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Optimization of Municipal Solid Waste Management Problem with Composting Plants: The case of Ilala Municipality

Mbido Kahebo[1], Egbert Mujuni[2], Allen Mushi[3]
[1]Department of Mathematics, Monduli Teachers' College, P.O. Box 5, Monduli, Arusha, Tanzania, mkahebokahebo@yahoo.com
[2]Department of Mathematics, University of Dar es salaam, P.O. Box 35062, Dar-es-salaam, Tanzania, emujuni@maths.udsm.ac.tz
[3]Department of Mathematics, University of Dar es salaam, P.O. Box 35062, Dar –es -salaam, Tanzania, allen.mushi@gmail.com

ABSTRACT

Solid Waste Management is one of the critical environmental challenges for quick urban developing countries. It involves a number of problems that requires optimization techniques for better decision making. These include the selection of collection points, disposal sites, and vehicle routing mechanisms. This paper addresses the problem of optimization of solid waste systems which involves the use of composting plants as a strategy in environmental management. A mathematical programming model is developed and tested on real data from Ilala Municipal in Dar es Salaam Tanzania. The formulated model resulted into lower transportation cost from sources to collection points, composting plant and landfill compared to previous results. Furthermore, it has been observed that construction of composting plants can provide extra income through sales of recyclable materials and compost manure and thereby reduce the overall system's running cost.

Keywords: Solid Waste Management, Combinatorial Optimization, Integer Programming.

1 INTRODUCTION

Solid waste is defined as the unwanted products in solid state derived from the activities of and discarded by society. It is produced either by product of production processes or arise from domestic or commercial sectors when the materials or objects are discarded after use. Waste material is an unavoidable by-product of human activities [1]. Economic development, urbanization and improved living standards in cities increase the quantity and complexity of generated solid waste. Waste is generated continuously in different ways from our daily activities. Each activity will generate different types of waste which will require its own separate or specialized treatment [2]. There are many types of solid waste, which include; Recyclable waste, Toxic waste and Green waste (compost and yard clippings). Many cities' green waste is collected separately from true garbage, so that it can be composted and returned to the earth.

Several approaches have been reported in tackling the Solid Waste Management cost optimization problem depending on the objectives of the models. Solution methods depend on the degree of difficulties in solving the problem which varies with problem size. Lackman [3] presented an economic model of solid waste disposal and recycling and designed a set of differential equations that describes properties and cost structures associated with solid waste activities. Malarin and Vaughan [4] presented an approach to the economic analysis of solid waste disposal alternatives. Their model was to analyze social costs, both financial and monetary equivalent of environmental and public good damages of solid waste disposal. They developed a Mixed Integer Programming model and used Jamaica as case study. Markovic et al [5] used Analytical Hierarchy Process for multi-objective optimization of the Solid Waste Management System for the City of Nis in Serbia. Objectives of their model were maximal system efficiency and maximal satisfaction of system service users. Sarika [6] reported on a Linear Programming model for the optimization of integrated Solid Waste Management for Mumbai City in India, with an objective function which involves both economic and environmental costs. A similar model has been developed by Chang and Lin [7] for Taiwan's Taichung special Municipality. This paper presents a similar study for the City of Dar es Salaam that aims at minimizing transportation and running costs given the influence of composting plants.

The rest of the paper is organized as follows; we give a brief description of the solid waste problem in the case study, provide a model that was used in this work, followed by Mathematical Programming formulations; summary of results is then presented and finally a conclusion on the research is reported together with suggestions for future research directions.

2 SOLID WASTE DISPOSAL SITUATION AT DAR ES SALAAM CITY

Dar es Salaam is the commercial capital city of Tanzania, situated along the Indian Ocean. It covers an area of 1393 sq km and has a population of about 3.4 million people or 25% of the total urban population in Tanzania [8]. Politically and administratively, the city is divided into three districts of Kinondoni, Ilala and Temeke. The City Council and the three Municipalities have for many years been confronted by growing volumes of solid waste and the inadequate provisions for its removal and disposal. Currently, the City generates between 3,100 tons of solid waste per day [9]. About 40% to 45% of the amount generated is being collected and disposed-off at the dump-site at the outskirts of the city [10].

Solid waste management is a problem in Dar es Salaam due to many factors that include: Absence of recycling and composting plants and improper locations for transfer stations for solid waste collection: Waste collection stations are inadequate, in which a large percentage–about 60% remains either in the places where it originates or staying longer in the collection points leading to a number of environmental and health hazards [11]. Landfill sites are not common in Dar es Salaam and the one available is about 30 kilometers away from the city centre. One trip could cost about one hour or more to reach the site [12].

The challenge addressed in this work is to propose the transportation strategies which can minimize both running and transportation cost, given the introduction of composting sites. This extends the previous work by Lyeme [13] which did not consider the component of composting sites.

