Hawassa University Journals - Ethiopia

Ethiopian Journal of Engineering and Technology (EJET)

Volume 5, 2026, Pages 1 – 16. https://doi.org/10.82127/ejet.v5i1.2102

Optimizing the Municipal Solid Waste Collection and Transportation Practice Using Integer Programming Model: A Case Study of Hawassa City

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Abstract

Municipal solid waste (MSW) describes the stream of solid waste generated by households, commercial establishments, industries and institutions which consists of everyday items such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint and batteries. Municipal solid waste management involves collection, storage, transportation and recycling. The process of collecting and transporting solid waste includes storing the waste at the generating and pick-up sites, collecting it, driving trucks around the neighbourhoods, and transporting to a transfer or disposal site. The transportation part of Hawassa City's solid waste management was the main focus of this study. In the city, waste is loaded onto collection trucks at each home's gate. This practice results higher transportation cost due to longer vehicle routing distance and absence of appropriate transfer areas. Therefore, determining the appropriate and number of transfer areas was the goal of this study to minimize the transportation cost. In order to achieve this objective an integer programming model was used as optimization technique particularly in Tabor sub city. This sub city was selected among eight sub cities of Hawassa since it constitutes largest population. Tabor sub city has five administrative Kebeles (Hogane Wacho, Tilte, Dume, Hiteta & Fara) and a population of 93,625. Hawassa city have a capacity of generating 0.43 kg waste per day per capita and Tabor sub city generates 28,181 kg per day. A 0-1 integer programming model gives two intermediate transfer areas in Hogane Wacho and Fara kebeles. The transportation cost per cargo was calculated for road transport mode which composed of costs for Cargo investment, operation & maintenance and fuel & lubricant from each collection points to the landfill and transfer areas. The transportation model *is formulated and solved using POM software and the minimized cost is 267,982.6 ETB which is less than the existing system transportation cost 298,703.38 ETB.*

Keywords: Municipal Solid Waste; Transportation Cost; Integer Programming; Transfer Area.

1. Introduction

Municipal Solid waste is temporarily unwanted solid materials generated from human activities in residential, industrial or commercial areas (Kaur, 2023). Municipal solid waste (MSW), also known as urban solid waste, is often made up of trash, food waste, construction and demolition debris, street sweepings, yard garbage, abandoned cars and appliances, and treatment plant waste (Singh, 2014). Management of municipal solid waste (MSW) is apriority of urban communities throughout the world.

There are various classifications for solid waste. It can be home, industrial, commercial, construction, or institutional depending on where it originated. Depending on what's inside, it could be plastic paper, glass, metal, organic substance, etc. It could be contagious, radioactive, flammable, toxic, or non-toxic depending on the potential hazards. Its management is organized into six major activities: waste generation, waste handling at the source, collection, transportation, processing and transformation, and disposal (Khan, 2022). Solid waste is collected and transported by the crew, then drive trucks about the neighbourhood, store the garbage at the generating and pick-up locations, and take the trucks to a transfer station or disposal location (Singh, 2014).

The globe produced 1.3 billion tons of waste annually in 2012; between 2025 and 2050, that amount is predicted to increase to 2.2 and 3.4 billion tons, respectively. Solid waste generation surpasses population growth and economic development in emerging nations, making garbage management a more pressing issue. The collection is expensive, difficult, and intricate. For example, waste management authorities in low-and middle-income countries use 3%–15% of city funds, with approximately 90% of this budget used solely for waste collection (Kumari, 2023). Among the system engineering model techniques for MSW management, optimization models are the most widely utilized. The local optimal point is also the global optimum point in convex optimization, which incorporates linear optimization models as a specific example. General nonlinear optimization, on the other hand, focuses on methods for local optimization, which means that a solution minimizes the objective function among feasible points that are close to each other (Rizvanouglu, 2020).

Typically, the vehicles pick up waste from pick-up locations and deliver it to the collection station or intermediary facilities. The cost of the transportation grows as waste volume and the distance travelled to disposal facilities. In order to minimize cost, the transfer of waste to the collection station is typically considered. The pickup truck crew will spend too much time travelling ineffectively if the disposal site is too far from the city. Therefore, using collection vehicles to get to the disposal site could not be cost-effective. As a result, transfer stations are set up at appropriate places. A strong multi-objective function for SWM is proposed, which considers the social, economic, and environmental aspects of sustainability when choosing the best sites for recycling facilities, landfills, appropriate technology, and waste transport vehicles in order to lower costs. (Hannan, 2018).

