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Implementation of a goal programming model for solid waste management: a case study of Dar es Salaam – Tanzania

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Abstract – In this research article, the multi-objective optimization model for solid waste management problem is solved by the goal programming method. The model has three objectives: total cost minimization, minimization of final waste disposal to the landfill, and environmental impact minimization. First, the model is solved for the higher priority goal, and then its value is never allowed to deteriorate. The model is solved for the next priority goal and so on until the problem is solved. The model was tested with real data for solid waste management system from Dar es Salaam city. The results determine the best locations for recycling plants, separating plants, composting plants, incinerating plants, landfill and waste flow allocation between them. Furthermore, the solution shows a high reduction of the amount of waste to the landfill and greenhouse gas emissions by 78% and 57.5% respectively if fully implemented compared to the current system.

Key words: Goal programming, GHG emissions, Ideal point, Solid waste management.

1 Introduction

A multi-objective optimization model for solid waste management (SWM) was developed and described by [1]. This study presents the implementation of the model using goal programming approach and presents analysis of results for the development of a city SWM plan for Dar es Salaam City in Tanzania. Fixed and variable costs were varied for the processing facilities, separation plants, composting plants, recycling plants, incinerators, and landfills. The SWM problem was addressed on the regional level in which wards are considered as generation sources with proposed facilities as management alternatives in the model. This regional model will help to obtain an optimal solution for the SWM system based on the most economically feasible and environmentally sound option.

Application of goal programming in multi-criteria decision analysis (MCDA) is a widely used method to study decision problems with multiple conflicting objectives [2]. There has been substantial research into applying goal programming to solid waste management system problems.

The study by [3] presents an integer linear goal programming model based on multi-time step optimal material flow analysis to attain the satisfaction of multiple objectives of economy and environmental risk. The model chooses different treatment and disposal facilities from a specified set and assigns the optimum amounts of waste to them by selecting transportation routes, depending on various primary issues to cost and risk. The hypothetical example of computer waste management was presented to show clearly the usefulness of the proposed formulation.

Goal programming model has been used to analyze the appropriate planning of Thailand's plastic recycling system that includes multiple objectives as was proposed by [4]. This model considers three objectives: total cost minimization, maximizing the amount of plastic recovery and maximizing the desired plastic materials in the recycling process. The results show that it is imperative to maximize the total cost budget in order to reach the targets on the amount of recycled plastic and desired plastic materials.

A mixed integer goal programming model has been formulated by [5] for paper recycling logistics system in India. The model objectives were the reduction in reverse logistics cost, upgrading the quality of the product by increasing source separation and increasing of paper waste recovery for environmental benefits. The proposed model also determined the location of the facility, route, and flow of various varieties

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of recyclable waste paper in the multi-item, multi-echelon and multi-facility decision-making framework.

Based on the above literature, we proposed a lexicographical multi-objective goal programming model applied on a real data for solid waste management system from Dar es Salaam city as opposed from the model by [3]. The model considered more environmental factors in the objective function which includes greenhouse gas (GHG) emissions CO_2 and CH_4 from different technologies. The interactive solution method to analyze the multi-objective model for the purpose of finding a preferred compromise solution has been applied.

The purpose of this study is to present the lexicographic goal programming formulation for the SWM model proposed by [1] and to demonstrate its application in a case study of Dar es Salaam city in Tanzania. Additionally, the study chooses methane and carbon dioxide emission as one of the three objective functions and uses trade-off curves to analyses how to balance cost and environmental impacts in designing solid waste management alternative technology in the context of low GHG emission. The Section 2 introduces the problem case, waste source data and transportation costs between links. Section 3 describes the lexicographic goal programming formulation of the problem. Section 4 presents the results and discussion of the proposed model. Finally, Section 5 provides conclusions and future research directions.

2 Dar es Salaam city's SWM problem

The model proposed is applied to a case study in the city council of Dar es Salaam, where the final disposal is a critical problem. It is the third fastest growing city in Africa and among the tenth fastest growing cities in the world [6]. The city has a population of 4.3 million in 2012 and projected population in 2025 will be 7 million [7] with a generation rate of 1 kg/person/day and generates about 4,252 tons/day of solid waste as shown in Table 1. Currently, the solid waste collection coverage is approximately 50% and unsorted, but in the city market (Kariakoo) biodegradable waste is collected separately [6]. The little recycling and composting of biodegradable waste are carried out, which has a rapidly decreasing residual capacity of waste amount by 50%.

Administratively the responsibility for SWM system in Dar es Salaam has been vested to three municipals: Ilala, Kinondoni, and Temeke municipal councils and Dar es Salaam city council as the lead partner [8]. A collection solid waste in Dar es Salaam is conveyed by MCPs, private companies, Non-Government Organization (NGO), Community Based Organization (CBOs), and the informal sector. The collection is carried out in daily or weekly basis and the final disposal of waste from all over the city takes place at Pugu Kinyamwezi dump site [6, 8].