3 MODEL FORMULATIONS

Figure 1 shows the waste flow situation in the study area. The residential, commercial and municipal service sources disposes their waste in the collection bins located near their sites. Collection wagons are responsible for transferring the waste from the waste bins to the collection points. A transfer vehicle is responsible for waste transfer from the collection points to the landfill. With the introduction of composting plants, the flow includes the movement of some solid waste from collection points to composting plants for further processing.

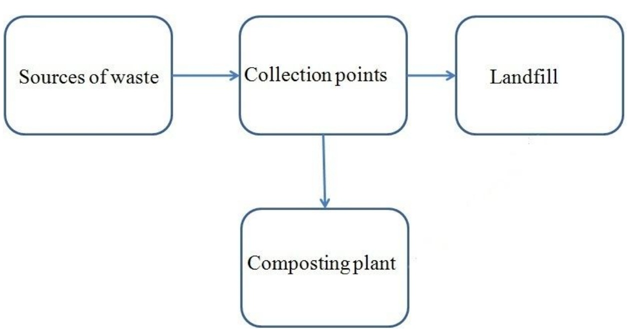

Figure 1: Schematic diagram of waste flow

3.1 Special features of solid waste collection at Ilala Municipality

- All generated solid waste in Ilala municipality are collected from the collection points and transferred to the composting plants or landfill;
- There is no waste separation at the source;
- Industrial and institutional wastes are transferred to the nearest collection point at the expense of their generators;
- Waste handling operations are executed on daily basis;
- Transportation cost is proportional to both the distance travelled and the volume of carried load;
- The collection of waste is done at the time when there is no traffic jam;
- The distances are measured from the centroid of either the streets or the facilities;
- All solid wastes sent to composting plants are composted to such an extent that no extra waste (left-over's) needs to be shipped from composting plants to the landfill.

3.2 Mathematical Model

Mathematical Programming model is developed using the following design of parameters and variables;

3.2.1Parameters

I *Set of all sources of solid waste generation;*
J *Set of all collection points;*
K *Set of all landfills;*
M Set of all composting plants;
F_j Daily running cost of the collection point *j*;
B_m Daily running cost of the composting plant *m* ;
L_k Daily capacity of the landfill *k* (tons);
P_m Daily capacity of composting plant *m* (tons);
U_j Daily capacity of collection point *j* (tons);
A Number of composting plants constructed;
N Number of collection points constructed;
W_i Amount of solid waste generated at source *i* (tons);
T_{ij} Daily transportation cost of waste from source *i* to collection point *j* per ton;
V_{jk} Daily transportation cost of waste from collection point *j* to landfill *k* per ton;
G_{jm} Daily transportation cost of waste from collection points to the composting plant per ton;
C A positive integer larger than the capacity of all collection points;
D The profit earned for each plastic bag of 50kg of composted manure;
Y A positive integer larger than the capacity of all composting plants

3.2.2Decision Variables

x_{ij} Amount (in tons) of daily solid waste to be removed from source $i \in I$ to collection point $j \in J$;

y_{jk} Amount (in tons) of solid waste to be removed from collection point $j \in J$ to landfill or Composting plant $k \in K$;

Q_j A decision variable which takes a value of 1 if solid waste is sent to collection point set up at the location $j \in J$ and 0 otherwise;

λ_m A decision variable which takes a value of 1 if solid waste is sent to the composting plant set up at location $m \in M$ and zero otherwise.

The aim is to minimize the cost of transporting waste from their sources to the composting plants and landfill through collection points. Objective function Z of the model calculates the sum of running cost (RC) and transportation costs (TC) i.e. $Z = RC + TC - E$, where E is the benefit obtained from composting plants.

The running cost RC is obtained by taking the sum of daily running costs and formulated as follows;

$$RC = \sum_{j=1}^{J} F_j Q_j + \sum_{m=1}^{M} B_m \lambda_m$$

Transportation costs have two components namely; from source to collection points (TC_1), and from com collection points to landfill or composting plants (TC_2) and given as follows;

$$TC_1(x) = \sum_{i=1}^{I} \sum_{j=1}^{J} T_{ij} x_{ij} \text{ and,}$$

$$TC_2(y) = \sum_{j=1}^{J} \sum_{k=1}^{K} V_{jk} y_{jk} + \sum_{j=1}^{J} \sum_{m=1}^{M} G_{jm} y_{jm}$$

Thus, the transportation costs TC is the sum of the two components above, i.e.

$$RC(x, y) = TC_1(x) + TC_2(y)$$

Benefit obtained from the composting plant is given by;

$$E = \sum_{m}^{M} P_m D$$

Therefore, the objective function Z is given by;