In Hawassa town, municipal solid waste primarily collected in houses and stored in every resident's compound. Then solid waste collection associations collect it and load on the vehicle and dispatches at the permanent disposal site. In the transportation process, waste collection vehicle clicks each of the resident's gate to load the waste. Due to this the vehicle tends to travel very longer distance which increases the transportation cost.

In transportation model one of the objectives of optimization tools is minimizing the transportation cost by shortening the distance and keeping the service at the better level. Hence, the aim of this research was to optimize the MSW collection and transportation practice of Hawassa city by reducing the vehicle transportation cost and distance along the collection area with the help of integer programming model. In this study, the transportation cost for the road transportation mode was calculated, the number of intermediate transfer stations was calculated and their contribution to the transportation model was examined, the current vehicle routing and transportation practices used by the city's solid waste collectors were studied, and an integer programming model was developed to optimise the transportation and collection activity.

2. Materials and Methods

The study was performed in Hawassa city located 275 km far from Addis Ababa.

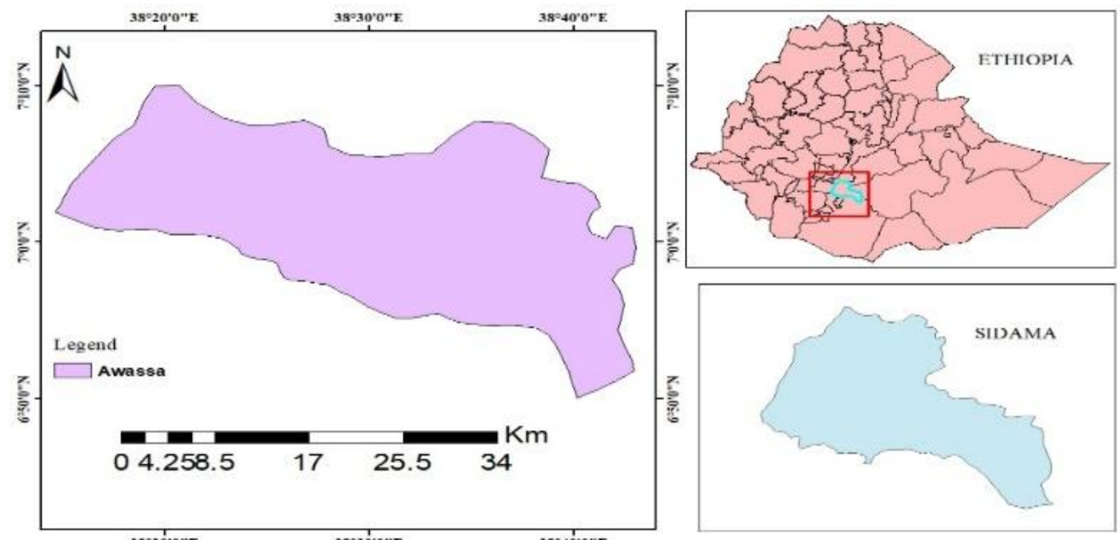

Figure 1. Map of study area

An integer programming issue is a mathematical optimization or feasibility program in which some or all of the variables are restricted to being integers. The term is frequently used to describe integer linear programming, where both the goal function and the constraints, aside from the integer constraints are linear. If some of the decision variables are not discrete, the problem is called a mixed-integer programming problem.

The three basic types of integer linear programming models are complete integer models, 0-1 integer models, and mixed integer models. Every decision variable in a complete integer model must have an integer solution value. Every decision variable in a 0-1 integer model has an integer value of either zero or one (Taha, 2020). A 0-1 integer programming model was used for this research, and it is represented as:

$$Maximize \sum_{j=1}^{n} cjxj \qquad \text{Equ…1}$$

Subjected to:

$$\sum_{j=1}^{n} aijxj = bi \qquad (i=1, 2, \ldots, m),$$

$$Xj \geq 0 \text{ and integer} \qquad (j= 1,2, \ldots ,n).$$

This research was explanatory research type to find out the causal relationships among different variables using research questions. Samples were selected from the entire population. In this case the population is characterized by the number of sub cities which are administered by Hawassa city administration.

