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An Integrated Solid Waste Management Model (Case Study of Accra Metropolitan Assembly)

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Abstract: In this research article, an Integrated Solid Waste Management Model is developed using Integer Linear Programming (ILP). Integrated into the current solid waste management programme (of waste collection and dumping) are compost and recycling plants. An objective function consisting of fixed and variable costs, transportation cost and environmental cost/credit is developed subject to capacity, mass balance and environmental constraints. Two case studies were carried out using the model. In the first case study, the model was tested with waste collection from three sources/zones in Accra Metropolitan Assembly (AMA) and dumping of waste at current three landfill sites. In the second case study, a new landfill site and a compost plant acquired by Zoom Lion Ghana Ltd., were integrated into the model. The results show that the operational cost for the Integrated Solid Waste Management model is close to that of the ‘’collection and dumping’’ programme initially. With increased revenue per tonne of compost and/or increased proportion of waste converted to compost, the overall operation cost reduces considerably in the case of the integrated solid waste management model making it more efficient with reduced environmental pollution. This finding is significant because it emphasizes the need to adopt integrated approach to solid waste management in the metropolis.

Key words: Integrated solid waste management, integer linear programming, model

INTRODUCTION

Protection of the environment and resources through environmentally sustainable waste management programme in the Accra Metropolis is becoming increasingly important. This requires a sustainable approach to waste management and integrated operations that will produce the most efficient and best practicable option. This is a challenging task since it involves taking into account the economic, technical, regulatory and environmental constraints and can become more complex if social and political considerations are also taken into account (Zoomlion Ghana Ltd., 2010, Waste Management Department of AMA, 2010).

Accra Metropolitan Assembly (AMA) is part of the capital city of the republic of Ghana. It covers a total surface area of about 200 km^2 (Ghana Districts, 2006). The population of AMA is about two million four hundred and twenty-two thousand nine hundred and four (2,422,904), which is growing at rate of 4.0% per annum (Ghana Statistical Service, 2009). AMA is generally characterized by fragmented residential, commercial and economic activities resulting in generation of all kinds of solid wastes, which the city authorities do not have the capacity to handle effectively (Appendix A).

It is estimated that between two thousand to two thousand five hundred (2000-2500) tonnes of solid waste is generated per day out of which about seventy-five percent (75%) is lifted daily by private Waste Management Companies to Sabah, Anyah and Ablekuma landfill sites (Table 1). The remaining twenty-five (25%) is collected either irregularly or not at all (Waste Management Department of AMA, 2010) resulting in formation of mountains of uncollected garbage periodically especially in the poor and middle-income areas. These heaps serve as potential sources of epidemics and other communicable diseases to residents. Besides, low density waste materials such as plastics, paper, dried leaves, etc., find there way into gutters and drainage systems either by the wind or indiscriminate disposal of waste by some residents choking these gutters and causing floods whenever it rains heavily in the city. In addition, water bodies are polluted by leachate from these piles of garbage that are heaped along them.

Table 1: Amount of waste (m) collected daily from zones/sources

Sub-metro	Central zone	West zone	East zone	Total
Waste (ton)	564.00	800.00	465.50	1829.50

Waste Management Department, AMA

At the moment the solid waste management programme is based on ‘collection and dumping’ since none of the waste management companies processes or recycles waste resulting in landfills being used up within short period of time. There is therefore the need to use an integrated solid waste management programme in order to provide a healthy environment to all city dwellers and

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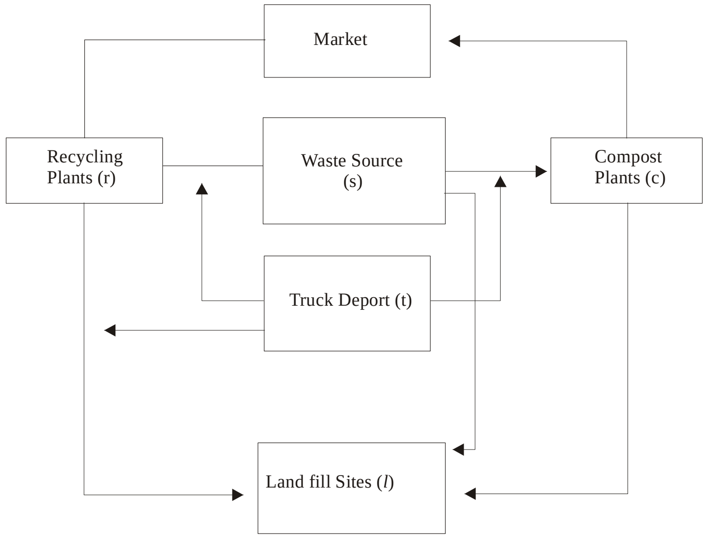

Fig. 1: Schematic representation of the model

to optimally use the available resources in the day to day management of waste.

The aim of this research study is to develop an integrated solid waste management model that can be used in the day to day planning and management of municipal/metropolitan solid waste collection, transportation, recycling, compositing and disposal. Data used in this research study were obtained from Waste Management Department of AMA, Zoom Lion Ghana Limited and other waste management companies in the metropolitan area.

Related work: A good number of studies have been done on different facets of solid waste management over the past three decades. Hocket *et al*. (1995), Daskalopoulos *et al*. (1998) and Rao *et al*. (1971) developed models, which determine the factors that influence waste composition and or waste generation. Badran and El-Haggar (2006) presented an optimization model to help in selecting collection stations from the possible locations in such a way as to minimize the daily transportation cost between the nodes in the model. Lund (1990) proposed a model, which utilizes recycling as an instrument to determine the level of annual landfill deposit, the life of span of landfill and therefore the time when a new landfill must be started.