The waste composition for each kind of material is shown in Table 2.

Table 1. Waste generation in Dar es Salaam.

Sources of waste	Amount in tons/day
Household	3,104
Commercial	223
Institution	20
Market	281
Street	5
Others	621
Total generation	4,252

Source: Director's Office Dar es Salaam City Council (Environment Management Department), 2014 [9].

Table 2. Waste composition in Dar es Salaam 2015.

Types of material	Percent	Parameter
Kitchen waste	39	β
Plastic	16	α_1
Glass and wood	10	
Paper	8	α_2
Leather and rubber	6	
Metal	5	α_2
Textile	5	
Ceramic and stone	6	
Glass	2	
Others	3	
Total	100	

Source: Director's Office Dar es Salaam City Council (Environment Management Department), 2014 [9].

2.1 Waste sources data

Dar es Salaam city has 103 wards in which 87 of them were considered as the waste generation sources due to the availability of data. Data on amount of solid waste generated in each ward is available at each municipal office in which the ward belongs. So the developed model for Dar es Salaam has 87 source locations of waste. For a given ward, we assume that the waste is located at the centroid of the ward. The amount of solid waste generated in each source is given in Table 3.

2.2 Daily capacities

The study revealed that in Dar es Salaam city the daily waste generation is 4,252 tons. Since it has been assumed that one separation plant can be used by at least four wards, therefore we have 20 proposed separation plants and the average capacity of the separation plant should be $\frac{4252}{20} \approx 215$ tons per day. On the other hand, from the environmental point of view, the capacity of a separation plant in Dar es Salaam city cannot exceed 300 tons per day. This is because increasing the daily capacity to more than 300 tons per day will require a large area, which cannot be easily available in Dar es Salaam city. Hence, maximum capacities of the separation plants range from 215 to 300 tons per day. The capacities for the remaining processing facilities and landfill were set at high values to give our model the autonomy of selection and not to inflict the upper limit on a certain waste management alternative or facility.

Table 3. Amount of solid waste generated in each source.

Name of ward	Waste amount (ton)	Name of ward	Waste amount (ton)
Bonyokwa	27	Kijitonyama	60
Buyuni	38	Kinondoni	65
Gerezani	55	Magomeni	55
Ilala	65	Makumbusho	50
Jangwani	40	Mwananyamala	55
Kariakoo	83	Mzimuni	50
Kisukulu	37	Ndugumbi	40
Kisutu	50	Tandale	75
Kivukoni	54	Goba	59
Liwiti	28	Kibamba	57
Mchafukoge	35	Mbezi	54
Mchikichini	34	Manzese	73
Minazimirefu	30	Mabibo	61
Upangamagharibi	35	Mburahati	54
Upangamashariki	34	Makuburi	45
Buguruni	50	Kimara	52
Kimanga	45	Sinza	60
Kinyerezi	51	Ubungo	65
Kipawa	55	Mbagalakuu	60
Kiwalani	50	Mbagala	64
Segerea	40	Charambe	47
Tabata	53	Chamazi	45
Vingunguti	57	Kijichi	50
Chanika	42	Toangoma	40
Gongolamboto	45	Kibondemaji	45
Kitunda	50	Kigamboni	60
Kivule	35	Mjimwema	45
Majohe	40	Somangila	30
Mongolandege	30	Kibada	54
Pugu	43	Tungi	40
Ukonga	56	Vijibweni	50
Mzinga	50	Azimio	45
Kipunguni	54	Kilakala	36
Bunju	47	Chang'ombe	51
Kawe	56	Keko	58
Kunduchi	50	Makangalawe	35
Makongo	45	Kurasini	39
Mbezijuu	35	Buza	30
Mbweni	37	Miburani	46
Mikocheni	45	Mtoni	56
Msasani	50	Sandali	31
Wazo	51	Tandika	74
Kigogo	54	Temeke	70
		Yombovituka	60
	Total		4,252

Source: Field data.

2.3 Transportation costs between links

Transportation costs depend on distance travelled and amount of solid waste transferred from one point to another point. The distances were determined from Google map while the amount of waste from waste sources to separation plants as well as to other processing facilities were determined by the model. The proposed locations of the separation, composting, recycling, incineration plants and landfills are represented by SP, RP, CP, IP, and LF respectively as shown in Figure 1. The transportation cost of 1 ton per km was given by the city council which was used to calculate the transportation cost between links, Table 4 shows transportation costs from separation plants to landfills respectively.

