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DEVELOPING AND OPTIMISING AN URBAN INTEGRATED SOLID WASTE MANAGEMENT MODEL: EFFECT OF TRANSFER STATIONS

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Abstract: Solid waste management (SWM) is among the poorly rendered services in developing countries – limited resources, increasing population, rapid urbanisation and application of unscientific, outdated systems leads to inefficiency. Lack of proper planning and inadequate data regarding solid waste generation and collection compound the solid waste management problem. Given the large number of available waste management options and the inter-relationships among them, identifying SWM strategies that satisfy economic or environmental objectives is a complex task. The paper integrates the effects of transfer station(s) to a mathematical model developed for a municipal Integrated Solid Waste Management (ISWM) system and focusses on the effect of inclusion of transfer stations on the overall efficiency and cost-effectiveness of an ISWM system. The model then serves as decision support tool to evaluate various waste management alternatives and identifies the least cost optimal combination of technologies for the collection, transport, treatment and disposal of waste. The constraints include those linking waste flows and mass balance, processing plants capacity, landfill capacity, transport vehicle capacity and number of trips. The linear programming model integrating different functional elements was solved by LINGO optimisation software and various possible waste management options were considered during analysis.

Keywords: Municipal Solid Waste (MSW); Solid Waste Management (SWM); optimisation; linear programming (LP); transfer stations; Kolkata Municipal Corporation (KMC)

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INTRODUCTION

As the world races toward its urban future, the amount of municipal solid waste (MSW) is growing even faster than the rate of urbanisation. It is estimated that in 2012, globally about 3 billion urban residents generated waste at a rate of 1.2 kg per person per day (1.3 billion tonnes per year). By 2025 this will likely increase to 4.3 billion urban residents generating about 1.42 kg/capita/day of municipal solid waste (2.2 billion tonnes per year) (Hoornweg & Bhada-Tata, 2012).

Environmentally acceptable management of MSW has become a global challenge due to limited resources, increasing population, rapid urbanisation and industrialisation. In developing nations, these factors are further exacerbated by inadequate financial resources, poor management and technical skills within municipalities and Urban Local Bodies (ULBs). Rapid increase in volume and types of solid and hazardous waste as a result of continuous economic growth, urbanisation and industrialisation, is becoming a critical problem for national and local governments to ensure effective and sustainable management of waste.

The developing countries are fast shifting from agriculture-based nations to industrial and services-oriented countries. Due to continuous migration of population from rural areas to towns and cities, in India the share of urban population has increased from 10.84% in 1901 to 26.15% in 1991 to 31.2% in 2011 (Singh, 2014; Kumar, 2015). The urban population in India generated about 1,14,576 MT/day of MSW in 1996; 1,27,486 MT/day during 2011-12; and 1,44,165 MT /day during 2013-14 (CPCB, 2012; CPCB, 2015). According to Planning Commission (2014) estimates, the total quantity of waste currently handled each day in the urban areas is estimated to be 1,70,000 MT i.e. about 62 million MT annually. Per capita waste generation in Indian cities varies from 0.2 kg to 0.6 kg per day (Ministry of Finance, 2009) depending upon the size of population. An assessment has been made that per capita waste generation is increasing by about 1.3% per year (Bhide & Shekdar, 1998; Shekdar, 1999; Imura *et al.*, 2005). Economical and infrastructural constraints, limited availability of land for disposal, lack of awareness and technical manpower, results in inefficient urban solid waste management. Although municipalities in India devote 75-95% of their financial resources towards collection and transportation of waste, yet, MSW collection efficiency ranges between 70-90% in major metro cities while it is around 50% in smaller towns — the remaining waste remains unattended in streets, dumps and low-lying areas and pollute the urban environment (Sharholy *et al.*, 2008; Annepu, 2012). In many cases, waste bins overflow and invite pests, rodents, birds and animals and cause vector-borne diseases to the residents.