Kirkeby *et al*. (2006) and Solano *et al*. (2002) proposed models for optimization and evaluating the overall environmental impacts of municipal solid waste management systems by the use of life cycle assessment.

Model formulation: Figure 1 depicts a schematic representation of the proposed model and the variables that are used in the model formulation and their respective definitions are as follows:

$(NT)_i$ is the actual number of trucks of type *i* to be used each day. X^i_{jcl} and X^i_{jrl} are the total number of trips that a truck of type *i* is expected to make each day to transport waste of type *j* from compost plant c and recycling plant *r* respectively to landfill site *s*. x^i_{jcl} and x^i_{jrl} are the number of trucks of type *i* used each day to transport waste of type *j* from compost plant *c* and recycling plant *r* respectively to landfill site *s*. W^i_{jsl} , W^i_{jsc} and W^i_{jsr} represent the total number of trips that a truck of type *i* is expected to make each day to transport waste of type *j* from waste source *s* to landfill site *l* compost plant *c*, and recycling plant r respectively. w^i_{jsl} w^i_{jsc} and w^i_{jsr} are the number of trucks of type *i* used each day to transport waste of type *j* from waste source s to landfill site *l*, compost plant *c*, and recycling plant r, respectively.

α^i_{sc} , α^i_{sr} and α^i_{sl} represent the required number of trips a truck of type *i* can make each day from waste source *s* to a compost plant *c*, recycling plant *r* and landfill site respectively while p(*i*) is the probability of a truck of type *i* breaking down in a day. β^i_{cl} and β^i_{rl} are the required number of trips a truck of type *i* can make each day from a compost plant *c* and recycling plant *r* to landfill site *l* respectively. C_0, C_r, C_i and C_l: represent the capacity or the maximum amount of waste (in tonnes) that can be handled at compost plant *c*, recycling plant *r*, truck depot t*t* and landfill site *l* each day respectively while θ_i is the capacity of truck of type *i* measured in tones.

m_{sc}, m_{sr} and m_{sl} are variables indicating amount of waste conveyed from waste sources to compost plant, recycling plant and landfill site respectively each day while m_s represents the amount of waste generated at source *s* (in tonnes) each day. m_{cl} and m_{rl} are variables indicating amount of waste conveyed from compost plant and recycling plant respectively to landfill site each day while $(tm)_l$ denotes the total amount of waste transported from waste source, compost plant and recycling plant to landfill sites. y_c, y_r, y_t and y_l are Boolean or decision variables indicating the existence or otherwise of compost plant, recycling plant, replacement truck depot and landfill site respectively. γ_c and γ_r represent the fractions of waste that is converted to product or conversion factor at compost plant *c* and recycling plant *r*, respectively. ρ_c and ρ_r represent the fractions of total amount waste at compost plants and recycling plant respectively discharged into the atmosphere in the form of water vapour and Green House Gases (GHGs) while ψ_a represents the EPA upper limit for noxious material, *a*.

Φ_c^a, Φ_r^a and Φ_l^a represent the amount of noxious material, *a*, emitted each day (per tonne of waste processed) at compost plant *c*, recycling plant *r* and landfill site *l* while Ω_a represents the carbon credit/penalty per tonne of noxious material emitted in excess of upper limit. ω_i is the fixed cost per day of truck of type *t*. u_{cl}^i and u_{rl}^i represent the costs of transporting unit weight of waste from a compost plant *c* and recycling plant *r* to a landfill site *l*, respectively using truck type *i* while v_{sc}^i, v_{sr}^i and v_{sl}^i are the costs of transporting unit weight of waste from source *s* to a compost plant *c* and recycling plant *r* to a landfill site *l* respectively using truck type *i*.

p_c, p_r, p_t and p_l represent the fixed costs of operating compost plant *c*, recycling plant *r*, truck depot *t* and landfill site *l*, respectively.

q_c, q_r and q_l represent variable costs required to handle unit weight of waste at compost plant *c*, recycling plant *r* and landfill site *l* respectively while R_c and R_r represent revenue generated per unit weight of product from compost plant *c* and recycling plant *r*, respectively.

Objective function formulation:

Fixed and variable cost function: If (NT), represents the number of trucks of type *i* used each day, p(i) the probability of a truck breaking down in a day and ω_i is the daily fixed cost of a truck of type *i*, then the total fixed cost of the trucks is given by:

$$A_1 = \sum_{i}^{I} \omega_i \Big((NT)_i + p(i)(NT)_i \Big) \tag{1}$$

Similarly if p_c, p_r, p_t and p_l represent the fixed cost of operating compost plant *c*, recycling plant *r*, truck depot *t* and landfill site *l* respectively; q_c, q_r and q_l the variable cost required to handle unit weight of waste at compost plant *c*, recycling plant *r* and landfill site *l* respectively; m_c, m_r and m_l are variables indicating amount of waste to be processed at compost plant, recycling plant and landfill site, respectively each day and y_c, y_r, y_t and y_l are decision variables indicating the existence or otherwise of compost plant, recycling plant, replacement truck depot and landfill site respectively, then the total investment cost of these facilities and handling cost is given by:

$$\begin{aligned} A2 = &\sum_{c}^{C} y_C \big(p_c + q_c m_c \big) + \sum_{r}^{R} y_r \big(p_r + q_r m_r \big) + \\ &\sum_{l}^{L} y_l \Big(p_l + q_l (tm)_l \Big) + \sum_{t}^{T} y_t p_t \end{aligned} \tag{2}$$