Table 1. Population size of Hawassa town in different sub cities (Source: Hawassa City Administration Socio-Economic Profile February 2023)

Sl. No.	**Sub City**	**Population (Urban 2014 E.C.)**		
		Male	**Female**	**Total**
1	Addis Ketema	19154	19150	38,304
2	Hayek Dar	19241	18107	37,348
3	Mehal Ketema	15980	15482	31,462
4	Bahil Adarash	16018	15889	31,907
5	Misrak	26163	23689	49,852
6	Menehariya	26937	25712	52,649
7	Tabor	49296	44329	93,625
8	Tulla Town	817	755	1,572
Total		**173,606**	**163,113**	**336,719**

Tabor sub-city was chosen as the study location among the eight sub-cities of Hawassa town due to its significantly large population size. For this optimization study, linear integer programming model were developed and solved. In order to develop the model, the appropriate data were collected through different techniques from the appropriate sources. The Hawassa municipal administration provided information about the number of citizens, sub cities, and block numbers. Temporary waste pickup locations and routes were gathered using GPS (Global Positioning System). Arc Map 10.8 was used to identify and locate the study region utilizing spatial data, such as road network maps and other maps, locations, and distances. In this study integer programming and transportation models were formulated and solved by QM for windows computer software packages.

Hawassa City's per capita municipal solid waste generation (MSWG) rates are projected to be 0.43 kg/day. The main sources of solid waste generation areas include residents, businesses, institutions, industries, hotels, and street sweepers (Hirpe, 2021). But the quantity of waste produced varies depending on the source. For instance, households generate 70% of all municipal solid waste, followed by companies (9%), industries (6%), hotels (3%), hospitals (1%), street sweepers (10%), and miscellaneous sources (1%). This demonstrates that houses are the primary source of solid waste generation (Tassie, 2019).

3. Results and Discussions

Results and discussion focused on analyzing the existing vehicle routing and transportation practices, calculating the number of transfer areas and analyzes their contribution for the transportation model, calculating the transportation cost for road transportation mode and Formulating integer programing model that optimizes the transportation.

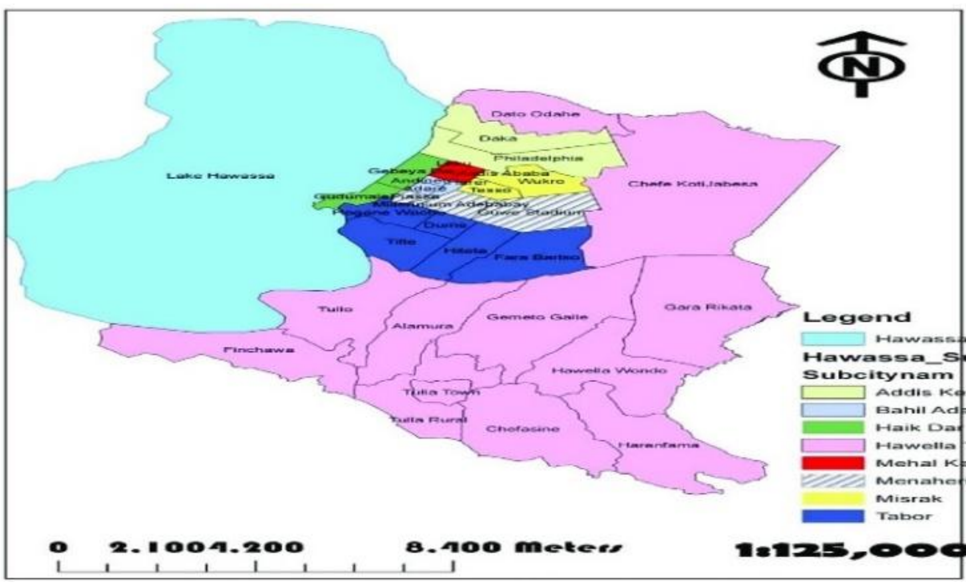

Figure 2. Administrative map of Hawassa city (source: Development-data-collection-and-dissemination)

. The collections areas are identified as the number of Kebeles available for Tabor sub city and there are five Kebeles in the sub city namely, Hogane Wacho Kebele, Dume Kebele, Hiteta Kebele, Fara Kebele and Tilte Kebele. Solid waste collection associations currently use a collection mechanism of clicking every resident’s gate and transporting the collected solid waste to the landfill which is located around Diaspora area. Based on this, we can measure the distance travelled to collect the waste from each of the residents and transport to the landfill area. This is performed directly from the google map of the sub city and Kebeles.