More than 90% of MSW collected is disposed off without any treatment in open dumps without following the principles of sanitary landfilling. Leachate produced by these open dumps contaminates ground and surface water resources (Tchobanoglous *et al.*, 1993) while methane generated from these landfills increase global warming effect (USEPA website; El-Fadel *et al.*, 1997; Talyan *et al.*, 2007). Besides these, landfill fires at these sites emit huge amounts of carbon monoxide, SO_2, NO_x, hydrocarbons, dioxins and furans causing air pollution hazards.

It is estimated that if the waste is disposed off without treatment, more than 1400 sq. km of land would be required in the country by the end of 2047 for its disposal of waste generated from 1997-2047 (Ministry of Finance, 2009). Considering a projected waste generation of 165 million tonnes by 2031, the requirement of land for setting up landfill for 20 years (considering 10 meter high waste pile) could be as high as 66,000 hectares of precious land, which our country cannot afford to waste (Planning Commission, 2014).

Although segregation at source is a pre-requisite for successful processing/treatment of waste, yet there is no organised and scientifically planned segregation of MSW in India either at household level or at community bins. Sorting and recycling of waste is mostly accomplished by unorganised sector i.e. ragpickers.

Most of the waste transportation vehicles employed by municipalities are old and without proper repair and maintenance. Running old vehicles without any scientific vehicle routing and planning, decreases waste collection and transportation efficiency and add pollutants to the air.

Waste disposed off in an unhygienic manner without any treatment not only deteriorates public health and degrades environment but also deprives the community of potential material and energy that could have been recovered prior to ultimate disposal. The untapped 62 million tons of waste generated annually in urban areas in India has a potential of generating 439 MW of power from 32,890 tons per day (TPD) of combustible wastes including Refused Derived Fuel (RDF), 1.3 million cubic metre of biogas per day or 72 MW of electricity from biogas and 5.4 million metric tonnes of compost annually to support agriculture (Planning Commission, 2014).

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LITERATURE REVIEW

Municipal solid waste management (MSWM) involves the application of the principle of Integrated Solid Waste Management (ISWM) (UNEP, 2009; ISWA, 2012; CPHEEO, 2000). ISWM is the application of suitable techniques, technologies and management systems covering all types of solid wastes from all sources to achieve the twin objectives of (a) waste reduction and (b) effective management of waste still produced after waste reduction. It is an easily-implementable and economically feasible comprehensive waste prevention, recycling, processing and disposal program that can effectively address and manage solid wastes.

Solid waste management is a multidisciplinary field requiring information about the physical, environmental, social, and economic implications of a SWM system. The ISWM approach is designed to minimise the initial generation of waste through source reduction, then through reusing and recycling to further reduce the volume of materials being sent to processing and landfills, compared to the conventional approach of simply focusing on disposal of solid waste. System analysis, a discipline that harmonises these ISWM strategies provides interdisciplinary support for SWM decision-making.

The first-generation solid waste management models used LP optimisation with a single objective optimisation scheme i.e. cost optimisation. These LP models considered only waste flows from transfer station to landfill sites and tend to minimise the partial costs involved in a SWM system (Anderson, 1968). Since then, several researchers have developed solid waste management models as decision-support tools for processing technology selection, siting and sizing of waste processing facilities, vehicle/ manpower management and overall system optimisation.

Different models of waste planning have been researched and applied in the SWM field in the following decades. The primary considerations involved are cost control, environmental sustainability and waste recycling. The techniques employed include linear programming (Christensen & Haddix, 1974; Fuertes *at al.*, 1974; Jenkins, 1982; Jacobs & Everett, 1992), mixed integer linear programming i.e. MILP (Badran & El-Haggar, 2006; Huang *et al.*, 1997), multi-objective programming (Sushi & Vart, 1989; Chang *et al.*, 1996), nonlinear programming (Huang at al., 1995a, 1995b), as well as their hybrids, which involve probability, fuzzy set and inexact analysis (Li & Huang, 2009; Huang & Cai, 2010; Piresa *et al.*, 2001). Due to complexity of the problem, research reports on nonlinear programming problems for solid waste management are scarce; some exceptions are Or & Curi (1993), Sun *et al.* (2013). In some of the works (Huang at al., 1995a, 1995b) the nonlinear objective functions are converted into linear functions or simplified into quadratic functions under some adopted conditions and assumptions.