Equation (1) and (2) gives the combined fixed investment and handling cost component of the objective function presented in Eq. (3):

$$\begin{aligned} A = &\sum_{i}^{I} \omega_i \Big((NT)_i + p(i)(NT)i \Big) + \\ &\sum_{c}^{C} y_C \big(p_c + q_c m_c \big) + \sum_{r}^{R} y_r \big(p_r + q_r m_r \big) + \\ &\sum_{l}^{L} y_l \big(p_l + q_l (tm)_l \big) + \sum_{t}^{T} y_t P_t \end{aligned} \tag{3}$$

Transportation cost function: If u_{cl}^i and u_{rl}^i are the cost of transporting unit weight of waste from a compost plant *c* and recycling plant *r* to a landfill site *l* respectively using truck type *i*; v_{sc}^i, v_{sr}^i and v_{sl}^i represent the cost of transporting unit weight of waste from source *s* to a compost plant *c* and recycling plant *r* and a landfill site *l* respectively using truck type *i*, then the total transportation cost of using truck of type *i* between all the facilities or nodes is given by:

$$\begin{aligned} B = &\sum_{s,c,i}^{S,C,I} m_{SC} v_{SC}^i + \sum_{i,s,r}^{I,S,R} m_{sr} v_{sr}^i + \sum_{i,s,l}^{I,S,L} m_{sl} v_{sl}^i \\ &+ \sum_{i,c,l}^{I,C,L} m_{cl} u_{cl}^i + \sum_{i,r,l}^{I,R,L} m_{rl} u_{rl}^i \end{aligned} \tag{4}$$

Revenue function: If R_c and R_r are revenues generated per unit weight of product from compost plant *c* and recycling plant *r* respectively; γ_c and γ_r are the conversion factors or fractions of waste that is converted at compost plant *c* and recycling plant *r* respectively and m_c and m_r are variables indicating amount of waste processed at compost plant and recycling plants respectively each day, then the total revenue generated is given by:

$$C = \sum_{c}^{C} R_c \gamma_c m_c + \sum_{r}^{R} R_r \gamma_r m_r \tag{5}$$

Environmental cost /carbon credit: Equation 6 gives the cost of discharging noxious material in excess of the maximum limit (ψ_a) or the Carbon Credit (CC) that will be obtaining by using environmentally friendly waste management policy.

$$D = \Omega_a \left[\sum_{c}^{C} \Phi_c^a m_c + \sum_{r}^{R} \Phi_r^a m_r + \sum_{l}^{L} \Phi_l^a (tm)_l - \psi_a \right] \tag{6}$$

Adding Eq. (3), (4), (5) and (6) gives the overall waste management cost or the objective function given in Eq.

$$\begin{aligned} F = [&\sum_{i}^{I} \omega_i \left((NT)_i + p(i)(NT)_i \right) \\ &\sum_{c}^{C} y_C \left(p_c + q_c m_c \right) + \sum_{r}^{R} y_r \left(p_r + q_r m_r \right) + \\ &\sum_{l}^{L} y_l \left(p_l + q_l (tm)_l \right) + \sum_{t}^{T} y_t P_t + \sum_{s,c,i}^{S,C,I} m_{sc} v_{sc}^i + \\ &\sum_{i,s,r}^{I,S,R} m_{sr} v_{sr}^i + \sum_{i,s,l}^{I,S,L} m_{sl} v_{sl}^i + \sum_{i,c,l}^{I,C,L} m_{cl} u_{cl}^i + \\ &\sum_{i,r,l}^{I,R,L} m_{rl} u_{rl} + \sum_{c}^{C} R_c \gamma_c m_c + \sum_{r}^{R} R_r \gamma_r m_r + \\ &\Omega_a [\sum_{c}^{C} \Phi_c^a m_c + \sum_{r}^{R} \Phi_r^a m_r + \sum_{l}^{L} \Phi_l^a (tm)_l - \psi_a] \end{aligned} \tag{7}$$

Model constraints:

Location and capacity constraints: The amount of waste m_x processed at a facility *x* with maximum capacity C_x cannot exceed this capacity. These are expressed in Eq. (8), (9) and (10) for compost plant *c*, recycling plant (*r*) and landfill site (*l*), respectively. Where, y_c, y_r and y_l are decision variables which take on the value, one if truck depot exist otherwise zero:

$$\sum_{s}^{S} m_{sc} \le C_c y_c \tag{8}$$

$$\sum_{s}^{S} m_{sr} \le C_r y_r \tag{9}$$

$$(tm)_l \le C_l y_l \tag{9}$$

If W_{jsl}^i , W_{jsc}^i and W_{jsr}^i denotes the total number of trips that a truck of type *i* makes each day to transport waste of type *j* from waste source *s* to landfill site *l*, compost plant *c* and recycling plant r respectively and θ_i is the capacity of truck of type *i* measured in tones, then the total capacity of these trucks must be at least equal to the amount of waste m_s generated at the source. This is expressed in Eq. (11):

$$\sum_{j,s,l}^{J,S,L} \theta_i W_{jsl}^i + \sum_{j,s,c}^{J,S,C} \theta_i W_{jsc}^i + \sum_{j,s,r}^{J,S,R} \theta_i W_{jsr}^i \ge m_s \tag{11}$$

Besides, if X_{jcl}^i and X_{jrl}^i denote the total number of trips that a truck of type *i* makes each day to transport waste of type *j* from compost plant *c* and recycling plant *r* respectively to landfill site *s* and γ_c and γ_r the compost and recycling plants conversion factors respectively, then the amount of waste generated (unprocessed waste) at recycling plant and compost plants cannot exceed amount of waste transported from these facilities to landfill site as illustrated in Eq. (12) and (13):

$$m_c \left(1 - \rho_c - \gamma_c \right) \le \sum_{j,c,l}^{J,C,L} \theta_i X_{jcl}^i \tag{12}$$

$$m_r \left(1 - \rho_r - \gamma_r \right) \le \sum_{j,r,l}^{J,R,L} \theta_i X_{jrl}^i \tag{13}$$