Tabor sub city comprises five administrative Kebeles and these Kebeles are shown in the following Figure 3.

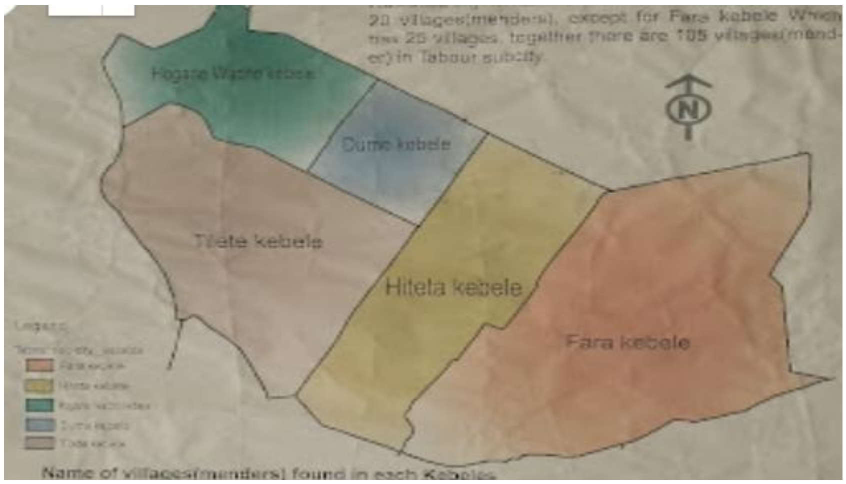

Figure 3. Administrative map of Tabor Sub city – Hawassa

(Source: https://www.google.com/maps)

The transportation distance is the distance the vehicle travelled for collection and travelling to the landfill from each collection areas (Kebeles). For instance, the collection and transportation distance from Hogane Wacho kebele households of tabor sub city to the landfill location is 16.63km (~17Km) for one trip.

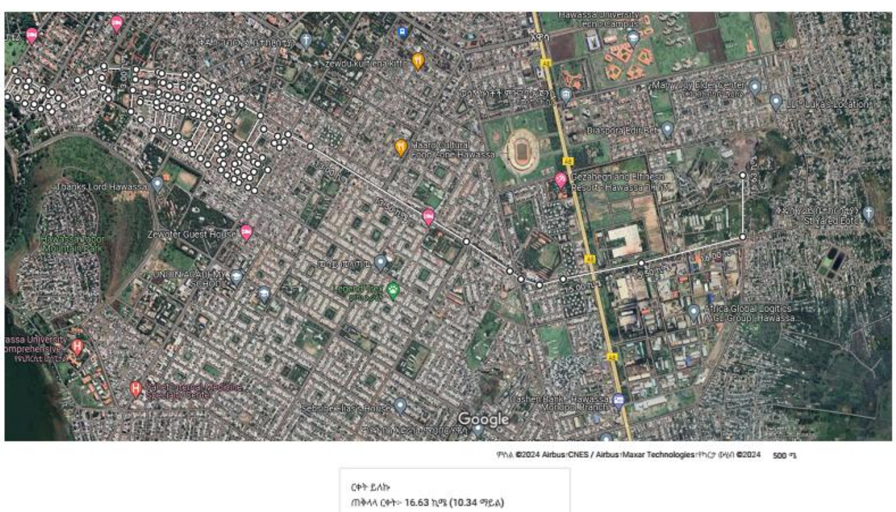

Figure 4. Collection and transportation distance from Hogane Wacho kebele to the landfill

Using the same technique the collection & transportation distance from other Kebeles to the landfill location was measured and summarized in the following table with the corresponding transportation cost. The fuel consumption per kilometer is 0.2 litters and the cost (price) of fuel per litter is 84.00 ETB according to the current price of fuel.