Linear programming is the most basic form of SWM modeling; the objective function is linear and the constraints comprising of equalities and inequalities are linear too. Cost is generally taken as the most appropriate objective function. The downside of LP models are that they may involve too many variables and constraints which affect computational time. In *mixed integer linear programming* models, some of the variables are constrained to be integers. *Inexact analysis* often treats the uncertain parameters as intervals with known lower and upper bounds and unclear distributions. In real-life problems, while the available information is often inadequate and the distribution functions are often unknown, it is generally possible to represent the obtained data with inexact numbers that can be readily used in the inexact programming models. However, traditional binary analysis methods for inexact linear programming and inexact quadratic programming involve unavoidable simplifications and assumptions, which often increased the chance for error in the problem solving process and adversely affected the quality of the results. Moreover, a more complex model often increases error in the solution and often produces less optimal results (Jin *et al.*, 2017). We have developed a basic LP model which is easy to understand and debug in LINGO optimisation solver; however during inclusion of transfer stations a few variables have been constrained as integers.

Daskalopoulos *et al.* (1998) had developed a MILP model for the management of different MSW streams, taking into account their rates and compositions, as well as their adverse environmental impacts. Using this model, the authors have identified optimal combination of technologies for handling, treatment and disposal of MSW in a more economical and environmental-friendly way. In this model, the optimal MSW flows to different types of treatment alternatives are determined by minimising a linear cost function. Constraints for the objective function are the capacity-constraints of the treatment plants and landfill site. Environmental costs were calculated based on greenhouse gas emissions and their global warming potentials. However, the model does not cover collection and transportation costs, which accounts for nearly 70-80% of total MSW management costs in developing economies.

Badran & El-Hagar (2006) had proposed a MILP model for optimal management of municipal solid waste at Port Said, Egypt. The idea is to choose a combination of collection stations from the possible locations in such a way as to minimise the daily transportation costs from the districts to the “collection stations”, and then from the collection stations to the composting plants and/or landfills. The constraints for the objective function (i.e. cost) are the capacity constraints for collection stations, composting plants and landfills. However, recycling, incineration and RDF plants as well as regulatory and environmental constraints have not been considered in this model.

Najm *et al.* (2002) had introduced optimisation techniques to design least cost solid waste management systems, considering variety of management processes. Their LP model accounts for solid waste generation rates, composition, collection, transportation, treatment, disposal as well as potential environmental impacts of various MSW management techniques. Environmental costs were determined based on the value that the society places on environmental damage which was assumed equal to the cost of abatement and remediation of potential pollution.

Costi *et al.* (2004) had proposed a mixed integer, non-linear decision model to plan the municipal solid waste management, defining the refuse flows that have to be sent to recycling /processing/ disposal units, suggesting the optimal number, the types and the siting of the plants. The objective function takes into account all possible economic costs, whereas constraints arise from minimum requirements for recycling, incineration process requirements, sanitary landfill conservation and mass balance. The model has been formulated considering stringent European legislation guidelines for MSW management concerning waste minimisation, recycling, energy and material recovery, and final disposal at landfill. Regulatory, technical and environmental constraints had been comprehensively covered in their model. However, unlike our model, Costi *et al.* (2004) had included waste flows from RDF-plant and stabilised organic matter treatment plant to incinerator. A very similar type of model was presented by Fiorucci *et al.* (2003), except that Costi *et al.* (2004) had incorporated the environmental impacts of solid waste management system as well in their model.

Rathi (2007) had developed a linear programming model to integrate different options and stakeholders involved in MSW management in Mumbai. Different economic and environmental costs associated with MSW management were considered. In the model, the author had taken into account community compost plants, mechanical aerobic compost plants and sanitary landfills as waste processing/disposal options while environmental costs were primarily taken from California Integrated Waste Management Board (1991) literature. Shortcomings in this model include absence of transfer stations even though distance from source to landfill exceeds 40 km in some cases, non-consideration of waste-to-energy treatment plants and certain costs taken directly from foreign literature. With quantity and quality of MSW undergoing sharp changes in the last few decades, waste-to-energy treatment plants are being actively promoted by policy-makers in India.