Equations (14-16) provide the constraints on waste transported from waste source to all facilities in the model:

$$\sum_{j,s,c}^{J,S,C} \theta_i W_{jsc}^i \ge m_{sc} \tag{14}$$

$$\sum_{j,s,r}^{J,S,R} \theta_i W_{jsr}^i \ge m_{sr} \tag{15}$$

$$\sum_{j,s,l}^{J,S,L} \theta_i W_{jsl}^i \ge m_{sl} \tag{16}$$

Equation (17) stresses the need to have at least one facility (e.g., a truck depot) to provide truck for any truck that breaks down while Eq. (18) also emphasizes the need for the total number of trucks used each day to be more than the number of trucks that break down:

$$\sum_{i}^{I} y_i \geq 1 \tag{17}$$

$$p(i)\ (NT)_i \leq (NT)_i \tag{18}$$

Furthermore, if w_{jsl}^i, w_{jsc}^i and w_{jsr}^i represent the number of trucks of type *i* used each day to transport waste of type *j* from waste source *s* to landfill site *l*, compost plant *c*, and recycling plant *r* respectively; x_{jcl}^i and x_{jrl}^i the number of trucks of type *i* used each day to transport waste of type *j* from compost plant *c* and recycling plant *r* respectively to landfill site *s*, then the total sum of truck of type *i* $(NT)_i$ used everyday is shown in equation 19. In addition, Eq. (20) gives the total number of all trucks, (NT) used in the model:

$$(NT)_i = \sum_{j,s,l}^{J,S,L} w_{jsl}^i + \sum_{j,s,c}^{J,S,C} w_{jsc}^i + \sum_{j,s,r}^{J,S,R} w_{jsr}^i + \sum_{j,c,l}^{J,C,L} x_{jcl}^i + \sum_{j,r,l}^{J,R,L} x_{jrl}^i \tag{19}$$

$$\sum_{i}^{I} (NT)_i = (NY) \tag{20}$$

If α_{sc}^i α_{sr}^i and α_{sl}^i represent the required number of trips a truck of type *i* can make each day from waste source *s* to a compost plant *c*, recycling plant *r* and landfill site *l*; W_{jsl}^i, W_{jsc}^i and W_{jsr}^i are the total number of trips that a truck of type *i* makes each day to transport waste of type *j* from waste source *s* to landfill site *l* compost plant *c*, and recycling plant r respectively and w_{jsl}^i, w_{jsc}^i and w_{jsr}^i the number of trucks of type *i* used each day to transport waste of type *j* from waste source *s* to landfill site *l*, compost plant *c*, and recycling plant *r*, respectively, then Eq. (21-23) give the constraints on the expected number of trips truck of type *i* will make each day from waste source *s* to recycling plant *r*, compost plant *c* and landfill site *l* then:

$$W_{jsl}^i = \alpha_{sl} w_{sl}^i \tag{21}$$

$$W_{jsc}^i = \alpha_{sc} w_{sc}^i \tag{22}$$

$$W_{jsr}^i = \alpha_{sr} w_{sr}^i \tag{23}$$

Similarly, if β_{cl}^i and β_{rl}^i are the required number of trips a truck of type *i* can make each day from a compost plant *c* and recycling plant *r* to landfill site *l*, respectively; X_{jcl}^i and X_{jrl}^i represent the total number of trips that a truck of type *i* makes each day to transport waste of type *j* from compost plant *c* and recycling plant *r* respectively to landfill site *s* and x_{jcl}^i and x_{jrl}^i the number of trucks of type *i* used each day to transport waste of type *j* from compost plant *c* and recycling plant *r* respectively to landfill site *s*, then the constraints on the expected number of trips truck of type *i* will make each day from recycling plant *r* and compost plant *c* to landfill site *l* are presented in Eq. (24-25):

$$X_{jrl}^i = \alpha_{rl} x_{rl}^i \tag{24}$$

$$X_{jcl}^i = \alpha_{cl} x_{cl}^i \tag{25}$$

Mass balance constraints: Equation 26 provides the constraints on total amount of waste transported from waste source, compost plant and recycling plant to landfill sites whilst Eq. (27) and (28) provides the material balance constraints on the unrecoverable waste from compost plant and recycling plant respectively that must be transported to landfill site each day:

$$\sum_{s,l}^{S,L} m_{sl} + \sum_{c,l}^{C,L} m_{cl} + \sum_{j,r,l}^{J,R,L} m_{rl} = (tm)_t \tag{26}$$

$$\sum_{s,c}^{S,C} m_{sc}(1 - \gamma_c - \rho_c) = \sum_{c,l}^{C,L} m_{cl} \tag{27}$$

$$\sum_{s,r}^{S,R} m_{sr}(1 - \gamma_r - \rho_r) = \sum_{r,l}^{R,L} m_{rl} \tag{28}$$

Environmental constraints: Here we consider EPA's maximum limit ψ_a for noxious material *a*. If Φ_c^a, Φ_r^a and Φ_l^a represent the amount of noxious material, *a*, produced each day at a compost plant, recycling plant and landfill site respectively are proportional to the amount of waste handled m_c, m_r, m_l at these facilities, then:

$$\sum_{c}^{C} \Phi_c^a m_c + \sum_{r}^{R} \Phi_r^a m_r + \sum_{l}^{L} \Phi_l^a (tm)_l \leq \psi_a \tag{29}$$