Table 2. Transportation distance and cost from each collection point to the Landfill area (Existing)

Collection Points (Kebeles)	Travel Distance (km)	Cost (ETB)/Trip
Hogane Wacho Kebele	17	285.6
Dume Kebele	14	235.2
Hiteta Kebele	36	604.8
Tilte Kebele	53	890.4
Fara Kebele	32	537.6
Total	**152**	**2,553.6**

The table shows that, the vehicle travels 152 kilometers for a single trip to collect solid waste from tabor sub city and transfer the waste to the landfill location. The transportation cost of fuel is calculated as 2,553.6 ETB for the single trip and this research aims to minimize this transportation distance and the corresponding cost. In order to minimize the total travel distance, some transfer areas can be introduced the sub city administration. To perform this task the application of a 0-1 integer programming model can be used. These transfer areas can be located in the five kebeles or not. We have five individual kebeles, Hogane Wacho Kebele (X_1), Tilte Kebele (X_2), Dume Kebele (X_3), Hiteta Kebele (X_4) and Fara Kebele (X_5), X_1=1 if the transfer area is established in Kebele (i); 0 otherwise.

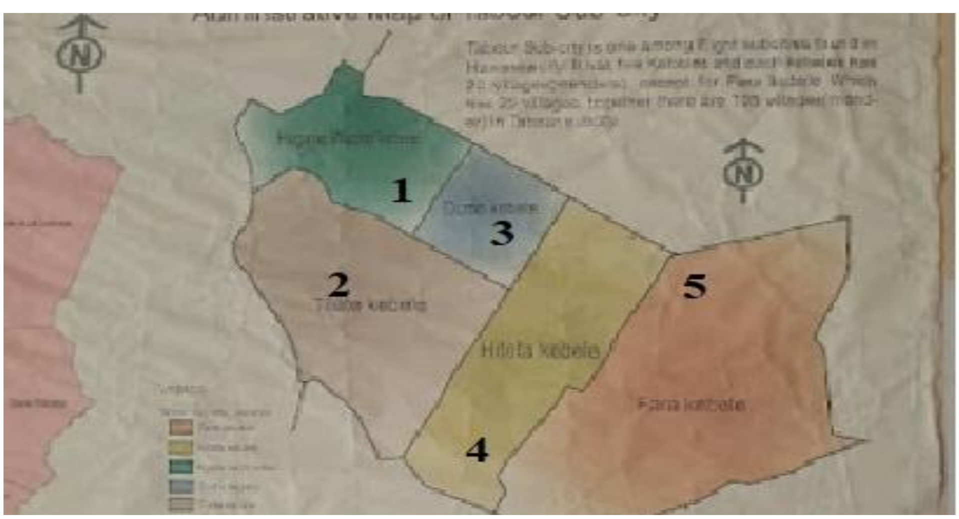

Figure 5. Kebeles Adjacency

The transfer area may be established in a kebele if the kebele demands or is adjacent to another kebele with a transfer area. Thus, the linear program will need one constraint for each kebele. The adjacency of each kebele is shown Figure 5 as;

Table 3. Adjacency representation

Kebeles Considered	**Adjacent Kebeles (By Number)**
Hogane Wacho Kebele	2,3
Tilte Kebele	1,3,4
Dume Kebele	1,2,4
Hiteta Kebele	2,3,5
Fara Kebele	4

The objective is to determine the minimum number of transfer areas in Tabor sub city and it becomes;Min Z $X_1 + X_2 + X_3 + X_4 + X_5$

Subjected to; $X_1 + X_2 + X_3 \geq 1$ (Hogane Wacho)

$X_1 + X_2 + X_3 + X_4 \geq 1$ (Tilte)

$X_1 + X_2 + X_3 + X_4 \geq 1$ (Dume)

$X_2 + X_3 + X_4 + X_5 \geq 1$ (Hiteta)

$X_4 + X_5 \geq 1$ (Fara)

$X_i = 0,1 \quad i = 1,2,3,4,5$

Using POM QM for windows software, let’s solve this problem.

Table 4. The solution gained from the software

Integer & Mixed Integer Programming Results

Transfer area solution

Variable	Type	Value
X1	0/1	1
X2	0/1	0
X3	0/1	0
X4	0/1	0
X5	0/1	1
Solution value		2

The optimal number of transfer areas for the sub city becomes two and located at Hogane Wacho Kebele and Fara Kebele. In order to calculate the total cost incurred for all trips, we need to know the amount of waste generated. The amount of waste generated depends on the population of the area. We have a data that Tabor sub city has around 93,625 peoples and the amount of waste generated per capita per day is 0.43kg. Another variable is the capacity of the vehicle and which is 3000 kg and we can calculate the number of trips required to transfer all the collected waste from each Kebeles.

