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Article *in* Civil Engineering and Environmental Systems · June 2012

DOI: 10.1080/10286608.2012.672411

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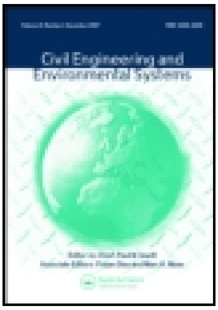

Civil Engineering and Environmental Systems
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gcee20

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To cite this article: A. S. Aremu & B. F. Sule (2012): A case study evaluation of the impacts of optimised waste bin locations in a developing city, Civil Engineering and Environmental Systems, DOI:10.1080/10286608.2012.672411

To link to this article: http://dx.doi.org/10.1080/10286608.2012.672411

Civil Engineering and Environmental Systems
2012, 1–10, iFirst

A case study evaluation of the impacts of optimised waste bin locations in a developing city

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(*Received 22 January 2011*)

This study was undertaken to evaluate the impacts of placing waste bins at optimal locations in the city of Ilorin, North Central Nigeria. The optimal locations of 1–10 waste bins were determined by the built-in solver for *p*-median problems in TransCAD v. 5.0 (Caliper, Corp.) software. The spatial performance of a particular number of waste bins created social, economic and environmental impacts which were evaluated from a combination of the attribute table from the *p*-median solution, solid waste generation data and collection operation data. The issues examined under these impacts were service coverage, public satisfaction, waste bin utility, costs associated with service provision and emissions from collection vehicles. The results indicate that service coverage and public satisfaction improved as the number of waste bins was increased from one to five. With 6–10 waste bins, 100% service coverage and public satisfaction was attained, however, some waste bins became underutilised. The service provision costs and emissions from the collection vehicle also increased as the number of waste bins increased. A multi-criteria analysis of these impacts can assist municipal authorities in achieving sustainable solid waste management.

Keywords: solid waste; optimised location; waste bin; developing country; impact

1. Introduction

Social, economic and environmental issues related to the management of solid waste pose challenges to municipal authorities and decision makers all over the world. These challenges are often felt more by developing countries even though municipalities spend 20–50% of their available recurrent budget on solid waste management, yet about 50% of the population is not served (World Bank 2009). Improving service coverage and efficiency of municipal solid waste collection activities within the urban spatial structure of developing countries has been a demanding task. This challenge is particularly encountered in the developing world because most of the urban settlements are characterised by high density, unplanned expansion of low-income settlements and ineffective control of land development (Cohen 2006).

In order to strengthen efforts to provide municipal solid waste management services to the populace, city authorities in developing countries, like Nigeria, place large moveable containers at designated service points along the shoulders of accessible roads for the storage of municipal

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ISSN 1028-6608 print/ISSN 1029-0249 online

http://dx.doi.org/10.1080/10286608.2012.672411
http://www.tandfonline.com

solid wastes. There are two aspects of the problem faced by the municipality in adopting this system. One aspect is that the waste generator is constrained to use the waste bin provided by the municipal authority at a designated service point. The second aspect is that the municipal authority has to allocate waste bins to different parts of the city, collect the waste bins, dispose the contents and return the empty waste bin to the service point. In this role, the municipal authority is faced with the challenge of efficient siting of waste bins in order to meet multi-objective targets.

Facility location models are among the main optimisation models used within public facility planning processes. These models are basically aimed at determining the most efficient location for all types of facilities according to one or more objectives such as cost minimisation and accessibility maximisation (Teixeira and Antunes 2008). However, these objectives are subject to physical, structural and policy constraints, in a static or deterministic setting (Current *et al.* 1997). Over the years, facility location models have been widely used for solving decision problems involving facility siting such as emergency service systems, communication networks, distribution systems, public, private and military facilities (Handler and Mirchandani 1979). The application of facility location models for spatial decision support in developing countries is mainly within the context of facilities that provide social services such as potable water, healthcare, education, sanitation and security (Oppong 1996). In the absence of such formal spatial decision, a political or pragmatic decision is made which is often far from the optimal solution (Smith and Rahman 2000). For numerous reasons, including inappropriate location of health and waste facilities, many urban areas in developing countries are deteriorating, with serious consequences for the residents.