Min

$$Z(x, y) = \sum_{j=1}^{J} F_j Q_j + \sum_{m=1}^{M} B_m \lambda_m + \sum_{i=1}^{I} \sum_{j=1}^{J} T_{ij} x_{ij} + \sum_{j=1}^{J} \sum_{k=1}^{K} V_{jk} y_{jk} + \sum_{j=1}^{J} \sum_{m=1}^{M} G_{jm} y_{jm} - \sum_{m}^{M} P_m D$$

Subject to;

$$\sum_{j=1}^{J} x_{ij} = w_i \text{ for all } i \in I \quad \text{(i)}$$

$$\sum_{j=1}^{J} \sum_{i=1}^{I} x_{ij} = \sum_{j=1}^{J} \sum_{k=1}^{K} y_{jk} + \sum_{j=1}^{J} \sum_{m=1}^{M} y_{jm} \quad \text{(ii)}$$

$$\sum_{i=1}^{I} x_{ij} \leq U_i \text{ for all } i \in I \quad \text{(iii)}$$

$$\sum_{j=1}^{J} y_{jm} \leq P_m \text{ for } m \in M \quad \text{(iv)}$$

$$\sum_{j=1}^{J} y_{jk} < L_k \; k \in K \quad \text{(v)}$$

$$\sum_{m=1}^{M} \lambda_m \leq A \quad \text{(vi)}$$

$$\sum_{j=1}^{J} Q_j U_j \geq \sum_{i=1}^{I} w_i \quad \text{(vii)}$$

$$\sum_{i=1}^{I} x_{ij} \leq Q_j C \text{ for all } j \in J \quad \text{(viii)}$$

$$\sum_{j=1}^{J} y_{jm} \leq \lambda_m Y \text{ for all } m \in M \quad \text{(ix)}$$

$$x_{ij} \geq 0,\; y_{jk} \geq 0,\; Q \in \{0,1\},\; \lambda \in \{0,1\} \quad \text{(x)}$$

Constraint (i) takes care of the fact that amount of solid waste shipped from source *i* must equal the amount generated at source *i*. Constraint (ii) represent the fact that the amount of solid waste collected from all sources must equal the amount sent to landfills and composting plants. Numbers (iii) – (v) gives upper bounds on the amounts that can be shipped to collection points, composting plants and landfills. The remaining constraints provide limits on the properties of the binary decision variables.

4 SUMMARY OF RESULTS

The model was solved using GNU Linear Programming Kit (GLPK) through the MathProg language which is available as open source. In this model we have applied only one composting plant and one landfill, which are the currently feasible options. The composting plant is currently under construction. Data used in the model were obtained from Ilala Municipal council and includes the cost estimates.

Summary of results are as presented in Table 1 and Table 2. Results are obtained by fixing number of collection points and capacity of composting plant, which shows that the more the capacity of composting plant the lesser the running cost of solid waste management. The daily capacity of composting plant is varied from 100 to 500 tons. In generating results we considered two cases; case A (Table 1) where we fixed the capacity of composting plant range from 100, 200, 300, 400, and 500 tons, and case B (Table 2) where we fixed capacity of all collection points at 250 tons and try find the number of collection points that minimizes the running cost.

Table 1: Fixed capacity of composting plant

Case	Capacity	Objective Function Values
a1	100	9,183,963
a2	200	7,096,693
a3	300	5,055,629
a4	400	3,178760
a5	500	1,392,944

Table 2: Results for different cases of number of collection points

Case	Number of Collection Points	Objective Function Values
b1	5	1,768,246
b2	6	1,455,901
b3	7	1,431,267
b4	8	1,412,647
b5	9	1,397,671
b6	10	1,393,587
b7	11	1,392,944
b8	12	1,392,944

The trends of the objective functions of the two cases A and B are as shown in Figure 2 and Figure 3 respectively. Figure 2 indicates that the objective function value decreases as the capacity of composing plant is increased. Similarly, Figure 3 shows the objective function decreases gradually as the number of collection points is increased. The best objective function is obtained when the number of collection point is 11. That is, any additional increase of the collection points above 11 does not improve anything since the objective function remains constant. The best solution is case b7, where the amount of waste flow from each source to the proposed collection points is as shown in Table 3.