3 Lexicographic goal programming formulation

Goal programming has been studied by many researchers and successfully applied to many diverse real life problems. The method was first proposed by [10] and now it has been accepted as a basic mathematical programming method for solving the decision-making problems with multiple objectives. The main objective of Goal Programming is to simultaneously satisfy a number of goals relevant to the decision-maker. First, the problem is solved for the higher priority goal, and then its value is never allowed to deteriorate. The problem is solved for the next priority goal and so on until the problem is solved.

Preemptive goal programming is a special case of goal programming in which the most important goals are optimized first before the least important goals. In the problem situation, a set of targets of achievement for each objective and the order of priorities in which goals are to be achieved is established. Then, for each priority, a target value is determined and the deviation variables are introduced. These deviation variables may be negative or positive (represented by d_i^+ and d_i^- respectively). The negative deviation variable d_i^- represents the quantification of the under-achievement of the ith goal while d_i^+ represents the quantification of the over-achievement of the ith goal. Finally for each priority, if the desire is to overachieve then, minimize d_i^+ or if to underachieve then, minimize d_i^-, or if to satisfy the target value exactly then minimizing both $d_i^+ + d_i^-$ is articulated as shown in Table 5 [11] and [12].

Now, we consider the model proposed by [1] in which the description of the model is given in Appendix A. The lexicographic goal programming formulation is considered where the goals are arranged in lexicographic order. In this problem, we consider the goal of cost minimization to be more important than minimizing greenhouse gas emissions and minimizing the final amount of waste to the landfill as decision makers' preferences. Let G_1, G_2, and G_3 represent the three goals. Then, the lexicographic goal programming problem is defined as follows:

$$\text{Min}\, Z_1 = \text{FC} + \text{VC} + \text{TV} - \text{R} \tag{1a}$$

where

$$\begin{aligned}\text{FC} = {} & \sum_{j=1}^{J} \text{FR}_j \text{R}_j + \sum_{h=1}^{H} \text{FM}_h \text{S}_h + \sum_{g=1}^{G} \text{FP}_g \text{U}_g \\ & + \sum_{k=1}^{K} \text{FS}_k \text{V}_k + \sum_{i=1}^{I} \text{FC}_l \text{W}_l + \sum_{m=1}^{M} \text{FE}_m \text{X}_m \\ & + \sum_{n=1}^{N} \text{FL}_n \text{Y}_n \end{aligned} \tag{2}$$

Figure 1. Map of Dar es Salaam showing the locations of waste facilities technology. Source: Adopted and modified from Regional Commissioner's Office, Dar es Salaam 2014 [9].

$$
\begin{aligned}
\mathrm{VC} = {} & \mathrm{VS}_k \sum_{k=1}^{K} \sum_{i=1}^{I} \mathrm{AW}_{ik} + \mathrm{VR}_j \sum_{j=1}^{J} \sum_{k=1}^{K} \mathrm{AS}_{kj} \\
& + \mathrm{VM}_h \sum_{h=1}^{H} \sum_{k=1}^{K} \mathrm{BS}_{kh} + \mathrm{VP}_g \sum_{g=1}^{G} \sum_{k=1}^{K} \mathrm{CS}_{kg} \\
& + \mathrm{VC}_l \sum_{l=1}^{L} \sum_{k=1}^{K} \mathrm{DS}_{kl} + \mathrm{VE}_m \sum_{m=1}^{M} \sum_{k=1}^{K} \mathrm{ES}_{km} \\
& + \mathrm{VL}_n \sum_{k=1}^{K} \sum_{n}^{N} \mathrm{LS}_{kn}
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
\mathrm{TC} = {} & \sum_{i=1}^{I} \sum_{k=1}^{K} \mathrm{TW}_{ik}\mathrm{AW}_{ik} + \sum_{k=1}^{K} \sum_{j=1}^{J} \mathrm{TS}_{kj}\mathrm{AS}_{kj} \\
& + \sum_{k=1}^{K} \sum_{h=1}^{H} \mathrm{TS}_{kh}\mathrm{BS}_{kh} + \sum_{k=1}^{K} \sum_{g=1}^{G} \mathrm{TS}_{kg}\mathrm{CS}_{kg} \\
& + \sum_{k=1}^{K} \sum_{l=1}^{L} \mathrm{TS}_{kl}\mathrm{DS}_{kl} + \sum_{k=1}^{K} \sum_{m=1}^{M} \mathrm{TS}_{km}\mathrm{ES}_{km} \\
& + \sum_{k=1}^{K} \sum_{n=1}^{N} \mathrm{TS}_{kn}\mathrm{LS}_{kn}
\end{aligned} \tag{4}
$$

Table 4. Transportation costs (tsh/ton) from separation to landfills.