For planning waste bin locations, Kao and Lin (2002) proposed the shortest service location model. The model was found to reduce the overlay of service areas and shortened the overall average walking distance to collection stops. However, the computation time by model is enormous because it involves many variables. The p-median problem is a commonly applied facility location problem which provides good solutions at reasonable computational expense and solution algorithms could be a part of general purpose software such as Geographic Information System (GIS) (Miller and Shaw 2001). More importantly, GIS serves as a significant aid in collecting and organising spatial data to heuristically solve p-median problems and display results (Church 2002).

In the context of determining the optimal service point (waste bin location) for the collection of municipal solid wastes, the p-median problem sites p waste bins among a set of m potential service points along a network to serve n waste generation points. For this purpose, a waste generation point is assigned to a municipal waste bin which is at the shortest distance from it. Vijay *et al.* (2008) presented a GIS-based algorithm which utilised the p-median problem for identification of optimised waste bin location and determination of the required number of waste bins to be sited. The algorithm also computes the command area of each waste bin based on shortest distance and descending slope. The application of this algorithm requires the specification of p value in the model.

However, if the value of p is specified to be large, it results in too many waste collection locations, underutilisation of waste bins and increased collection cost, while a low value of p in the model results in fewer waste collection locations, reduction in public satisfaction and environmental problems such as overflowing waste bins and litter. Additionally, spatial decision making problems, like that of waste bin location, often involve the consideration of several factors beyond simple distance or terrain. Conversely, factors such as level of acceptability of service, service coverage, air quality risks, frequency of collection, cost analysis for provision and collection of waste bins, and utility of waste bins for each choice of p needs to be determined for sustainability of solid management programmes. This study groups these factors under social, economic and environmental impacts, which are referred to as the triple bottom line of sustainability (Troschinetz and Mihelcic 2009, Mihelcic and Zimmerman 2010) and analyses the impacts of different numbers of waste bin at optimised locations.

2. The *p*-median formulation for optimisation of waste bin locations

The mathematical formulation of the *p*-median model to locate waste bins and allocate waste generators to them is given by the equation (modified from Miller and Shaw 2001):

$$\text{Minimise} \quad Z = \sum_{i=1}^{n}\sum_{j=1}^{m} w_i c_{ij} x_{ij} \tag{1}$$

$$\text{Subject to} \tag{2}$$

$$x_j - x_{ij} \geq 0, \quad i = 1, \ldots, n; \;\; j = 1, \ldots, m \tag{3}$$

$$\sum_{j=1}^{m} x_j = p, \tag{4}$$

where Z is the total weighted distance between waste generation points and service points,

$\{1, \ldots, n\}$ a set of solid waste generation points, $\{1, \ldots, m\}$
a set of potential service points where a waste bin could be placed,
w_i amount of solid waste generated at waste generation point i, $w_i > 0$
c_{ij} the shortest distance between waste generation point i and service point j

$$x_{ij} = \begin{cases} 1 & \text{If waste generation point } i \text{ is assigned to service point } j \\ 0 & \text{Otherwise} \end{cases}$$

$$x_j = \begin{cases} 1 & \text{If a waste bin is located at service point } j \\ 0 & \text{Otherwise} \end{cases}$$

and p the number of waste bins to be located

The assumption of the *p*-median is that the waste generator will patronise the nearest service point. Constraint (2) ensures that a waste generator is assigned only to one service point (the nearest service point). Constraint (3) allows a waste generator to be assigned to a service point if a waste bin is located at that service point. Constraint (4) allows exactly p number of waste bins to be sited. Solution methods for *p*-median problems include enumeration, graph theoretic, mathematical programming and heuristic procedures (Miller and Shaw 2001). Also some GIS software packages, such as ArcInfo and TransCAD, combine input database and algorithms to solve *p*-median problems.

