lower than the “Middle External Costs” in the project range (between the years 2015 and 2040), some additional scenarios were developed to lower the uncertainty in the study. For developing these scenarios, it was assumed that all the external costs would decrease or increase linearly at the same rate with each other. Accordingly, the scenarios of “Lower-middle External Costs” (2, 2, 30, 30, 14) and “Upper-middle External Costs” (4, 4, 60, 60, 28) were obtained by decreasing and increasing the values of “Middle External Costs” (3, 3, 45, 45, 21) by the rate of one-third, respectively. Similarly, the scenarios of “Lower External Costs” (1, 1, 15, 15, 7) and “Upper External Costs” (5, 5, 75, 75, 35) were also obtained by changing the middle values by the rate of two-third. The last two scenarios included “Zero External Costs” scenario (0, 0, 0, 0, 0) with no external costs (i.e., “Decision_1”), and “Extreme External Costs” (6, 6, 90, 90, 42) with two times of middle values.

Objective function of optimization model

The total cost function of the model can be theoretically expressed as follows:

$$\text{Total cost of a system} = \text{Sum of the total costs of all processes in the system} \tag{1}$$

$$\begin{aligned}\text{Total cost of a process} &= \text{Sum of the net internal costs of process}\\ &\quad + \text{External costs of process}\end{aligned} \tag{2}$$

$$\begin{aligned}\text{Net internal cost of a process} &= \text{Sum of the internal costs of process}\\ &\quad - \text{Sum of the internal benefits of process}\end{aligned} \tag{3}$$

Accordingly, the objective function of the cost optimization model which developed to minimize the total cost of the system is expressed as follows:

$$\text{minimize} \quad Q = Q_U + Q_B + Q_T + Q_E - J_R - J_C - J_E - J_S \tag{4}$$

where: Q is total cost of the system, Q_U is the sum of the up-front costs of all processes in the system, Q_B is the sum of the building, operation, maintenance and back-end costs of all processes in the system, Q_T is total transportation costs of the system, Q_E is the sum of the external costs of all processes in the system (zero for “Decision_1”), J_R is the sum of the revenues from recycled materials, J_C is the sum of the revenues from compost sale, J_E is the sum of the revenues from energy sale, J_S is the sum of the revenues from scrap sale.

Monte Carlo simulation

Our deterministic external cost scenarios contain uncertainty at some level because of the regional econometric differences of the studies (i.e., UK for Jamasb et al. [9] and Turkey for this study) and the assumption of linear increase and/or decrease of the external costs for the scenario. Besides, it can clearly be seen that the range of process-based *E*/*I* values for all treatment and disposal processes used in our study are not compatible with the range of external costs given by Jamasb et al. [9] for the same processes (please see Table 2). On the other hand, no specific uncertainty analysis was implemented for our external cost scenarios because of the lack of local econometric values for the study area. Instead, a simulation study was performed using @Risk software package (Palisade Inc.), which combines a compatible Monte Carlo Simulation tool with Microsoft Excel, to evaluate inconsistency between the external cost ranges of our study and the external cost ranges of the all literature data given in Table 2.

For the Monte Carlo Simulation studies, the range of external costs for all treatment and disposal processes used in our study and the range of external costs given in the literature were separately determined. The ranges for the all processes used in our study were restricted to the corresponding literature ranges. For example, our external cost range for incinerators (15–90 Euro) was restricted to the range of 3.7–48.21 Euro according to our incineration-related literature data (please see Table 2). Finally, the probability densities of these new ranges were simulated with iteration number of 1,000,000 in @Risk. All the distribution functions of the ranges for simulations were determined as generalized beta distribution which provides some simplicity for using minimum and maximum values, and approximates to normal distribution substantially.

Result and discussions

Results of optimization model

For each external cost scenario, final decisions were separately obtained for different transportation distance limits (i.e., 30,…, 110, 120) and the different numbers of allowable landfill areas (i.e., 1, 2 and 6) suggested by local decision makers according with the study area (please see Fig. 1). For the all scenarios used in the study, the findings obtained for the transportation distances of 60 km and higher (70, 80, 110, and 120 km) revealed no differences. Additionally, no appropriate result for any transportation limit or scenario could be obtained in the situation that the number of allowable landfill areas was limited to 1. Table 3 shows the findings obtained for the situation of restriction of the number of allowable landfill areas to 2. This restriction was called as “Restriction_2” in this study. Table 4 shows the results obtained for the situation in which the allowable number of landfill areas was not limited. The maximum allowable landfill number for this study is 6 because of the maximum waste station number in the study area, and this restriction was called as “Restriction_6”.