SP/LF	Kinyamwezi
Ilala	11,625
Upanga	20,175
Segerea	15,000
Buguruni	17,025
Ukonga	15,450
Pugu	8,700
Kawe	27,600
Bunju	32,100
Kigogo	18,150
Tandale	21,225
Mbezi	12,825
Kibamba	23,850
Kimara	17,250
Ubungo	20,100
Mbagala	18,375
Kibondemaji	21,075
Mjimwema	34,350
Vijibweni	37,425
Chang'ombe	17,025
Mtoni	18,225

Source: Field data.

Table 5. Procedure for achieving a goal.

Minimize	Goal	If goal is achieved
d_i^-	Minimize the underachievement	$d_i^- = 0,\ d_i^+ \geq 0$
d_i^+	Minimize the overachievement	$d_i^- \geq 0,\ d_i^+ = 0$
$d_i^- + d_i^+$	Minimize both under and overachievement	$d_i^- = 0,\ d_i^+ = 0$

$$R = Q_j \sum_{k=1}^{K} \sum_{j=1}^{J} \mathrm{AS}_{kj} + Q_h \sum_{k=1}^{K} \sum_{h=1}^{H} \mathrm{BS}_{kh} + Q_g \sum_{k=1}^{K} \sum_{g=1}^{G} \mathrm{CS}_{kg} + Q_l \sum_{k=1}^{K} \sum_{l=1}^{L} \mathrm{DS}_{kl} + Q_m \sum_{k=1}^{K} \sum_{m=1}^{M} \mathrm{ES}_{km} \quad (5)$$

subject to the constraints:

$$\sum_{k=1}^{K} \mathrm{AW}_{ik} = \mathrm{A}, \quad \text{for } i = (1, \ldots, I) \quad (6)$$

$$\sum_{j=1}^{J} \sum_{k=1}^{K} \mathrm{AS}_{kj} = \sum_{i=1}^{I} \sum_{k=1}^{K} \alpha_1 \mathrm{AW}_{ik} \quad (7)$$

$$\sum_{k=1}^{K} \sum_{h=1}^{H} \mathrm{BS}_{kh} = \sum_{i=1}^{I} \sum_{k=1}^{K} \alpha_2 \mathrm{AW}_{ik} \quad (8)$$

$$\sum_{k=1}^{K} \sum_{g=1}^{G} \mathrm{CS}_{kg} = \sum_{i=1}^{I} \sum_{k=1}^{K} \alpha_3 \mathrm{AW}_{ik} \quad (9)$$

$$\sum_{k=1}^{K} \sum_{l=1}^{L} \mathrm{DS}_{kl} = \sum_{i=1}^{I} \sum_{k=1}^{K} \beta \mathrm{AW}_{ik} \quad (10)$$

$$\sum_{k=1}^{K} \sum_{m=1}^{M} \mathrm{ES}_{km} = \sum_{i=1}^{I} \sum_{k=1}^{K} \gamma \mathrm{AW}_{ik} \quad (11)$$

$$\sum_{k=1}^{K} \sum_{n=1}^{N} \mathrm{LS}_{kn} = \sum_{i=1}^{I} \sum_{k=1}^{K} (1 - \alpha_1 - \alpha_2 - \alpha_3 - \beta - \gamma) \mathrm{AW}_{ik} \quad (12)$$

$$\sum_{i=1}^{I} \mathrm{AW}_{ik} \leq \mathrm{CS}_k V_k, \quad \text{for } k = (1, \ldots, K) \quad (13)$$

$$\sum_{k=1}^{K} \mathrm{AS}_{kj} \leq \mathrm{CR}_j R_j, \quad \text{for } j = (1, \ldots, J) \quad (14)$$

$$\sum_{k=1}^{K} \mathrm{BS}_{kh} \leq \mathrm{CR}_h S_h, \quad \text{for } h = (1, \ldots, H) \quad (15)$$

$$\sum_{k=1}^{K} \mathrm{CS}_{kg} \leq \mathrm{CR}_g U_g, \quad \text{for } g = (1, \ldots, G) \quad (16)$$

$$\sum_{k=1}^{K} \mathrm{DS}_{kl} \leq \mathrm{CC}_l W_l, \quad \text{for } l = (1, \ldots, L) \quad (17)$$

$$\sum_{k=1}^{K} \mathrm{ES}_{kl} \leq \mathrm{CC}_l W_l, \quad \text{for } l = (1, \ldots, L) \quad (18)$$

$$\sum_{k=1}^{K} \mathrm{LS}_{kn} \leq \mathrm{CL}_n Y_n, \quad \text{for } n = (1, \ldots, N) \quad (19)$$