3. Case study application

The city of Ilorin is the largest urban centre in Kwara State, Nigeria. Ilorin has a population of about 800,000 and is subdivided into three local government areas: Ilorin West, Ilorin East and Ilorin South. The city occupies an area of 89 km^2 and lies at a latitude 8 °30′N and a longitude 4 °35′E (Abdulrasaq 1998). A typical part of the city in Ilorin West Local Government Area bounded on all sides by roads was selected as the study area. The Kwara State Waste Management Company (KWMC) is the organisation responsible for the management of solid wastes within the city, including the study area. The company places fabricated metal roll on–roll off waste bins of capacity 7.54 m^3 on publicly accessible roads for the storage of municipal solid wastes and use medium-duty collection vehicles (Iveco Euro Cargo 100E18) to haul the waste bins.

4. Methodology

Field study was carried out to obtain demographic, solid waste and collection operation data. The map of the study area was digitised and all the information relevant to the study were georeferenced. The Facility Location Function in the GIS package, TransCAD v. 5.0 (Caliper, Corp.), was used to solve the *p*-median problem. The 'client' represents the waste generation point; the 'facility' represents the waste bin while the 'cost' is the distance between the waste generation point and the waste bin. The solution to the problem is for the model to generate the optimal location for waste bin(s), out of potential service points, with minimum sum of distance from waste generation points to the waste bin(s). The value of *p* was taken from 1 to 10 (placing 1–10 waste bins within the study area) and the attribute table for each solution was exported for analysis of the impacts.

Positive social impact forms the basis of most solid waste management programmes throughout the world. The strategy is to capture solid wastes generated from most parts of the city, fully utilise the waste bins and haul them to the disposal site. Also, public satisfaction on a provided social service is often considered a testimony of good governance. In this regard, social impact was measured as public satisfaction, service coverage and utilisation of individual waste bin. Public satisfaction is the number of waste generation points served within 200 m walking distance to the optimised waste bin location(s) in relation to the total number waste generation points in the study area. Service coverage is the amount of solid wastes captured by the waste bins in relation to the total amount of solid wastes generated in the study area. A waste bin is considered fully utilised if it receives enough solid waste to reach its full capacity within one week, otherwise it is considered underutilised.

Availability of financial resources is the key to sustainability of solid waste management efforts by municipalities in developing countries, hence, there is a need to reduce costs and improve service delivery. In this study, economic impact was measured in terms of the cost for purchasing waste bin(s) and the cost of fuel consumed during various unit operations involved in the collection activity. The fuel consumed by the collection vehicle during various stages of waste bin collection was obtained from the values reported by Nguyen and Wilson (2009), i.e. 3.15 l/h for stationary unit operations and 0.335 l/km for dynamic unit operations. The time spent on each of these unit operations was obtained from Aremu *et al.* (2010) while the distance from the optimised waste bin location to the disposal site was obtained from the digitised map of Ilorin metropolis.

Recent environmental and health concerns have placed priority on reducing emission of greenhouse gases (GHGs) and criteria air pollutants (CAPs) from human activities including solid waste management. Environmental impact within the framework of this study was measured in terms of the principal GHG emissions; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and CAPs; nitrogen oxide (NO_x), carbon monoxide (CO) and particulate matter greater than 10 μm in diameter (PM_{10}), associated with collection vehicles. Emission rates were assumed equal to the values quoted by Agar *et al.* (2007).

5. Results and discussion

From field studies, a total of 187 waste generation points including 113 residential buildings, 30 commercial buildings and 44 mixed dwellings existed within the study area. The output of solid waste from these land-use types is 843.38 kg and it was dispersed across the residential, commercial and mixed dwellings. The study equally identified 269 potential waste bin locations after eliminating unsuitable sites. The digitised map of the study area showing the waste generation points and potential waste bin locations along the shoulder of accessible roads is shown in Figure 1.