Rawal *et al.* (2012) had divided the study area into zones — each zone has a ward which is the ‘waste centre’ or ‘waste source’; this is similar to our work — we have assumed borough centres as waste generation points. They proposed a VRP (Vehicle Routing Problem) method that first minimised MSW collection vehicle routes. The optimised collection points were further utilised in the development of optimised model formulations. They compared two models — one, integer-linear (IL) programming program, where variables are the number of trucks and the other, mixed integer linear (MIL) program where variables are the amount of waste actually transported. However, in this model, stabilised organic material plant construction and operation cost and environmental cost have been excluded.

Although sufficient literature is available worldwide linking ISWM and operations research, yet not much work has been carried out in India in this field. Again, most of the ISWM mathematical models proposed in developed countries lacks in collection and transportation constraint details, although a major fraction of total SWM budget is spent on this. Also, unlike our model, a majority of the available literature has not considered separate sorting station, transfer station facilities and separate collection and transportation of inerts.

Environmental costs have not been considered in this present model, since environmental valuation can be very subjective depending on perspectives and methodology adopted. Also not much literature is available in environmental cost studies in Indian context. The present model not only decides waste flows to various processing plants and landfill but also decides the number and types of transport vehicles required under optimised conditions. Further, using this model we have tried to locate optimised siting of transfer stations (clubbed along with the treatment plants).

MODEL DESCRIPTION

Integrated Solid Waste Management (ISWM) is considered for a city with proper segregation and treatment along with the following basic assumptions:

i. Borough (administrative divisions of municipality) centres have been assumed as the waste generation points.
ii. Proper segregation done at source by providing two bins – one for biodegradable waste and the other for non-biodegradable waste. Source

segregation of waste has been suggested in CPHEEO Manual on Municipal Solid Waste Management (2000) and made mandatory as per CPHHEO Municipal Solid Waste Management Manual (2016).

iii. Intermediate/Central sorting (ICS) facility to be provided from where recyclable material will be sent for recycling. Revenue can be earned by selling the recyclables from recycling facility. Necessity of sorting station(s) for successful processing has been highlighted both in CPHEEO Manual 2000 as well as in CPHEEO Manual 2016.

iv. Garbage enters central/intermediate sorter and subsequently to the different processing plants, while silt/rubbish goes straight to landfill without sorting or processing.

v. Treatment and disposal of garbage will be done as per its characteristics — like high calorific value of waste may go for incineration and biodegradable organic waste for composting. In all treatment techniques, pre-sorting facilities will be there for further segregating the inert and recyclable from the waste coming from central sorter. Inert, process rejects and residues from treatment plant will go to engineered landfill.

vi. The municipality uses departmental and hired vehicles to transport wastes. Departmental vehicle takes garbage fraction only while hired vehicles transport both garbage and silt/rubbish (silt and garbage are not mixed, but collected separately).

vii. There are different types of departmental vehicles but only one type of hired vehicle.

Assumptions vi and vii makes the model closely resemble the secondary waste transportation system in Kolkata area (Chattopadhyay *et al.*, 2009; Hazra & Goel, 2009).

viii. The city is divided into zones for each dumpsite. KMC pays departmental vehicles on the basis of trips made, while privately-owned vehicles are paid on the basis of waste amount transported to landfill sites. For disbursal of payment, KMC has divided Kolkata into several zones — zones nearer to landfill have lower payment rates; while faraway zones have higher rates.

ix. Minimum and maximum number of trips of departmental vehicles as well as for hired vehicles is fixed for each zone.

x. The departmental vehicles will have to undertake certain minimum number of trips for each zone.

xi. The drivers and helpers of departmental vehicles will be paid incentives if they carry out more than minimum number of trips. Hired vehicles will be paid on the basis of tonnage of waste they transport to the dumpsites.