Variable specification: The decision variables y_c, y_r, y_t and y_l are Boolean indicating the existence or otherwise of a facility hence:

$$y_c,\ y_r,\ y_t,\ y_l \in \{0, 1\}$$

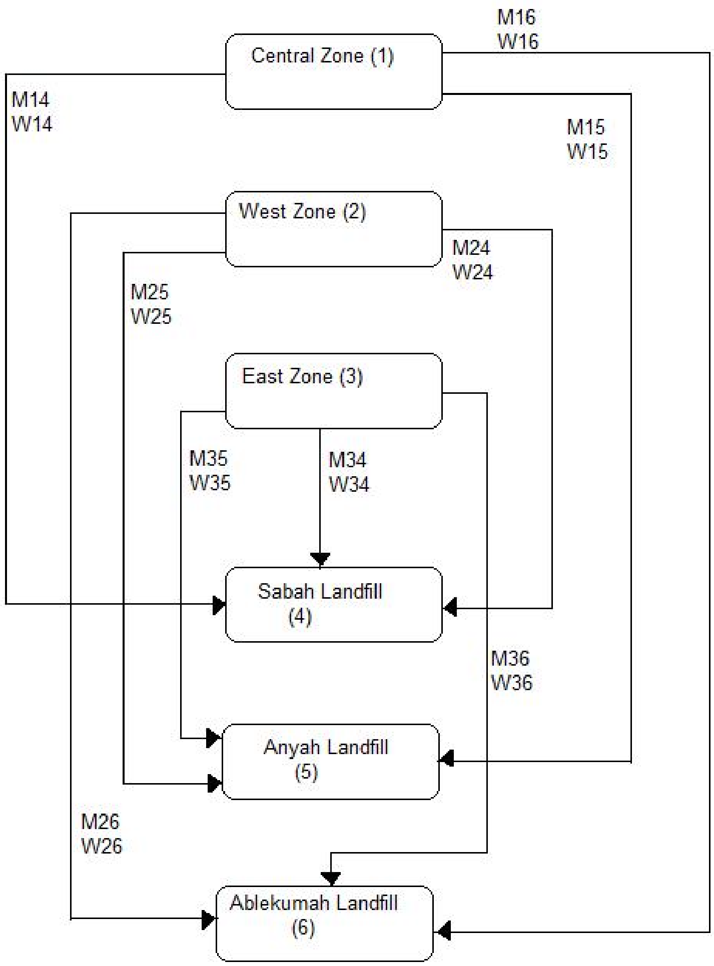

Fig. 2: Model diagram for first scenario

Furthermore, the expected number of truck required in transporting waste between the nodes in the model and the number of replacement trucks required each day are all positive integers. Thus:

$$x^i_{jcl}, x^i_{jrl}, w^i_{jsc}, w^i_{jsr} \in Y \text{ , where Y=\{0,1,2,...\}}$$

Finally, the flow of waste between node/facilities must be positive real numbers hence:

$$m_{sl}, m_{sc}, m_{sr}, m_{cl}, m_s, m_{rl}, m_c, m_r, (tm)_l \geq 0$$

Case study: Under the case study, two scenarios are considered, namely First Scenario and Second Scenario. In the first scenario, the model we have developed so far is tested with collection of waste from three zones/points and duping at three landfill sites as presented in Fig. 2. The second scenario involves addition of a compost plant and an additional landfill to the first scenario (Fig. 3).

The effect of the compost plant on the overall operation cost will be examined for different conversion factors, revenue per tonne of waste and the minimum revenue below which the plant should not be operated. The results will then be examined. It is important to note that the environmental aspect though considered in the model is omitted in the case study since data on emission of green house gases are not available. In addition, the metropolitan areas are grouped into three waste collection points/sources; Central Zone, East Zone and West Zones according to distance from waste sources (Table 1). Lingo solver will be used to solve the above minimization problems.

Input data: Table 1 to 6 provide the input data used to run the model for the case study. Unless otherwise stated, all costs are in Ghana Cedis (GC) and all numbers presented in brackets in the tables are expected number of trips trucks are expected to make between respective nodes in the model.