$$\mathrm{AW}_{ik} \geq 0,\ \mathrm{AS}_{kj} \geq 0,\ \mathrm{BS}_{kh} \geq 0,\ \mathrm{CS}_{kg} \geq 0,\ \mathrm{DS}_{kl} \geq 0,\ \mathrm{ES}_{km} \geq 0,\ \mathrm{LS}_{kn} \geq 0 \quad \text{for } h = (1, \ldots, H);\ i = (1, \ldots I);\ J = (1, \ldots J); k = (1, \ldots K); l = (1, \ldots L); m = (1, \ldots M); n = (1, \ldots N) \quad (20)$$

$$R_j = 0 \text{ or } 1, \quad \text{for } j = (1, \ldots, J) \quad (21)$$

$$S_h = 0 \text{ or } 1, \quad \text{for } h = (1, \ldots, H) \quad (22)$$

$$U_g = 0 \text{ or } 1, \quad \text{for } g = (1, \ldots, G) \quad (23)$$

$$V_k = 0 \text{ or } 1, \quad \text{for } k = (1, \ldots, K) \tag{24}$$

$$W_l = 0 \text{ or } 1, \quad \text{for } l = (1, \ldots, L) \tag{25}$$

$$X_m = 0 \text{ or } 1, \quad \text{for } m = (1, \ldots, M) \tag{26}$$

$$Y_n = 0 \text{ or } 1, \quad \text{for } n = (1, \ldots, N) \tag{27}$$

Equation (1a) is the total cost minimization, this contains the cost for transportation, recycling, separation, composting, incineration, and recovered from the disposal of waste. The costs for every operating facility and capital costs are contained. Solving linear programming problem (1a) subject to the constraints (6)–(27) by GLPK software, we get the optimum value of $G_1 = Z_1^*$. The importance of minimizing greenhouse gases is the second goal, so we have the following lexicographical goal programming problem:

$$\begin{aligned}\text{Min } Z_2 = {} & G_j^{\text{GHE}} \sum_{j=1}^{J} \sum_{k=1}^{K} \text{AS}_{kj} + G_h^{\text{GHE}} \sum_{h=1}^{J} \sum_{k=1}^{H} \text{BS}_{kh} \\ & + G_g^{\text{GHE}} \sum_{g=1}^{G} \sum_{k=1}^{K} \text{CS}_{kj} + G_l^{\text{GHE}} \sum_{l=1}^{L} \sum_{k=1}^{K} \text{DS}_{kl} \\ & + G_m^{\text{GHE}} \sum_{m=1}^{M} \sum_{k=1}^{K} \text{ES}_{km} + G_n^{\text{GHE}} \sum_{n=1}^{N} \sum_{k=1}^{K} \text{LS}_{kn} \\ & + d_1^+ + d_1^- \end{aligned} \tag{1b}$$

subject to the constraint:

$$\text{Min } Z_1 = \text{FC} + \text{VC} + \text{TV} - \text{R} - d_1^+ + d_1^- = Z_1^* \tag{28}$$

$$d_1^+, d_1^- \geq 0 \tag{29}$$

and constraints (6)–(27). Equation (1b) is the minimization of the total environment impact (GHG emissions) from solid waste, which includes carbon and methane emissions due to recycling, composting, incineration and disposal to the landfill. Now solving equation (1b), we get the optimum value of $G_2 = Z_2^*$. Lastly, the importance of minimizing final amount of waste to the landfill is implemented, so we have the following lexicographic goal programming problem:

$$\text{Min } Z_3 = \sum_{k=1}^{K} \sum_{n=1}^{N} \text{LS}_{kn} + d_2^+ + d_2^- \tag{1c}$$

subject to the constraint:

$$\begin{aligned}\text{Min } Z_2 = {} & G_j^{\text{GHE}} \sum_{j=1}^{J} \sum_{k=1}^{K} \text{AS}_{kj} + G_h^{\text{GHE}} \sum_{h=1}^{J} \sum_{k=1}^{H} \text{BS}_{kh} \\ & + G_g^{\text{GHE}} \sum_{g=1}^{G} \sum_{k=1}^{K} \text{CS}_{kj} + G_l^{\text{GHE}} \sum_{l=1}^{L} \sum_{k=1}^{K} \text{DS}_{kl} \\ & + G_m^{\text{GHE}} \sum_{m=1}^{M} \sum_{k=1}^{K} \text{ES}_{km} + G_n^{\text{GHE}} \sum_{n=1}^{N} \sum_{k=1}^{K} \text{LS}_{kn} \\ & - d_2^+ + d_2^- = Z_2^* \end{aligned} \tag{30}$$

Table 6. Deviation variable values.

Deviation variable	Value
d_3^+	0
d_1^-	0
d_2^+	0.13
d_2^-	0
d_3^+	0
d_3^-	0.02

$$d_2^+, d_2^- \geq 0 \tag{31}$$

and constraints (6)–(29). Equation (1c) deal with the minimization of the final waste disposal to the landfill that is the total amount of waste per day disposed to the landfill from separation facilities. Solving equation (1c), we get the optimum value of $G_3 = Z_3^*$.