Assumptions ix to xi are made so that the model simulates the prevalent practice adopted by KMC administration for vehicle/fleet management during secondary collection and transportation of waste.

xii. For running the model, average waste generation data of the boroughs of the concerned municipality needs to be considered.

xiii. Based on average waste actually carried by different types of vehicles from different boroughs, borough-wise minimum and maximum garbage carrying range (in fraction) for both departmental and hired vehicles need to be fixed. This makes the model flexible and more realistic.

xiv. Environmental costs of the processing plants and landfilling has not been taken into account.

Based on the above assumptions, a material flow chart (**Fig. 1**) for every 100 MT of garbage generated at source has been developed. Out of this 100 MT MSW generated, 5 MT of waste components is segregated and recycled at household level; the rest 95 MT enters the

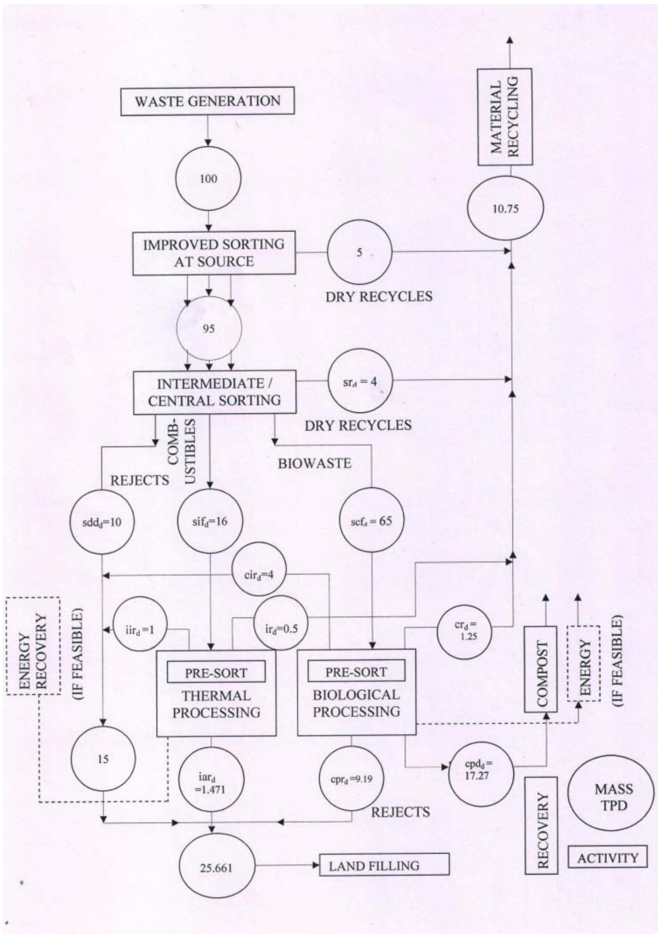

Fig. 1 Material flowchart for garbage fraction.

central sorting facility of a dumpsite and is subjected to different processing techniques present within that dumpsite. The silt/rubbish fraction collected separately by the hired vehicles will head straightway to the landfill site located within each dumpsite, without passing through sorter/incinerator/composting plant.

Let us assume the general case where the city has *D* numbers of dumpsites at *D* locations. Each dumpsite *d* has one central sorting station, one incinerator, one composting facility, one landfill and one recycling facility. From the central sorting facility, one stream is recycled to recycling facility, while other streams may go to incinerator, composting plant, or landfill as per the material flow chart illustrated in the **Fig. 1**. The incinerator and composting unit has pre-sorting units attached to them, so as to increase the efficiency of these processes. From these pre-sorting units, a small recyclable fraction may be dispatched to recycling facility while the inert fraction may be taken directly to landfill. Notations used to denote input values and variables are reported in the Appendix.