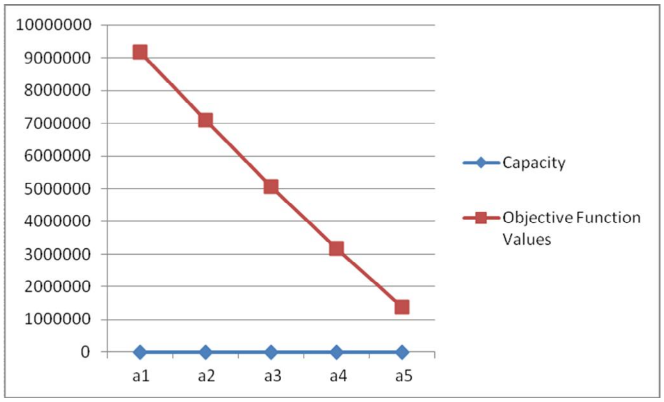

Figure 2: Trends in Objective function by varying capacity

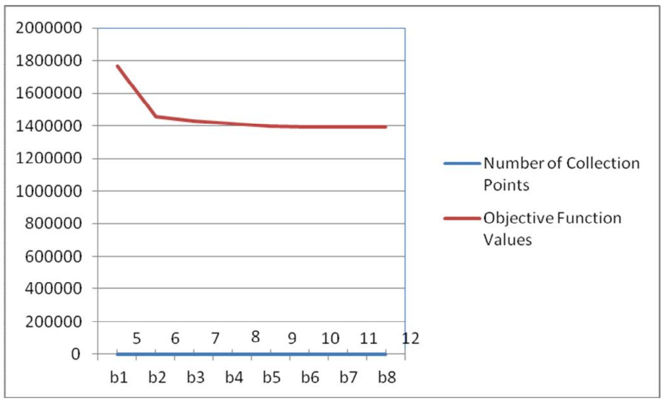

Figure 3: Trends in objective value by varying collection points

Table 3: Distribution of waste from different sources (streets) to different collection points for case b7.

Source	Collection Points	Tones
Mapala	Kitunda	30
Amana	Pugu	26
Bungoni	Kinyerezi	14
Chanika	Pugu	20
Airport	Kinyerezi	30
Kipunguni	Pugu	25
Kajiungeni	Buguruni	27
Segerea	Kipawa	11
Kimanga	Mchikichini	27
Madafu	Kipawa	28
Kichangani	Kinyerezi	27
Miembeni	Kinyerezi	23
Cleist	Chanika	27
Mafia	Pugu	27
Uhuru	Kinyerezi	29
Kisutu	Ukonga	20
Kivukoni	Msongola	32
Samora	Ukonga	28
Yombo	Msongola	29
Mshihiri	Ukonga	28
Arnatouglo	Ukonga	28
AllyKhan	Ukonga	28
Mnyamani	Kipawa	31
Bungoni	Pugu	26
Mchikichini	Pugu	27
Kinyerezi	Ukonga	24
Sitakishari	Pugu	23
Yangeyange	Kipawa	28
Segerea	Buguruni	15
Chang'ombe	Mchikichini	31
Bima	Chanika	30
G/Mboto	Pugu	30
Mtakuja	Kinyerezi	25
Lindi	Kinyerezi	24
Nkhrumah	Pugu	26
Swahili	Chanika	27
Kisutu	Kinyerezi	12
Ghandi	Pugu	30
S/Robert	Kitunda	27
Kilagala	Ukonga	30
Aggrey	Kitunda	25
PPF	Ukonga	32
Muhimbili	Ukonga	32
TOTAL		**1109**

The objective function of the best solution has a total value of Tsh. 1,392,944 per day. This value represents a significant improvement of the work of Lyeme [13] where the value of objective was Ths 8,627,669. It is noted that the proposed model results in a reduced running cost mainly due to the presence of composting plant in the model formulation.

Clearly, the solution of the developed model can be applied in any other municipality in Tanzania where there are decomposing plants, subject to addressing challenges of unplanned settlements which differs from one municipal to another.

5 CONCLUSION

In this work we have developed a mathematical model and tested the model using real data from Ilala Municipal in Dar es Salaam Tanzania. The developed model incorporated the presence of compositing plant at Buguruni Kisiwani. Thus, the formulated model resulted into lower cost of transporting solid waste from sources to collection points, composting plant and landfill compared to the previously developed model by Lyeme [13] on the same data source.

Furthermore, it has been observed that construction of composting plants can provide extra income through sales of recyclable materials and compost manure and thereby reduce the overall system's running cost.

The study shows that composing plants reduce the cost of managing solid wastes. Since about 67% of the total amount of municipal solid waste generated in Dar es Salaam is organic matter (Oberlin [18]), composting plants can play a significant role in reducing the running costs of solid waste disposal. Moreover, composing plants can play a significant role in diverting waste from landfills, and thus conserving landfill space and reduce the production of air polluting gases.

Moreover, composing plants produce organic fertilizer for quality soil improvement.

5.1 Future Work

It would be interesting to include the concept of recycling plant and the gas generation rate in a landfill, as environmental management strategies such as air pollution or noise pollution control in the model formulation. To minimize transportation cost, inclusion of composting plants near collection points is worth investigating. Furthermore, this model can be improved by including other objective functions and solve as a multi-criteria decision analysis problem. Tanzania has several cities, the research can be replicated to other cities and consider specific features in each for better understanding of the problem in Tanzanian environment.

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