Finally, for obtaining the optimum values of locations of processing facilities and allocations of amount of waste between them, we have the following lexicographic goal programming problem:

$$\text{Min } Z = d_1^+ + d_2^+ + d_3^+ \tag{1d}$$

subject to

$$\text{Min } Z_3 = \sum_{k=1}^{K} \sum_{n=1}^{N} \text{LS}_{kn} - d_3^+ + d_3^- = Z_3^* \tag{32}$$

$$d_3^+, d_3^- \geq 0 \tag{33}$$

and constraints (6)–(33). The equation (1d) deals with the minimization of the positive deviation variable since our target is to minimize the overachievement of the total cost, GHG emissions and final waste to the landfill. After solving equation (1d), we get the optimum locations of recycling plants, separating plants, composting plants, incinerating plants, landfill and amount of waste flow allocation between them, which will provide the minimum values of cost, greenhouse gases emissions as well as the final amount of waste to the landfill.

4 Summary of results and discussion

The model is developed in GLPK Integer Optimizer version 4.57 using GLPSOL (LP/MIP) solver and performed on an Intel(R) Core(TM) i3 CPU, 2.53 GHz computer with 4 GB of RAM. Some of the costs are as follows: Fixed cost for the opening of each facility is 550,545 tsh, Variable operating cost for solid waste in different facilities is 65,000 tsh/ton and Fixed transportation cost is 750 tsh/km/ton. The model has been run and an integer optimal solution found within 57 min. Table 6 shows the results of the last formulated objective function in which all deviation variables are zero, this means that all goals are perfectly satisfied. The values for all objective functions are shown in Table 7 which gives the minimum values for both objectives. The trade-off between cost and greenhouse gas equivalents (GHE) emissions as well as cost and final disposal waste to the landfill were generated and analyzed as shown in Figures 2 and 3 respectively.

Table 7. Objective function value.

Priority goal	Objective function	Values
1	Z_1	Tsh. 4078,644.75
2	Z_2	631 CO_2 eq
3	Z_3	936 tons
	Z	0

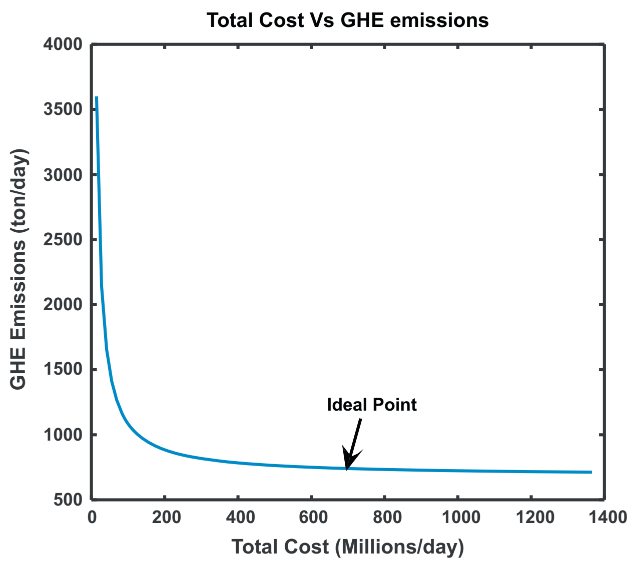

Figure 2. Trade-off curve between cost and greenhouse gas equivalents (GHE) emissions.

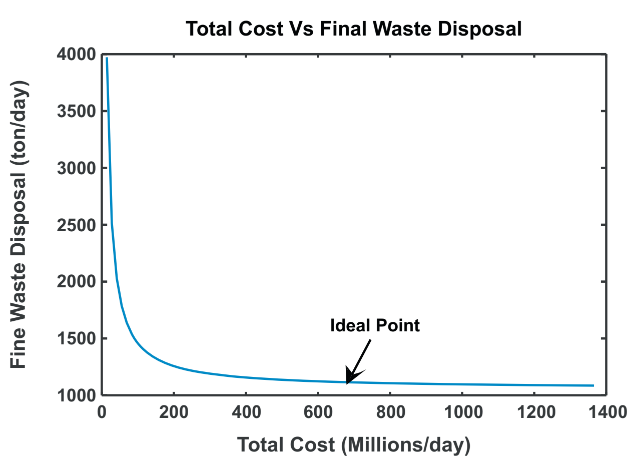

Figure 3. Trade-off curve between cost and final waste disposal to the landfill.