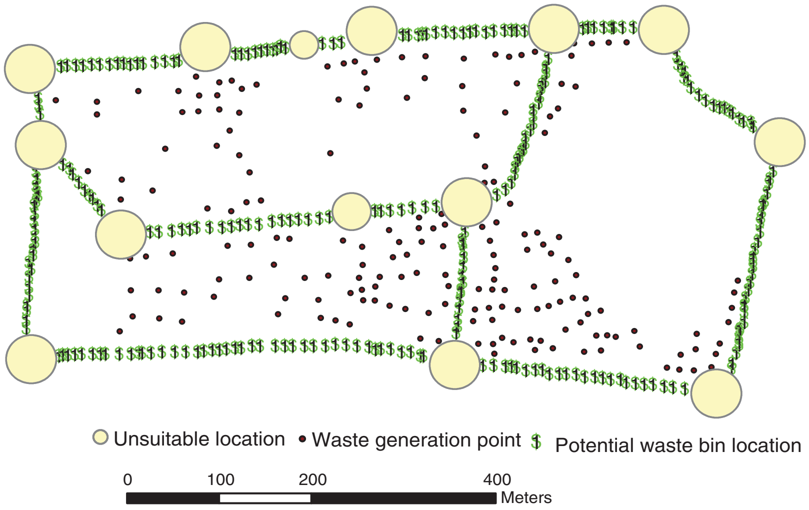

Figure 1. Digitised map of the study area showing waste generation points, potential waste bin locations and unsuitable sites for waste bins.

The result of 10 computer runs ($p = 1 - 10$) using the Facility Location Function in TransCAD v. 5.0 software gave the optimal location for siting 1–10 waste bins out of the 269 potential waste bin locations within the study area. From the result, as the number of waste bins increased, the walking distance to the optimised location of the waste bins decreased as presented in Table 1. It shows that shorter walking distance to service points is achievable with more number of waste bins at appropriate (optimised) locations.

The social impact in terms of service coverage (the percentage of solid wastes captured by each waste bin) and public satisfaction (the number of waste generation points served) is shown in Figure 2. As the value of p increased from 1 to 5, the percentage of solid waste captured by the waste bins at optimised locations increased from 55.83% to 98.20%. Also, the waste generation points served by the waste bins increased from 50.27% when $p = 1$ to 99.47% when $p = 5$. As an illustration, Figures 3 and 4 show the service coverage of waste bins when $p = 2$ and 4,

Table 1. Number of solid waste generation points within each range of walking distance to the waste bin at optimised location.

No. of waste bins	1	2	3	4	5	6	7	8	9	10	
Walking distance to waste bin (m)	No. of waste generation points covered										
0-50	10	16	17	28	33	37	46	42	51	57	Acceptable walking distance
51-100	28	41	53	65	74	78	76	105	103	103	
101-150	31	52	62	61	59	63	56	37	30	26	
151-200	25	31	30	22	20	9	9	3	3	1	
201-250	27	26	20	10	1	0	0	0	0	0	Unacceptable walking distance
251-300	14	8	4	1	0	0	0	0	0	0	
301-350	19	12	1	0	0	0	0	0	0	0	
351-400	18	1	0	0	0	0	0	0	0	0	
401-450	9	0	0	0	0	0	0	0	0	0	
451-500	5	0	0	0	0	0	0	0	0	0	
501-550	1	0	0	0	0	0	0	0	0	0	

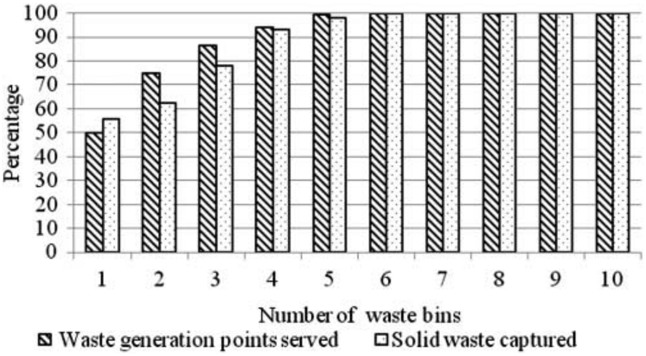

Figure 2. Percentage of solid wastes captured and waste generation points served by different numbers of waste bin at optimised locations.