Basically, it is possible to mention three common grounds for Tables 3 and 4. Firstly, none of the decisions contain the MRF process. In our opinion, the main reason for this fact may be that the revenues from recycled materials (i.e., 250, 0, 100, 225, 0, 200 and 0 Euro per ton, respectively) and recycling rates (i.e., 0.02, 0, 0.05, 0.30, 0, 0.15 and 0, respectively) of the MRF process for different municipal waste types such as other waste types, biodegradable kitchen-park-garden wastes, paper, carton-bulky carton, plastic, glass, metal-bulky metal, other combustibles, other bulky combustibles parts were so low in our model. Moreover, it may also be said that the separate collection ratios of recyclable waste materials at source used in our model (i.e., 0, 0.05–0.15, 0.60, 0.60, 0.60, 0.60, 0.15, respectively) were so high and unrealistic [please note that the all technical and economical data for the processes used in the model which has to minimize the total cost of the system are formulated based on the up-to-date local data taken from the operational reports of the public waste management organization of Kocaeli (IZAYDAS)].

Secondly, every decision which contains an incinerator alternative gives this alternative as big scale. Similarly,

Table 3 The results for the situation of restriction of the number of maximum landfill areas to 2

Scenarios	Maximum transport distance (km)	Types of system costs (million Euro)		Final decisions for process types and locations			
		Net internal cost	External costs	MRF	Composting	Incinerator (big)	Landfill (small)
Zero External Costs ("Decision_1")	30	54,769	0	–	F1–F4–F6	F2	F1–F5
	40	17,067	0	–	F4–F6	F2	F3–F5
	50	1959	0	–	F3–F5	F2	F3–F5
	60	764	0	–	–	F3	F1–F3
Lower External Costs ("Decision_2")	30[a]	54,769	280	–	F1–F4–F6	F2	F1–F5
	40	17,067	283	–	F4–F6	F2	F3–F5
	50[c]	1959	283	–	F3–F5	F2	F3–F5
	60[b]	764	286	–	–	F3	F1–F3
Lower-middle External Costs ("Decision_2")	30[a]	54,769	544	–	F1–F4–F6	F2	F1–F5
	40	17,067	547	–	F4–F6	F2	F3–F5
	50[c]	1959	547	–	F3–F5	F2	F3–F5
	60[b]	764	549	–	–	F3	F1–F3
Middle (Current) External Costs ("Decision_2")	30[a]	54,769	807	–	F1–F4–F6	F2	F1–F5
	40	17,067	810	–	F4–F6	F2	F3–F5
	50[c]	1959	810	–	F3–F5	F2	F3–F5
	60[b]	764	813	–	–	F3	F1–F3
Upper-middle External Costs ("Decision_2")	30[a]	54,769	1071	–	F1–F4–F6	F2	F1–F5
	40	17,067	1074	–	F4–F6	F2	F3–F5
	50[c]	1959	1074	–	F3–F5	F2	F3–F5
	60[b]	764	1077	–	–	F3	F1–F3
Upper External Costs ("Decision_2")	30[a]	54,769	1335	–	F1–F4–F6	F2	F1–F5
	40	17,067	1338	–	F4–F6	F2	F3–F5
	50[c]	1959	1338	–	F3–F5	F2	F3–F5
	60[b]	764	1340	–	–	F3	F1–F3
Extreme External Costs ("Decision_2")	30[a]	54,769	1598	–	F1–F4–F6	F2	F1–F5
	40	17,067	1601	–	F4–F6	F2	F3–F5
	50[c]	1959	1601	–	F3–F5	F2	F3–F5
	60[b]	764	1604	–	–	F3	F1–F3

This situation was called as "Restriction_2" in this paper

[a] It refers the most suitable final decision for the related scenario in terms of the external costs of the system

[b] It refers the most suitable final decision for the related scenario in terms of the net internal cost and the total cost of the system