Table 5. Trips required and MSW generation

Collection Points	**Population**	**MSW generation / day in Kg**	**Rate per day (kg)**	**No. of Required Trips**
Hogane Wacho Kebele	17,475	5,260	0.43	1.5
Tilte Kebele	23,340	7,025		2.0
Dume Kebele	8,200	2,468		0.7
Hiteta Kebele	18,725	5,636		1.6
Fara Kebele	25,885	7,791		2.2
Total	93,625	28,181		

The total cost shown in the table below is for transporting the waste from each kebeles to the landfill area. And we need to find the transportation cost for the new transfer areas. Transportation Cost Model per Unit of Cargo (Uk) is formulated as (Sahin B. a., 2005);

$$UK = X \cdot (UL) \cdot LT + Y \cdot (UL) \cdot LT + Z \cdot (UL) \cdot LT \qquad \text{Equ… 2}$$

$U_K = Z \cdot (U_L) \cdot L_T$ is transport cost per unit cargo for road transport.

where subscripts S, R, and K denotes seaway, railway, and road, respectively.

Applying a broad and simple approach to all forms of transportation, we have levelized investment cost (U_c), Operation and maintenance (Um), Fuel cost (Uf), and External costs (Uex) per cargo. The unit cargo investment cost, Uc, can be found as shown below (Sahin B. a., 2009):

$$U_c = \frac{\left\{\sum_{t=1}^{n} I_c \left[\left(1-\left(\left(t-\frac{1}{n}\right)\right)i+(1/n)\right)\right](1+r)^{-t}\right\}[2L+V_s Z_{sa}]}{2Y_k Y_d V_s\,(8760-Z_{bt}-Z_{bk})\sum_{t=1}^{n}(1+r)^{-t}} \qquad \text{Equ…3}$$

Where:

I_C represents investment cost including infrastructure, *Z_{bk} is annual idle time*

L is route length *i represents interest rate.*

V_S is service speed of vehicle,

Z_{sa} represents waiting time between sequential trips,

Y_k is cargo capacity of vehicle,

Y_d shows fullness ratio of vehicle,

Z_{bt} is annual maintenance-repair time,

Operational and Maintenance Costs per Unit of Cargo (U_m) (Sahin B. a., 2009):

$$U_m = \frac{\left\{\sum_{t=1}^{n}\left[C_{mo}(1+e_m)^t + \left(sI_C\left(1-(t/n)\right)\right)(1+e_s)^t\right](1+r)^{-t}\right\}\times[2L+V_s Z_{sa}]}{2Y_K Y_d V_s(8760-Z_{bt}-Z_{bk})\sum_{t=1}^{n}(1+r)^{-t}} \quad \text{Equ… 4}$$

Where:

C_{mo} is annual operation and maintenance costs,

e_m is escalation rate for future operational and maintenance costs,

s is insurance percentage ($\%I_c$), and

e_s is escalation rate for future insurance cost.

Fuel and lubricant costs per unit of cargo, Uf, can be shown as (Sahin B. a., 2009):

$$U_f = \frac{(B_f P_{f+B_o P_o})L\sum_{=1}^{n}\left[(1+e_f)^t(1+r)^{-t}\right]}{(Y_k Y_d)\left[\sum_{t=1}^{n}[(1+r)^{-t}]\right]} \quad \text{Equ…5}$$

Where:

B_f is fuel consumption per km (main +aux.),

Pf is fuel price,

Bo is lubricant consumption per km (main + aux.),

Po is lubricant price, and

ef is escalation rate for future fuel cost

After having the above formulas, total transportation cost per cargo, UK, is shown below:

$U_K = U_c + U_m + U_f + U_{ex}$ (\$/ton) Equ… 6

and then specific cost, U_{KL}, becomes

$U_{KL} = \frac{UK}{LT}$ (\$/ton · km) Equ… 7

Table 6. Transportation cost variable values

Mode: Road				
Sl. No.	**Description**	**Symbol**	**Unit**	**Value**
1	Investment cost	Ic	ETB	1.6 million
2	Average Economic life cycle	n	Years	11 years
3	Insurance percentage (%Ic)	s	ETB	0.02
4	Service speed of vehicle	Vk	Km/hr.	45
5	Cargo capacity	Yk	Kg	3000
6	Annual maintenance - repair time	Zbt	Hours	336
7	Annual idle time	Zbk	Hours	6240
8	Fuel consumption per km	Bf	Liter/km	0.2
9	Lubricant consumption per km	Bo	Liter/km	0.0075
10	Fuel price	Pf	ETB/liter	84
11	Lubricant price	Po	ETB/liter	525
12	Annual operation and maintenance	Cmo	ETB/yr.	195,800
13	Interest rate	i		0.172
14	Discount rate	r		0.1
15	Escalation rate for operational	em		0.2
16	Escalation rate for future fuel cost	ef		0.4522
17	Escalation rate for future insurance cost	es		0.03
18	Escalation rate for future external cost	ex		0
19	Route length	L	Km	Varies
20	Waiting time between sequential trips	Zsa	Hours	40
21	Specific cost of accident	Cac	ETB/kg.km	0
22	Specific cost of pollution	Cp	ETB/kg.km	0
23	Specific cost of noise	Cn	ETB/kg.km	0
24	Average fullness ratio	Yd		0.9
25	Reference fullness ratio for specific	Yd*		0

Using the formula shown above, transportation cost from each supply area to the demand area calculated using excel for road transportation mode and tabulated as follow the Table 7.

Table 7. Summary of Transportation cost

From	To											
	Cost ETB											
	Landfill				Hogane Wacho Transfer Area				Fara k. Transfer Area			
	U_c	U_m	U_f	U_k	U_c	U_m	U_f	U_k	U_c	U_m	U_f	U_k
Hogane W. K.	1.123	2.11	3.73	6.96	1.11	2.10	3.07	6.28	1.12	2.11	3.73	6.96
Tilte Kebele	1.29	2.27	11.64	15.20	1.18	2.21	8.78	12.16	1.18	2.23	9.44	12.85
Dume Kebele	1.09	2.06	1.54	4.69	1.1	2.06	1.43	4.58	1.09	2.06	1.32	4.47
Hiteta Kebele	1.16	2.2	7.9	11.26	1.17	2.2	8.12	11.49	1.16	2.19	7.46	10.81
Fara Kebele	1.16	2.11	7.03	10.29	1.16	2.19	7.46	10.81	1.15	2.17	6.59	9.91

Transporting a product from multiple origins to multiple destinations at the lowest possible cost is the primary goal of the Transportation Model, a special example of the Linear Programming Problem.

The general formulation of transportation problem is:

$$min \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} c_{ij}\, x_{ij}$$

Subjected to;

$\sum_{j=1}^{j=n} x_{ij} \leq s_i \quad (i = 1,2, \dots, m)$ (Supply Constraints)

$\sum_{i=1}^{i=m} x_{ij} \geq dj \quad (j = 1,2, \dots, n)$ (Demand Constraints)

(i = 1,2, …, m; j = 1,2, …, n)

$X_{ij} \geq 0$ and the network can be drawn as:

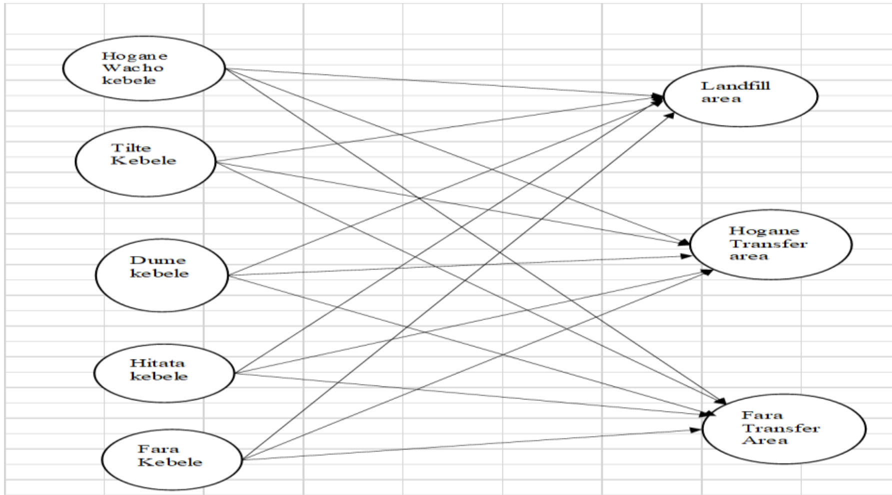

Figure 6. Transportation problem Network

This transportation tableau is unbalanced and we need to balance by adding additional supply (Dummy).