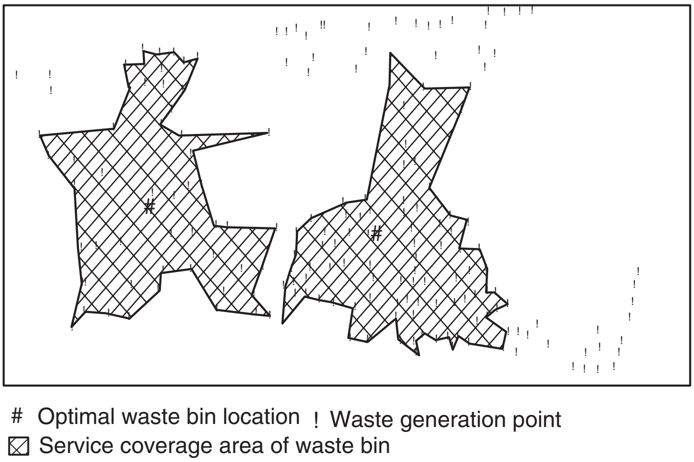

Figure 3. Optimised location of waste bins for $p = 2$ and waste generation points served by each waste bin.

respectively. For values of p greater than 5, the service coverage and public satisfaction was 100% as shown in Figure 5 when $p = 7$. Two waste bins became underutilised when $p = 6$ and the number of underutilised waste bins progressively increased to 7 when $p = 10$ (Figure 6). The collection frequency of the waste bins at optimised location was four times per week when $p = 1$, five times per week when $p = 2$, seven times per week when $p = 3$, 4, 5 and 6. However, since 100% service coverage was not achieved for $1 \leq p \leq 5$, the collection frequency of these waste bins is likely to increase because of waste deposits from unserved areas.

With regard to economic impact, the distance covered by the collection vehicle to haul different numbers of waste bins at optimised location per week and associated fuel cost is as shown in Figure 7. The total distance between optimised waste bin locations and the disposal site increased as the value of p was increased but a decrease was observed when $p = 5$ and 6 because these locations were closer to the disposal site. The total fuel consumed per week was derived by considering the distance of each optimised waste bin location to the disposal site, the collection frequency per week and the fuel consumed during various activities associated with collection operation. Generally an increase in the value of p results in an increase in the fuel cost per week. However, a commensurate decrease in the fuel cost (as a result of decrease in the travelled distance) was not found when $p = 5$ and 6 because the collection vehicle encountered more intersections during the trip; hence it consumed more fuel.

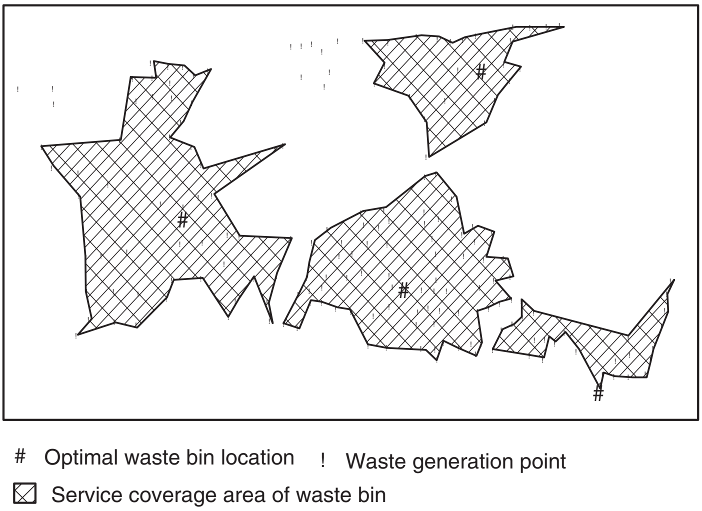

Figure 4. Optimised location of waste bins for $p = 4$ and waste generation points served by each waste bin.

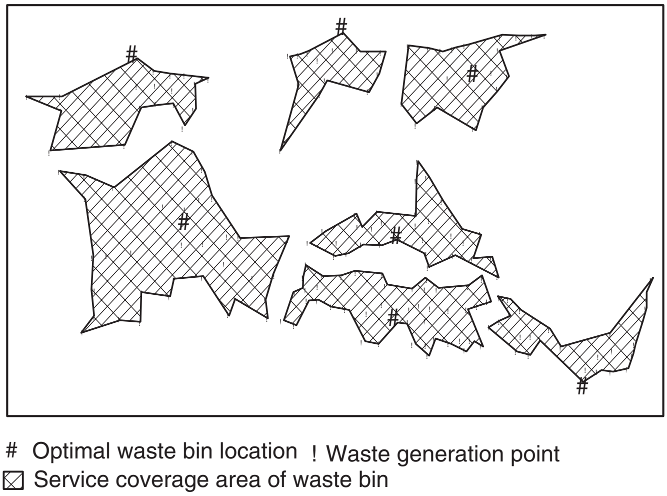

Figure 5. Optimised location of waste bins for $p = 7$ and waste generation points served by each waste bin.