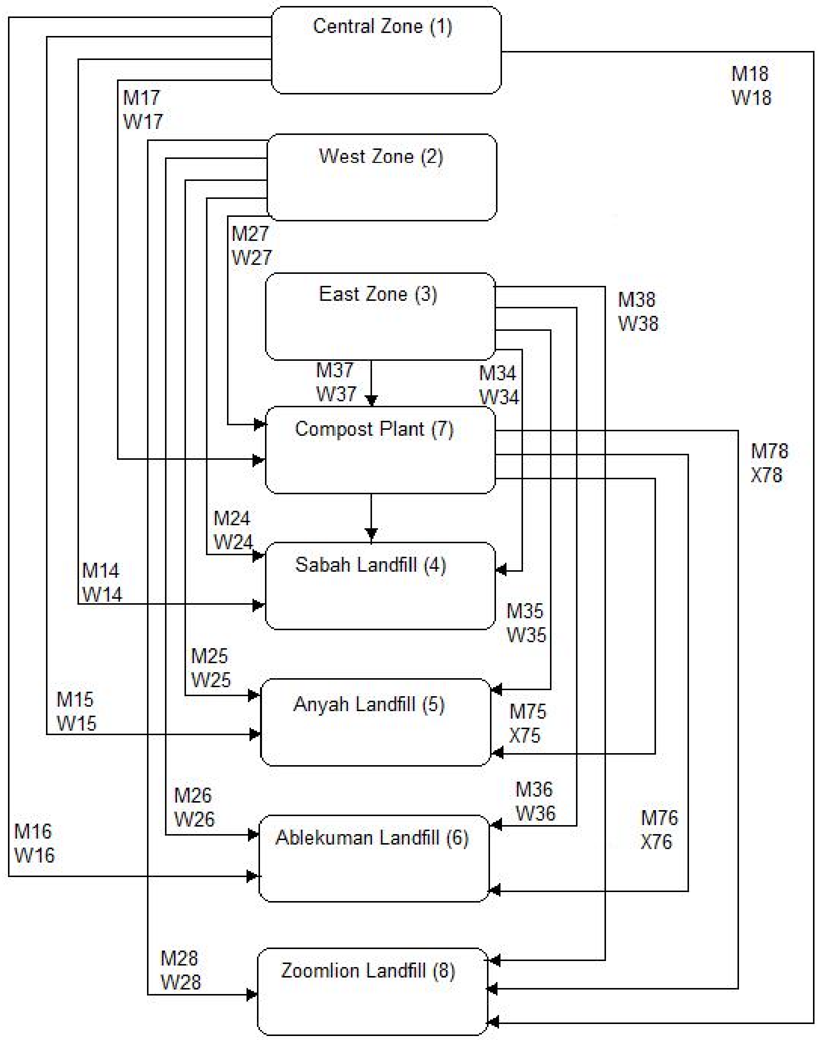

Fig. 3: Model diagram for second scenario

Table 2: Capacity of facilities (c)

Facility	Capacity(ton)
Truck	6
Compost Plant	900
Sabah Landfill	700
Anyah Landfill	600
Ablekuma Landfill	600
Zoomlion Landfill	700

Zoomlion Ghana Ltd. and Author

RESULTS

First case study: The solution to the problem shows that the minimum operation cost is Fifteen Thousand, Six Hundred and Ten Ghana Cedis, Five Pesewas (GH¢ 15,610.05). Appendix B for the solution of first case study.

In order to achieve this, sixty-nine (69) trucks are required. Out of these twelve trucks (6×8×12 = 576 ton capacity) are allocated to convey five hundred and sixty-four (564) tonnes of waste from Central Zone (1) to Sabah Landfill Site (4). No truck is allocated to convey waste from this source to Anyah Landfill (5) and Ablekuma Landfill (6) sites.

Four trucks (6×6×4 = 144 ton capacity) are allocated to convey one hundred and thirty-six (136) tonnes of waste from West Zone (2) to Sabah Landfill Site (4), four trucks (6×5×4 = 120 ton capacity) to convey one hundred and twenty (120) tonnes of waste from the same source to Anyah Landfill while twenty-three trucks (6×4×23 = 552 ton capacity) are made available to transport five hundred and forty-four (544) tonnes of waste from West Zone (2) to Ablekuma Landfill (6).

The remaining twenty-six (26) trucks representing (6×3×26 = 468 ton capacity) are allocated to transport four hundred and sixty-five (465.50) tonnes of waste from

Table 3: Unit transportation costs (v) and expected number of trips (presented in bracket) between waste sources and landfill sites

	Sabah (4)	Anyah (5)	Ablekuma(6)	Zoomlion (8)
Central (1)	3(8)	5(5)	6(5)	6(4)
West (2)	5(6)	6(5)	7(4)	6(3)
East (3)	9(2)	6(3)	8(3)	9(2)

Waste Management Department of AMA, Zoomlion Ghana Ltd., and Author

Table 4: Unit transportation costs (u) and expected number of trips (presented in bracket) between compost plant and landfill sites

	Sabah (4)	Anyah (5)	Ablekuma (6)	Zoomlion (8)
Copost Plant (7)	6(2)	4(3)	3(3)	1(5)

Waste Management Department of AMA, Zoomlion Ghana Ltd., and Author

Table 5: Unit transportation costs (v) and expected number of trips (presented in Bracket) between waste sources and compost plant

	Central (1)	West (2)	East(3)
Copost Plant (7)	3(3)	5(3)	6(2)

Waste Management Department of AMA, Zoomlion Ghana Ltd., and Author

Table 6: Fixed cost (p), variable costs (q), revenue per tonne (R_c), conversion factors (γ_c) and probability of truck breakdown (ρ_c)

Facility	p	q	P(i)	R_c	γ_c	ρ_c
Truck	45.5		0.1			
Compost Plant	3900	15		57	0.3	0.35
Sabah Landfill	300	0.8				
Anyah Landfill	250	0.8				
Ablekuma Landfill	250	0.8				
Zoom-lion Landfill	300	0.8				

Zoomlion Ghana Ltd., and Author

Table 7: Revenue per tonne, total revenue, objective value and total trucks

R_c (GH¢/ton)	OBJ(F)x10^{-3} (GH¢)	R_{ev} x10^{-3} (GH¢)	(NT)	M_7 (ton)
10.00	19.64	0.00	76	0.00
20.00	19.64	0.00	76	0.00
30.00	19.64	0.00	76	0.00
40.00	19.64	0.00	76	0.00
50.00	19.35	7.71	82	514.3
60.00	17.5	15.23	95	846.0
70.00	14.82	18.90	97	900.0
80.00	12.12	21.60	97	900.0
90.00	9.42	24.30	979	00.0
100.00	6.72	27.00	979	00.0

East Zone (3) to Anyah Landfill (5). In all, a total of one thousand eight hundred twenty-nine tonnes and five hundred kilograms 564+136+120+544+465.50 = 1829.50 ton capacity) is collected which is equal to the total amount of waste collected from the three sources daily.