In addition, the ideal point was determined to be Tsh 74.1 million/day, 631 tons of GHG emissions/day, and 936 tons/day respectively. Based on consultation with the decision maker, a region of interest on the Pareto front was determined for further investigation. The interesting relationship is shown in Figures 2 and 3, whereby whenever total cost increases there is the decrease of both GHE emissions and final waste disposal to the landfill. This effect can be considered in details during the post analysis of the optimal solution. The mass flows from separation plant through the waste processing facilities and landfills are presented in Appendix B.

Furthermore, the model proposed 16 separation plants and 5 recycling plants for plastics. Three metals and paper recycling plants have been proposed. In addition to that, the model proposed seven composting plants, as well as three incineration plants. At the moment Dar es Salaam city used only one dump site at Pugu Kinyamwezi, therefore the developed model has been applied with that single landfill and later in sensitivity analysis other landfills will be included. Currently, Dar es Salaam has no formal waste diversion strategy, rather about 40% of the generated waste were transferred to the landfill, this shows that about 60% remaining are left on the open dump which favors GHG emissions [13]. The formulated model reduced amount of waste to the landfill and GHG emissions by 78% and 57.5% respectively.

5 Conclusions and future research directions

In this paper, the multi-objective optimization model proposed by [1] has been solved by lexicographic goal programming technique. Three objectives have been considered, cost minimization, minimization of final waste disposal to the landfill and environmental impact minimization.

The lexicographic goal programming method has been employed to solve the proposed model. In this method first, the problem is solved for the higher priority goal, and then its value is never allowed to deteriorate. The problem is solved for the next priority goal and so on until the problem is solved.

The model has been tested by real data from Dar es Salaam city council, whereby a large percentage of solid waste is dumped into open areas. GNU Linear Programming Kit (GLPK) software for Linux has been used to solve the model. The output of the model provides a reduced amount of waste to the landfill and GHG emissions by 72.8% and 55.2% respectively. Moreover, the model proposed 16 separation plants, 5 recycling plants for plastics and 3 metals recycling plants. Three recycling plants for paper, seven composting plants as well as three incineration plants have been proposed.

Future research needs a post optimality analysis of sensitive parameters of the model, this will give a better insight of possible further final waste minimization to the landfill, cost saving as well as greenhouse gas emission reductions. The introduction of waste separation at the source, implementation and compliance to regulations to be considered for a successful waste management relief is another area for further research.

6 Implications and influences

The findings of this study will add more knowledge on the existing literature and will act as supportive insights for further research on the optimization model for municipal solid waste management systems. The study will help the government (Decision Makers) to make policies and plan programs for municipal solid waste management system by considering environmental impact. It will also help people to have a better insight and understanding on the optimization of municipal solid waste management system.

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Appendix A

Definition of parameters

FS_k – Fixed cost of the separation plant represented as per unit weight.

FR_j – Fixed cost of the plastic recycling plant represented as per unit weight.

FM_h – Fixed cost of the metal recycling plant represented as per unit weight.

FP_g – Fixed cost of the paper recycling plant represented as per unit weight.

FC_l – Fixed cost of the composting plant represented as per unit weight.

FE_m – Fixed cost of the incinerator plant represented as per unit weight.

FL_n – Fixed cost of the landfill represented as per unit weight.

CS_k – Daily capacity of the separation plant.

CR_j – Daily capacity of the plastic recycling plant.

CM_h – Daily capacity of the metal recycling plant.

CP_g – Daily capacity of the paper recycling plant.

CC_l – Daily capacity of the composting plant.

CE_m – Daily capacity of the incinerator plant.

CL_n – Daily capacity of the landfill.

VS_k – Cost per unit weight processed at the separation plant k.

VR_j – Cost per unit weight processed at the plastic recycling plant j.

VM_h – Cost per unit weight processed at the metal recycling plant h.

VP_g – Cost per unit weight processed at the paper recycling plant g.

VC_l – Cost per unit weight processed at the composting plant l.

VE_m – Cost per unit weight processed at the incinerator plant m.

VL_n – Cost per unit weight processed at the landfill n.

TW_{ik} – Transportation cost per unit weight of waste from source i to separation plant k.

TS_{kj} – Transportation cost per unit weight of waste from separator k to plastic recycling plant j.

TS_{kh} – Transportation cost per unit weight of waste from separator k to metal recycling plant h.

TSk_g – Transportation cost per unit weight of waste from separator k to paper recycling plant g.

TS_{kl} – Transportation cost per unit weight of waste from separator k to composting plant i.

TS_{km} – Transportation cost per unit weight of waste from separator k to incinerator m.

TS_{kn} – Transportation cost per unit weight of waste from separator k to landfill n.

Q_j – Revenue generated per unit weight of product from plastic recycling plant j.

Q_h – Revenue generated per unit weight of product from metal recycling plant h.

Q_g – Revenue generated per unit weight of product from paper recycling plant g.

Q_l – Revenue generated per unit weight of product from composting plant l.