We need to minimise the total cost of solid waste management. The objective function, taken as the total cost of solid waste management, may be expressed as:

$$\begin{aligned} &\textit{Objective function} = CTRANSP + CINCENT + CTCX + CTCS + CTCI + \\ &CTCC - CTREVR - CTREVC - CTREVI \end{aligned} \tag{1}$$

where *CTCX*, *CTCS*, *CTCI*, *CTCC* are the total land-filling cost, sorting cost, incineration cost and composting cost for all dumpsites *d*.

The developed ISWM LP-model has been elaborated in Paul (2018) and Paul *et al.* (2019).

CURRENT SWM STATUS IN KOLKATA AND APPLYING THE MODEL FOR THE CITY

The city of Kolkata (formerly Calcutta) is more than 300 years old and it served as the capital of India during the British governance until 1911. Kolkata (**Fig. 2**) is the capital of the Indian state of West Bengal; and is the main business, commercial, and financial hub of eastern India and the north-eastern states. Kolkata (latitude 22° 33′ North and longitude 88° 30′ East) has an area of about 187.33 sq. km and a population of about 10 million (including floating population).

In Kolkata, the major disposal ground is Dhapa (21.47 ha) located in the eastern side of the city. It receives about 3000-3200 MT of solid waste per day. Another site at Garden Reach (3.52 ha) receives only about 100-150 MT of solid waste per day. Considering putrescible nature of waste, collection and disposal has to be done on a daily basis. In the early morning hours, conservancy staffs arrive at their assigned areas with handcarts and blow their whistles requesting residents to deposit wastes in their handcarts. The handcarts are then taken to the nearby vat/container locations and MSW is

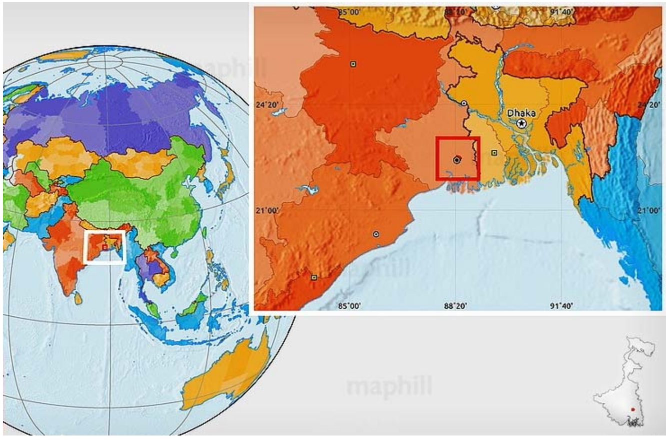

Fig. 2 Location of Kolkata city, West Bengal, India (image extracted from www.maphill.com).

transferred to the vats/container locations. Total collection points in the city is around 650 with 365 mild-steel MS skips/containers, 20 direct loading, and 265 open vat points (Chattopadhyay *et al.*, 2009).

Currently, waste transport system utilises private-owned lorries to transport 40% of the daily generated garbage and entire amount of the silt/rubbish. Haulage capacity of these vehicles is currently 7 MT for garbage and 9 MT for silt, assuming waste is being loaded onto these lorries using payloaders. Each lorry visits open vat location(s) and after their haulage capacity is exceeded, the vehicles proceed to the dumping ground.

The remaining 60% of MSW (garbage only) is transported by six categories of KMC-owned vehicles. Of late, KMC has embarked on modernising its waste transportation fleet by purchasing compactors and the transportation system has undergone remarkable change over the last few years.

- Container carrying vehicles (Dumper-Placers): One Dumper-Placer (DP) can hoist and transport only one skip/container at a time to the disposal ground. KMC currently uses two types on skips— 4.5 m^3 size (1.75 MT haulage capacity DP) and 7 m^3 size (2 MT haulage capacity DP). DD1 and DD2 refer to 1.75MT and 2MT Dumper Placer respectively.
- Payloader loaded Tipper Trucks (11m^3), DD3: These trucks haul around 7.0 MT of MSW in one single trip to Dhapa.
- Stationary compactor-cum-hook loader combination (10.5m^3/9MT), DD4: KMC is purchasing 198 stationary compactors to be placed at 85 compactor stations. These compactors reduce 30% waste volume by applying 140 bar pressure. KMC is also acquiring 54 hook loaders, to haul these stationary compactors to Dhapa. Each hook loader can haul one stationary compactor at a time.
- Movable compactors (14m^3/10MT). DD5: KMC is purchasing 64 numbers of 14m^3 capacity movable compactors. It takes waste from six 4.5m^3 skips (or