Second case study: The minimum operation cost is Eighteen Thousand, One Hundred and Forty-Seven Ghana Cedis, Ninety-Nine Pesewas (GH¢ 18,147.99), which is higher than the value obtained in the first case study. This is due to the huge financial investment made in putting up the compost plant and the additional landfill site. Appendix C for the solution for the second case study.

In all eighty-seven (87) trucks are required. Out of these ten trucks (6×8×10 = 480 ton capacity) are allocated to convey four hundred and seventy-four (474) tonnes of waste from Central Zone (1) to Sabah Landfill Site (4). Five trucks (6×3×5 = 90 ton capacity) are assigned to convey ninety (90) tonnes of waste from Central Zone to compost plant. Six trucks (6×6×6 = 216 ton capacity) are assigned to convey two hundred and sixteen (216) tonnes of waste from West Zone (2) to Sabah Landfill Site (4), one truck (6×5×1 = 30 ton capacity) is allocated to convey twenty-six (26) tonnes of waste from the same source to Anyah Landfill site (5) while thirty-one trucks (6×3×31 = 558 ton capacity) are allocated to transport five hundred and fifty-eight (558) tonnes of waste from West Zone (2) to compost plant (7). Twenty-six (6×3×26 = 468 ton capacity) are allocated to transport four hundred and sixty-five tones and five hundred kilograms (465.50) from East Zone (3) to Anyah Landfill (5) site. The remaining eight trucks (6×5×8 = 240 ton capacity) are assigned to transport two hundred and twenty-six tones and eight hundred kilograms (226.80) of waste from the compost plant to the Zoom Lion landfill site.

The above procedure is repeated for different values of revenue per tonne of compost R_c, the total revenue generated from sale of compost R_{ev}, total number of trucks (NT) and amount of waste processed M_7. The same is done for different fractions of waste converted to compost (i.e., conversion factor γ_c), which is related to various levels of segregation of waste from sources and the results are presented in Table 7 and 8, respectively.

The results in Table 7 and Fig. 4 show that if the prevailing market price of the compost is less or equal to Forty Ghana Cedis (GH¢ 40.00), the compost plant must be shut down since no amount of waste is transported to

Table 8: Conversion factor, total revenue, objective value, waste processed and total trucks

γ_c	Obj(F)x 10^{-3} (GH¢)	R_{ev} x 10^{-3} (GH¢)	M_7 (ton)	(NT)
0.25	19.64	0.00	0.0	76
0.27	19.22	8.03	522.0	83
0.30	18.15	11.08	648.0	87
0.32	17.12	16.42	900.0	95
0.34	15.96	17.44	900.0	94
0.36	14.76	18.47	900.0	92
0.38	13.60	19.49	900.0	91
0.40	12.39	20.52	900.0	89
0.43	10.72	22.06	900.0	88
0.45	9.52	23.90	900.0	86

Table 9: Minimum revenue per tonne and corresponding conversion factor

γ_c	0.25	0.27	0.30	0.32	0.34	0.36	0.38	0.40	0.43	0.45
Rc (min)	59.5	54.5	48.5	45.0	41.5	39.0	36.5	34.0	31.5	29.5

the plant for processing and so no revenue is realized. At market value of Fifty Ghana Cedis per tonne of compost, about five hundred and fourteen (514) tonnes of waste is transported to the plant for processing resulting in generation of Seven Ghana Cedis, Seventy One Pesewas (GH¢ 7.71) revenue and subsequent reduction in the overall operation cost.

The market price of the compost serves as a driving force and as it increases, it forces more waste to the compost plant generating more revenue resulting in further reduction in the objective function value or the overall cost of operation. At a market value of Sixty-Eight Ghana Cedis (GH¢ 68.00) the overall operation cost reduces to Fifteen Thousand Three Hundred and Fifty-Eight Ghana Cedis, Fifty Pesewas (GH¢ 15358.50). This is a less than the minimum operation cost of Fifteen Thousand, Six Hundred and Ten Ghana Cedis, Five Pesewas (GH¢ 15,610.05) obtained in the first case study. It therefore follows that if the market value of the compost is above Sixty-Eight Ghana Cedis (GH¢ 68.00), the integrated model will be costing less to operate than the ``collection and dumping'' approach being used at the moment.

Table 8 shows the effect of conversion factor on the revenue from sale of compost, amount of waste (M_7) processed at the compost plant, the total number of trucks required for the operation and the overall operation cost. For twenty-five percent (25%) conversion of total waste processed to compost, no waste is conveyed to compost plant for processing (indicating the plant must not be operated at this conversion). No revenue is therefore generated.

The overall cost is Nineteen Thousand, Six Hundred and Forty Ghana Cedis (GH¢ 19,640.00) and the total number of trucks required is seventy-six (76). At twenty-seven percent (27%) conversion however, five hundred and fifty-two (552) tonnes of waste is transported to compost plant for processing resulting in increase in total number of trucks to eighty-three (83), revenue of Eight Ghana Cedis, Three Pesewas (GH¢ 8.03) and decrease in the overall cost to Nineteen Thousand, Two Hundred and Twenty Ghana Cedis (GH¢ 19,220.00). As more and more fractions of the total waste processed is converted to