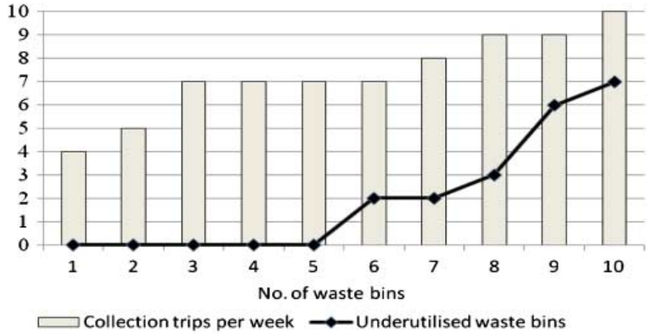

Figure 6. Weekly collection trips and number of underutilised waste bins versus number of waste bins.

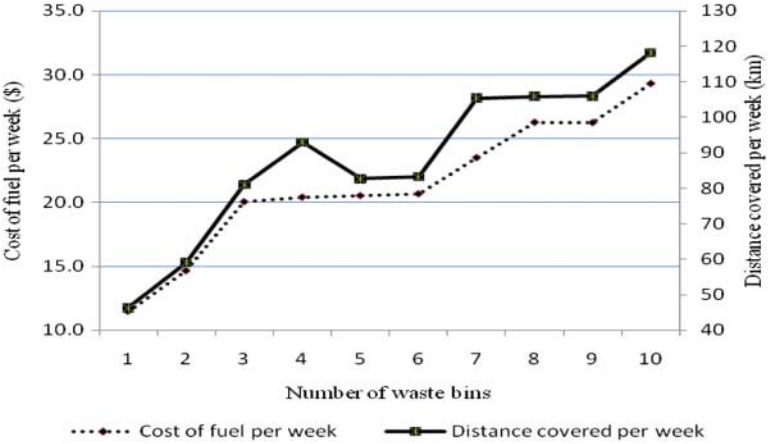

Figure 7. Weekly distance travelled by the waste collection vehicle and associated cost of fuel versus number of waste bins.

The expected emissions from the collection vehicles in terms of GHGs (N_2O, CH_4 and CO_2) and CAPs (NO_x, CO and PM_{10}) are shown in Figures 8 and 9, respectively. Within the GHGs, the amount of CO_2 emissions is about 10^4 times more than N_2O and CH_4 emissions. Also, within CAPs, CO and NO_x emissions are large compared to PM_{10} emission. GHG emissions cause global warming, which is the most burning and concerning issue nowadays (Hassan *et al.* 2010). The environmental and health impacts of generalised global warming include increased exposure to water stress, ecosystem instability, damage from floods and storms, morbidity and mortality, and decrease in cereal production (Mihelcic and Zimmerman 2010). CAPs are also responsible for asphyxiation and several cardiovascular problems, formation of ozone, acid rain, or snow, and visibility reduction. However, the calculated emissions in this study present a platform for comparison of expected emissions when different numbers of waste bins were sited without regard to the effects of the ambient concentration of these emissions. In this regard, the GHGs and CAPs increased as the value of p was increased.