[c] It refers the most suitable final decision for the related scenario in terms of the moderate final decision perspective which aims to simultaneously satisfy the minimum net internal cost and the minimum external costs expectations, in a moderate level

every decision which contains a landfill alternative gives this alternative as small scale. It is clear that the model tends to sent waste mass to landfill areas as less as possible mainly because of the legislative biodegradable waste constraint for landfills. In addition, these two reactions of the model may be explained by high total cost values of landfill processes per unit waste compared to incinerations. For example, in the "Middle External Costs" scenario, the total cost value for landfills for per unit waste is equal to [(8,000,000 Euro/annual waste amount for a small size landfill area or 16,000,000 Euro/annual waste amount for a large size landfill area) + (32.62 + 7.62) + (Q_{T}) + (21) − (0) − (0) − (2.4) − (0)], and the total cost value for incineration is equal to [(0 Euro because of tipping fee) + (17 or 20) + (Q_{T}) + (45) − (0) − (0) − (0 Euro because of tipping fee) − (600,000 Euro/annual waste amount for a big incinerators and 400,000 Euro/annual waste amount for a small incinerators)] (please see

Table 4 The results for the situation in which the allowable number of landfill areas was not limited

Scenarios	Maximum transport distance (km)	Types of system costs (million Euro)		Final decisions for process types and locations			
		Net internal cost	External costs	MRF	Composting	Incinerator (big)	Landfill (small)
Zero External Costs (“Decision_1”)	30	25,308	0	–	F1–F3–F4–F6	–	F1–F2–F3–F4–F5–F6
	40	2161	0	–	F4–F6	F2	F1–F2–F4–F6
	50	1479	0	–	F1–F3–F5	–	F1–F2–F3–F4–F5
	60	764	0	–	–	F3	F1–F3
Lower External Costs (“Decision_2”)	30	25,308	130	–	F1–F3–F4–F6	–	F1–F2–F3–F4–F5–F6
	40	2161	283	–	F4–F6	F2	F1–F2–F4–F6
	50[a,c]	1479	130	–	F1–F3–F5	–	F1–F2–F3–F4–F5
	60[b]	764	286	–	–	F3	F1–F3
Lower-middle External Costs (“Decision_2”)	30	25,309	260	–	F1–F3–F4–F6	–	F1–F2–F3–F4–F5–F6
	40	2162	542	–	F4–F6	F2	F1–F2–F4–F6
	50[a,c]	1479	260	–	F1–F3–F5	–	F1–F2–F3–F4–F5
	60[b]	764	549	–	–	F3	F1–F3
Middle (Current) External Costs (“Decision_2”)	30	25,309	390	–	F1–F3–F4–F6	–	F1–F2–F3–F4–F5–F6
	40	2162	802	–	F4–F6	F2	F1–F2–F4–F6
	50[a,c]	1479	390	–	F1–F3–F5	–	F1–F2–F3–F4–F5
	60[b]	764	813	–	–	F3	F1–F3
Upper-middle External Costs (“Decision_2”)	30	25,309	520	–	F1–F3–F4–F6	–	F1–F2–F3–F4–F5–F6
	40	2162	1062	–	F4–F6	F2	F1–F2–F4–F6
	50[a]	1479	520	–	F1–F3–F5	–	F1–F2–F3–F4–F5
	60[b,c]	1289	520	–	F3	–	F1–F2–F3–F4–F5
Upper External Costs (“Decision_2”)	30	25,308	651	–	F1–F3–F4–F6	–	F1–F2–F3–F4–F5–F6
	40	2161	1322	–	F4–F6	F2	F1–F2–F4–F6
	50[a]	1479	651	–	F1–F3–F5	–	F1–F2–F3–F4–F5
	60[b,c]	1289	651	–	F3	–	F1–F2–F3–F4–F5
Extreme External Costs (“Decision_2”)	30	25,308	781	–	F1–F3–F4–F6	–	F1–F2–F3–F4–F5–F6
	40	2161	1582	–	F4–F6	F2	F1–F2–F4–F6
	50[a]	1479	781	–	F1–F3–F5	–	F1–F2–F3–F4–F5
	60[b,c]	1289	781	–	F3	–	F1–F2–F3–F4–F5

This situation was called as “Restriction_6” in this paper

[a] It refers the most suitable final decision for the related scenario in terms of the external costs of the system

[b] It refers the most suitable final decision for the related scenario in terms of the net internal cost and the total cost of the system

[c] It refers the most suitable final decision for the related scenario in terms of the moderate final decision perspective which aims to simultaneously satisfy the minimum net internal cost and the minimum external costs expectations, in a moderate level

Table 1 and the objective function which is like $[Q = (Q_{\mathrm{U}}) + (Q_{\mathrm{B}}) + (Q_{\mathrm{T}}) + (Q_{\mathrm{E}}) - (J_{\mathrm{R}}) - (J_{\mathrm{C}}) - (J_{\mathrm{E}}) - (J_{\mathrm{S}})]$, together).