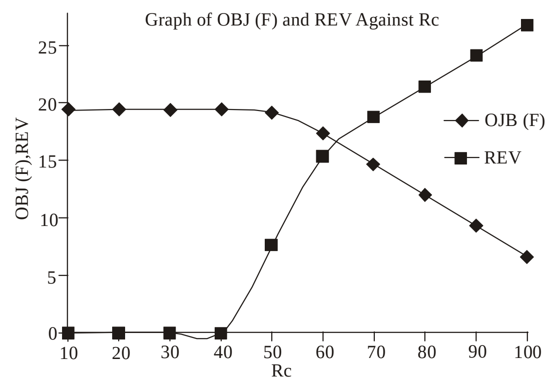

Fig. 4: Graph of objective value and total revenue verses revenue per tonne of compost

compost (i.e., as more separation is done at waste generation points), more compost is produced, revenue generated increases causing the objective function value or total cost to reduce significantly. Besides, as more waste is converted, the amount of unrecoverable waste that must be transport from compost plant to landfill sites reduces, thus prolonging life span of the landfills and therefore deferring the cost of acquiring new one. Moreover, fewer trucks are required to transport waste from the compost plants to the landfill site resulting in reduction in total number of trucks as the conversion factor increases from highest of ninety-five (95) to the lowest of eighty-six (86) trucks.

From Table 7 and 8, it is clear that for a fixed conversion factor there is a minimum amount, that one tonne of compost must be sold otherwise the compost plant must be shut down. Conversely, for fixed revenue (R_c) per tonne of compost, there exists a minimum conversion factor $\gamma_{c(min)}$ below which the compost plant must not be operated. To obtain the operation chart in Figure 5, the conversion factors are fixed at various values and the minimum revenue per tonne of compost is obtained from the solution. The results are tabulated and plotted as presented in Table 9 and Fig. 5. The curve shows strong correlation between R_c and γ_c (with correlation factor $R^2 = 0.9994$).

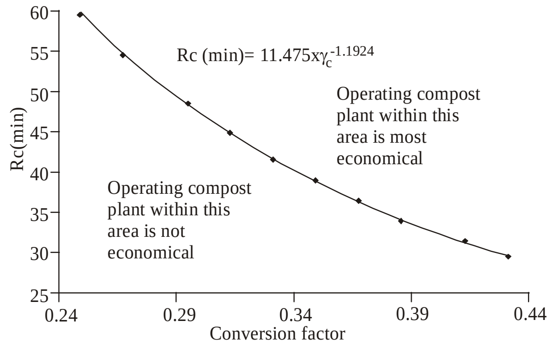

Fig. 5: Graph of minimum revenue per tonne of compost against conversion factor

It therefore follows that given the market price of compost (R_c) and the composition of waste or the fraction of waste that can be converted to compost (γ_c), one can use Fig. 5 to determine whether it will be more economical to shut down the compost plant than to operate it. This can be done by locating the point (γ_c, R_c) on the chart and if it lies below the minimum line, then it is not economical or cost effective to run the plant and so management can decide to shut it down. If the point lies above the minimum curve however, then the plant can be operated.

CONCLUSION

Increasing urbanization in the metropolis is making land acquisition for opening new landfill sites more difficult and expensive. At the moment, the waste management method used by the private waste management companies consists of only collection and dumping of waste at landfill sites causing the landfill to be used up within a short period of time as demonstrated in the first case study using the model developed.

In the second case study, integration of compost plant into the waste management programme diverts large volume of organic materials in the waste for processing into compost resulting in the following advantages over the first one: (i) Good planning and management of solid waste as the model will help allocate the optimal number of trucks required for the operations, determine the flow of waste between the nodes/facilities and indicate when a facility must be run or shut down in order to optimize operations. (ii) Reduction in the overall cost of waste management as a result of revenue generated from the sale of compost produced from the organic waste. (iii) Reduction in the quantum of waste sent to landfill sites thereby prolonging their life span and the subsequent deferring of the cost of acquiring a new one. (iv) Sustained cleaned environment since all waste generated will be collected and the decomposition of the organic components of the waste will occur under controlled conditions. This finding is significant because it emphasizes the need to adopt integrated approach to solid waste management in the metropolis.

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Appendix:

Appendix A: Average composition of waste generated daily

Waste type	Organic	Plastic	Metal	Paper
Percen-tages	65.0	3.5	2.5	6.0
	Glass	Textile	Inert	Others
Percen-tages	3.0	1.7	17.1	1.2

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Appendix B: Solution for first case study

Variable	Value	Variable	Value
NT	69.00	M35	465.00
TM4	700.00	M36	0.00
TM5	585.50	W14	12.00
TM6	544.00	W15	0.00
M14	564.00	W16	0.00
M15	0.00	W24	4.00
M16	0.00	W25	4.00
M24	136.00	W26	23.00
M25	120.00	W34	0.00
M26	544.00	W35	26.00
M34	0.00	W36	0.00

Global optimal solution found; Objective value: 15610.00; Total solver Iterations: 0

Appendix C: Solution for second case study

Variable	Value	Variable	Value
NT	87.00	M28	0.00
TM4	690.00	M38	0.00
TM5	491.00	M78	226.00
TM6	0.00	W14	12.00
M7	648.00	W15	0.00
TM8	226.00	W16	0.00
M14	474.00	W17	5.00
M15	0.00	W24	6.00
M16	0.00	W25	1.00
M24	216.00	W26	0.00
M25	26.00	W27	31.00
M26	0.00	W34	0.00
M34	0.00	W35	26.00
M35	465.00	W36	0.00
M36	0.00	W37	0.00
M17	90.00	W18	0.00
M27	558.00	W28	0.00
M37	0.00	W38	0.00
M74	0.00	X78	8.00
M75	0.00	X74	0.00
M76	0.00	X75	0.00
M18	0.00	X76	0.00

Global optimal solution found; Objective value: 18147.99; Total solver iterations: 588

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