A number of inferences can be drawn from the resulting impacts of the optimised waste bin locations within the study area. For example, social impact could be prioritised because it forms the basis for most solid waste management programmes throughout the world. The desire to prioritise social impact means capturing all the solid wastes generated from community, minimising underutilisation of waste bins and maximising public satisfaction. Within the context of the study area, the use of five or six waste bins at the present optimised locations is appropriate if social

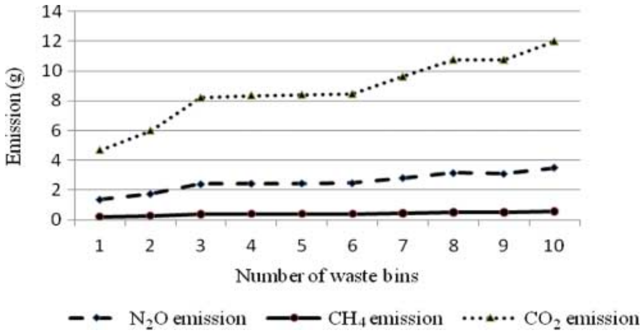

Figure 8. GHG emissions associated with the collection of various waste bin numbers at optimised locations.

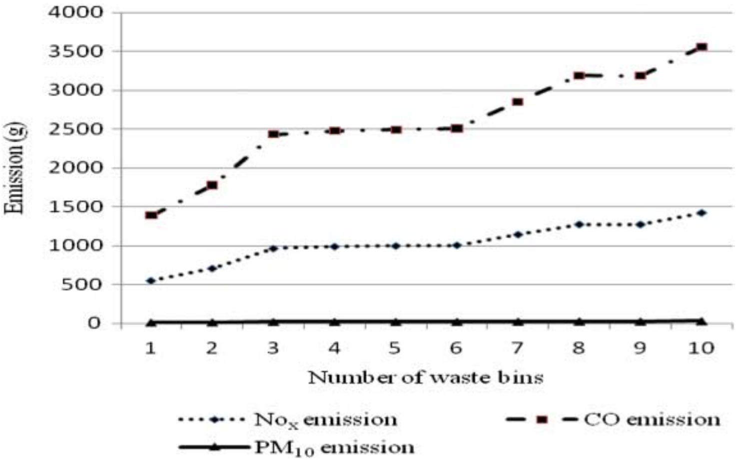

Figure 9. CAP emissions associated with the collection of various waste bin numbers at optimised locations.

impact is of the highest priority. The spatial location of the five waste bins optimised their capacities to produce zero underutilisation of waste bins, achieved 99.47% public satisfaction, 98.2% service coverage and produced less economic or environmental impact. The use of six waste bins resulted in two waste bins being underutilised, 100% public satisfaction and service coverage, and produced more economic or environmental impact. Several other waste bin numbers at optimised locations have varying impacts and tradeoffs could be made to determine the most appropriate number to be sited based on the available resources.

6. Conclusion

The application of an optimisation technique to locate waste bins within the existing spatial infrastructure of cities in developing countries is an avenue to improve municipal solid waste management. The spatial performance of waste bins at optimised locations creates social, economic and environmental impacts which form the pillar of sustainability for any waste management system. In this study, the built-in solver for *p*-median problems in the TransCAD v. 5.0 (Caliper, Corp.) software was used to determine the optimal location of 1–10 waste bins in a study area and the attribute table from the *p*-median solution was analysed to reflect the social, economic and environmental impacts of the optimised waste bin locations. The social impact in terms of service coverage and public satisfaction improved as the number of waste bins was increased from 1 to 5 while 100% service coverage and public satisfaction was achieved with 6–10 waste bins. The average walking distance to the waste bins decreased as the number of waste bins increased; however, some waste bins became underutilised when the number was increased beyond 5. The economic and environmental impacts of placing different number of waste bins within the study area also increased as the number of waste bins increased. The result of this study has shown that different numbers of waste bins at optimised locations have varying impacts. A multi-criteria analysis of these impacts can assist municipal solid waste management authorities to choose the most appropriate number of waste bins to be sited for a given service area.

Acknowledgements

We acknowledge the support of Dr. Joni Downs of the Department of Geography, University of South Florida, USA, who made the TransCAD software available for solving the *p*-median problem. We also appreciate the remarkable input of Prof.

James Mihelcic of the Department of Civil and Environmental Engineering, University of South Florida, USA. The authors also thank the U.S. Department; sponsor of the Fulbright Junior Staff Development program for their financial support to the lead author. Helpful comments and suggestions by anonymous referees and the Associate Editor are appreciated.

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