Thirdly and finally, as can be seen in Tables 3 and 4, the net internal cost and the total cost of the system of the scenarios tend to decrease when the constraint value of maximum transport distance increases. Furthermore, the external costs of the scenarios tend to increase when the constraint value of maximum transport distance increases. On the other hand, this situation showed some deviation such as to decrease or to remain stable for the transportation constraint of 50 km in terms of the external costs of the scenarios (please see Table 4). In our cost minimization model, the most conservative transportation constraint value (i.e., allowable maximum waste transportation distance) is 30 km. The model naturally has the least number of decision alternatives for the system in this value. The number of the decision alternatives for a scenario tends to increase when this constraint is loosened (e.g., from 30 to 40 km or 50 km, etc.). An increase in the number of decision alternatives means the possibility of reaching a cheaper system alternative. On the other hand, the transport costs would increase when the allowable maximum waste transportation distance is longer. As it can be seen from Tables 3 and 4, our cost minimization model overcomes this contradiction by searching for new alternatives which have less number of processes and/or cheaper options like composting. The aforementioned total cost reduction, however, cannot be totally explained with the numbers and/or the types of the processes in the decision. For example, all the final decisions for 40 and 50 km transport distances in Table 3 were the same in terms of the types and numbers of the processes. Similarly, external costs of these scenarios were the same, too. But the locations of the composting processes were different. In this situation, it can be said that the amount of the transportation cost (Q_{T}) is a key factor which determines the total cost of the scenarios because of the direct connection of the transportation costs with the process locations. For this reason, the internal transportation costs of the study must be re-examined and the external transportation costs must also be taken into account for the scenarios in future studies. Unfortunately, this external cost type was not used in this study because of the absence of this type of data in Jamasb et al. [9].

As can be seen from Table 3, the most appropriate final decision in terms of the net internal cost of the system was the decision reached for the limits of 60 km when the number of landfill areas was restricted to 2 ("Restriction_2") and external costs were not taken into account. This decision, which was called as "Decision_1" for "Restriction_2", showed no difference in any transportation distance or external cost scenario. In other words, "Decision_2" did not differ from "Decision_1" in terms of the net internal cost for "Restriction_2". If Table 4 was examined, it could be seen that the most appropriate decision for "Zero External Costs" in terms of the net internal cost was again the decision reached for the transportation distance of 60 when the number of landfill areas was restricted to 6 and external costs were not taken into account. This situation, which was called as "Decision_1" for "Restriction_6", was valid for the scenarios of "Lower External Costs", "Lower-middle External Costs" and "Middle External Costs" as well. However, it was observed that the decision differed from the "Decision_1" in the "Upper-middle External Costs", "Upper External Costs" and "Extreme External Costs" scenarios for "Restriction_6". Although the most appropriate decision was for the transportation distance of 60 again, the numbers and types of the treatment and disposal processes required to be applied together differed in this decision. It was proved that "Decision_1" was not an absolute right for the "Restriction_6" in terms of the net internal cost of the system. Furthermore, the final decisions of the all scenario obtained for "Restriction_6" showed equal or lower cost values than the final decisions of the same scenarios obtained for "Restriction_2" in terms of not only the total cost but also the external costs (please see the subscripts of "c" in Tables 3 and 4). "Restriction_2" has less number of the system alternatives because it is a more conservative constraint than "Restriction_6", and it means the more expensive alternatives. All in all, it is clear that the allowable number of landfill areas (and/or other processes) as a restriction is also a key factor which determines the cost of the scenarios.

The most appropriate final decision in terms of the external costs was the decision which was obtained in 60 km for "Decision_1" in "Zero External Costs" scenario for both landfill constraints because of the minimum total cost at the same externality level. But this decision immediately differed in the next scenarios (30 km for "Restriction_2" and 50 km for "Restriction_6"). In other words, it was also proved that "Decision_1" was not an absolute right in terms of the external costs of the system.