Q_m – Revenue generated per unit weight of product from incinerator plant m.

α_1 – Fractional of plastic material in the waste.

α_2 – Fractional of metal material in the waste.

α_3 – Fractional of paper material in the waste.

β – Fractional of compostable material in the waste.

γ – Fractional of dry material in the waste.

G_j^{GHE} – Emission coefficients for greenhouse effect in ton of CO_2 and CH_4 per unit weight of waste from plastic recycling plant j.

G_h^{GHE} – Emission coefficients for greenhouse effect in ton of CO_2 and CH_4 per unit weight of waste from metal recycling plant h.

G_g^{GHE} – Emission coefficients for greenhouse effect in ton of CO_2 and CH_4 per unit weight of waste from paper recycling plant g.

G_l^{GHE} – Emission coefficients for greenhouse effect in ton of CO_2 and CH_4 per unit weight of waste from composting plant l.

G_m^{GHE} – Emission coefficients for greenhouse effect in ton of CO_2 and CH_4 per unit weight of waste from incinerator plant m.

G_n^{GHE} – Emission coefficients for greenhouse effect in ton of CO_2 and CH_4 per unit weight of waste from landfill n.

A_i – Amount of daily waste generated at source i.

Appendix B

Waste flow allocations

Table 8. Waste amount (ton) flow from separation to plastic recycling plants.

Separation plant	Plastic recycling plant				
	Ilala	Ukonga	Kawe	Mjimwema	Mtoni
Ilala	60				
Upanga	43.2				
Segerea		60			
Buguruni	40				20
Ukonga		60			
Pugu		60			
Kawe			60		
Bunju			9.4		
Kigogo	56.8		3.2		
Tandale			60		
Mbezi		20	40		
Mbagala					60
Mjimwema				47.8	
Vijibweni				30	
Chang'ombe					60
Mtoni					60
Total	140	140	140	120.4	140

Table 9. Waste amount (ton) flow from separation to metal recycling plants.

Separation plant	Metal recycling plant				
	Buguruni	Tandale	Pugu	Vijibweni	Mbezi
Ilala	18				
Upanga	2	11			
Segerea			2		16
Buguruni	18				
Ukonga			18		
Pugu			18		
Kawe		18			
Bunju					2.8
Kigogo		18			
Tandale		18			
Mbezi					18
Mbagala			18		
Mjimwema				14.3	
Vijibweni				9	
Chang'ombe	18				
Mtoni	9		9		
Total	65	65	65	23.3	36.8

Table 10. Waste amount (ton) flow from separation to paper recycling plants.

Separation plant	Paper recycling plant		
	Kigogo	Chang'ombe	Segerea
Ilala			24
Upanga	17.3		
Segerea			24
Buguruni	12.1	11.9	
Ukonga	13.6		10.4
Pugu			24
Kawe	24		
Bunju			3.8
Kigogo	24		
Tandale	24		
Mbezi			24
Mbagala		24	
Mjimwema		19.1	
Vijibweni		12	
Chang'ombe		24	
Mtoni		24	
Total	115	115	110.2

Table 11. Waste amount (ton) flow from separation to composting plants.

Separation plant	Composting plant							
	Kigogo	Buguruni	Kawe	Mbagala	Ukonga	Kigamboni	Tandika	Mbezi
Ilala		111		6				
Upanga	60.2	12					12	
Segerea							111	84.7
Buguruni		117						
Ukonga					117			
Pugu					117			
Kawe			117					
Bunju								18.3
Kigogo	117							
Tandale	62.8		54.2					
Mbezi								117
Mbagala				117				
Mjimwema						93.2		
Vijibweni						58.5		
Chang'ombe							117	
Mtoni				117			117	
Total	240	230	240	240	234	141.7	347	103

Table 12. Waste amount (ton) flow from separation to incineration plants.

Separation plant	Incineration plant		
	Kisukulu	Chamazi	Buza
Ilala			15
Upanga		10.8	
Segerea	15		
Buguruni		10.4	4.6
Ukonga			15
Pugu		15	
Kawe	15		
Bunju	2.4		
Kigogo	8.7		6.3
Tandale	15		
Mbezi	15		
Mgagala			15
Mjimwema		12	
Vijibweni		8	
Chang'ombe			15
Mtoni		15	
Total	71	71.2	71

Table 13. Waste amount (ton) flow from separation to landfill.

Separation plant	Landfill Kinyamwezi
Ilala	66
Upanga	47.5
Segerea	66
Buguruni	66
Ukonga	66
Pugu	66
Kawe	66
Bunju	10.3
Kigogo	66
Tandale	66
Mbezi	66
Mbagala	66
Mjimwema	52.6
Vijibweni	33
Chang'ombe	66
Mtoni	66
Total	935.4

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