Table 8. The tableau for transportation of MSW (balanced)

From	**To**			**Supply in kg**
	Cost in ETB			
	Landfill	**Hogane W. K. Transfer**	**Fara k. Transfer**	
Hogane Wacho	6.963	6.286	6.963	5,260
Tilte Kebele	15.20	12.158	12.855	7,025
Dume Kebele	4.699	4.587	4.476	2,468
Hiteta Kebele	11.260	11.491	10.814	5,636
Fara Kebele	10.299	10.814	9.914	7,791
Dummy	0	0	0	73,172
Demand in kg	73,171	14,754	13,428	

The linear programming model for the balanced problem is formulated as follows:

Minimize Z = ETB6.963X11 + 6.286X12 + 6.963X13 + 15.2X21+12.158X22 +12.855X23 + 4.699X31 + 4.587X32 + 4.476X33 + 11.26X41 +11.491X42 + 10.814X43 + 10.299X51 +10.814X52 + 9.914X53 + 0X61 + 0X62 + 0X63

S. to,

X11 + X12 + X13 ≤ 5,260   kg/day Hogane Wacho kebele capacity

X21 + X22 + X23 ≤ 7, 025 kg/day Tilte capacity

X31 +X32 +X33 ≤ 2,468 kg/day Dume capacity

X41 + X42 + X43 ≤ 5,636 kg/day Hiteta capacity

X51 + X52 X53 ≤ 7,791 kg/day Fara kebele capacity

X11 + X21 +X31 = 73,171 kg/day, land fill demand

X12 + X22 + X32 = 14,754 kg/day, Hogane W. K. transfer rea demand

X13 +X23 +X33 = 13,428 kg/day, Fara k. transfer area demand

Xij≥0

Let’s solve this problem using software package (POM software package)

Table 9. Solution of the software is shown as follows

Municipal Solid Waste Transportation Solution

solution value = $267,982.6	Landfill	Hogane W.K TA	Fara K. TA
Hogane Wacho K.		5,260	
Tilte Kebele		7,025	
Dume Kebele		2,467	1
Hiteta kebele			5,636
Fara Kebele			7,791
Dummy	73,171	2	

The minimum total transportation cost is:

Minimize Z = (6.286×5,260) + (12.158×7,025) + (4.587×2,467) (4.587×1) + (10.814×5,636) + (9.91×7,791) = **267,982 ETB**

4. Conclusion

The management of municipal solid waste necessitates a very intricate framework that entails carrying out several tasks related to various phases of the waste life cycle, including collection, transformation, and disposal. Numerous strategic, tactical, and operational decisions must be made for each task. Choosing garbage treatment facilities and/or landfills, finding collection locations, dividing the service area into districts, choosing collection days for each zone and waste type, deciding on fleet composition, and scheduling and routing collection vehicles are a few examples of such decisions. Optimization models majorly used from among the system engineering models tools for such type of problem. This study focused on the optimization of municipal solid waste collection and transportation system of Hawassa city using integer programing model. To conduct this study the researcher firstly analyzes the existing practice.

On this phase the researcher understands that MSW is collector vehicle clicks each households' gate to collect the waste and transport to the landfill area located around diaspora. This way of collection and transportation results higher transportation cost.

To tackle this challenge this research tries to determine intermediate transfer areas. These transfer areas were determined using 0-1 integer programing model in Tabor sub city. This sub city was selected among eight sub cities of Hawassa since it constitutes the largest population. Tabor sub city has five administrative Kebeles (Hogane Wacho, Tilte, Dume, Hiteta & Fara) with total population of 93,625. Using 0-1 integer programming model, two transfer area (Hogane Wacho Transfer area and Fara transfer area) identified and the transportation model was formulated to get total minimized transportation cost. The transportation cost per cargo was calculated for road transport mode from each collection point to the landfill and transfer areas. The transportation model problem solved using POM software and the minimized cost is 267,982.6 ETB which is less than the existing transportation cost 298,703.38 ETB. As a result, these intermediate transfer areas have positive contribution in the minimization of transportation cost.

Acknowledgement

First, we want to express our gratitude to Almighty God to enabling us to complete this research. Appreciative credit is to Hawassa city administration and Tabor sub city administration workers for their inputs, commitment, and support through the research work process.

Funding

This research was funded by Office of the Vice President for Research and Collaboration, Hawassa University, Ethiopia.

Competing Interests

The authors declare no competing interests.

Concerns to Publish

All the authors concern to the publication of this article.

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