And finally, Tables 3 and 4 allows to look at the results from another perspective aside from the net internal cost and the external cost perspectives. This perspective which can be named as the moderate final decision perspective aims to simultaneously satisfy the minimum net internal cost expectation of the investors and the minimum external costs expectation of the public, in a moderate level. As can be seen from the Tables 3 and 4, all moderate final decisions indicate meaningful decision changes. These changes proved that "Decision_1" was not an absolute right in terms of a moderate economic perspective. According to these changes, the transportation constraint of 50 km seems like a critical value for our study area except the results of

Retriction_6 obtained for “Upper-middle External Costs”, “Upper External Costs” and “Extreme External Costs” scenarios.

In this study, cost differentiation per capita caused by the preference of “Decision_1” or “Decision_2” in terms of the total cost of the system was also evaluated for “Restriction_6” (because “Decision_2” did not differ from “Decision_1” in terms of the total cost for “Restriction_2”, but for “Restriction_6”). For that purpose, the values of annual waste treatment and disposal cost per capita were examined for a population of approximately 1,500,000 people and for a 25-year-project-period. Accordingly, the average annual cost per capita for “Decision_1” and “Decision_2” in terms of the total cost of the system for “Restriction_6” were calculated as 49 and 48 Euro/person for “Upper External Costs” scenario, 56 and 51 Euro/person for “Upper-middle External Costs” scenario, and 63 and 55 Euro/person for “Extreme_External Costs” scenario, respectively. If “Decision_2” was chosen as the final decision, the benefit from the external costs was observed as 15–22 Euro/person while the net internal costs increased to 14 Euro/person. Therefore, it could be said that application of the decisions obtained from the external cost-included scenarios provide annual benefits in the range of 1–8 Euro/person in comparison to the first decision. This reduction corresponds to a reduction in the range of 2–13 % in terms of the total cost of the system. These findings indicate that possible increases in external costs will provide significant benefits when external costs are taken into consideration in the decision stage.

Results of simulation study

According to sensitivity analysis of the Monte Carlo Simulation studies, correlations of the external costs of the scenarios with individual external costs of the treatment and disposal processes used in our study were 0.9, 0.4, and 0.05 for incineration, landfill, and MRF areas, compatible with the correlation degrees obtained for the literature values. These results indicate the domination of the external costs of the incineration in terms of the total cost of the system. Considering this, and that process-based E/I ratios is an explanatory parameter for the decision (please see Table 2), the internal cost and benefit values of the processes used in this study, especially the tipping fee values of incineration, must be re-examined for future studies.

As to the simulation results, the ranges of external costs used in this study for incineration, landfill and MRF areas (MRF and composting together) provided 39, 36 and 23 % as the percentage of consistence with the corresponding literature ranges, respectively. In the probability densities of the simulation study, external costs of the scenarios were estimated in the range of 54–115 Euro with the mean of 84 Euro for our study, and in the range of 7–72 Euro with the mean of 39 Euro for the literature. These results indicate meaningful uncertainties for our external cost ranges. For this reason, the decision making process must be repeated for real external costs of the study area before the final decision.

Conclusion

According to the findings obtained in the paper, the decisions reached by taking into account the external costs in accordance with the social cost approach may cause significant differences in some possible scenarios in comparison to the usual waste management applications which are prevailing in current practices, where the external costs are not concerned . There are two important points these possible differences indicate. Firstly, taking into account the external costs along with allowable transportation distances and process numbers of study area during the decision stage can reduce total cost per capita. The annual amounts of these reductions were determined as 1–8 Euro/person in this paper. In this case, when an application such as internalization of the external costs (this is also a controversial process) is preferred, the amount that the settlers need to pay will be reduced. Secondly, it can be said that the global ecological crisis is the sum of the all external costs originated from the economic activities of mankind. Therefore, eliminating all the external costs also means eliminating the crisis theoretically. And, the question of how and where the municipal solid wastes will be disposed represents one of the symptoms for ecologic crisis. According to our findings, social cost approach may offer some creative changes against the symptoms of the ecological crisis rather than the usual classical paradigm that just relies on some possible improvements on environmental science and technologies such as best available technologies (BAT) and best environmental practice (BEP), on regulations, and on taxations. A process producing the most accurate decision by taking into account the external costs (or our moderate decision approach) would be better for the directors who have the responsibility to conserve the environment via reducing the external costs.

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