Table 1. Average physical composition of municipal solid waste (considering garbage fraction)

Total compostables	Recyclables				Others including inerts						Total
	Paper	Plastic	Glass	Metal	Inert in garbage	Rubber and Leather	Rags	Wooden matter	Coconut	Bones	
50.56	6.07	4.88	0.34	0.19	29.60	0.68	1.87	1.15	4.50	0.16	100
50.56	11.48				37.96						100

(All values are expressed in percentage on wet weight basis)

- from handcarts), compact it at 140 bar pressure, and hauls waste to the landfill site.
- Movable compactors ($8m^3$/7MT). DD6: KMC is purchasing 4 numbers of $8m^3$ capacity movable compactors. These smaller sized compactors can manoeuvre narrow streets and lanes.

Waste is simply dumped and spread at the landfilling sites by the dumpers without any sorting, treatment and/or compaction. Only a minor fraction of waste is segregated and recycled at household level and by ragpickers at vats and landfills. KMC spends 70 to 75% of its total SWM budgetary allocation on collection of solid waste, 25 to 30% on transportation, thus leaving a meager 5% for final disposal. On an average, 305 vehicles collect and transport waste to disposal ground daily, out of which 105 are KMC-owned and 200 are private hired vehicles.

Currently, there is no incinerator/RDF plant in Kolkata. Neither waste segregation/sorting exist nor is sanitary landfilling practiced. A 700 MT/d compost plant running on PPP (public-private partnership) model at Dhapa disposal ground processes only 150 MT/d during most of the times. However, with the Ministry of Urban Development, Govt. of India promoting and funding "Swachh Bharat Mission" in a big way, one expects SWM will be managed in a more modern and scientific way in very near future. "Swachh Bharat Mission" envisages capacity augmentation of urban local bodies (ULBs), 100% collection, transportation and processing of solid waste and private-public partnership (PPP) in setting up and operation of waste processing units. This will require re-organising and overhauling the entire SWM system for Kolkata. The paper thus proposes an ideal ISWM system model for Kolkata having two-bin system at household level, sorting stations (ICS), processing plants (incinerators, composting plants), transfer stations and sanitary landfills but with the same waste characteristics and waste transportation infrastructure as currently exist—with the ultimate goal to optimise the overall cost of such an SWM system.

Considering the fact that landfill space for Dhapa has already got exhausted, we propose setting up of three dumpsites at North (near Akandaberia, Haroa), South (near Kalicharanpur village, Nepalgunj) and East (near Noara, Bodura) of Kolkata. Paul *et al.* (2014) in their article on landfill site selection had detailed the logic and methodology followed in shortlisting these three dumpsites. A borough may find it economic to divert its waste to any of the North, South or East dumpsites as dictated by our model. Each dumpsite has a central sorting station, an incinerator, a composting plant and a sanitary landfill facility. The shortest path distance between each borough center (assumed to be waste source) and dumpsite has been calculated using Geographic Information System (GIS). Based on these shortest path distances, the waste transportation costs for departmental and hired vehicles have been computed. **Fig. 3** shows the borough divisions of KMC area, their centers and the three proposed dumpsites.

Present physical composition of Kolkata waste (garbage portion only) and the recyclable portion at sources/vat points/landfills are illustrated below in **Table 1** and **2** (Chattopadhyay *et al.*, 2007, 2009; Paul *et al.*, 2019).

From data presented in **Table 1** and **Table 2**, we have calculated the amount of total recyclable materials, total input material for the incinerator and total input for composting plant located at each of the proposed dumpsites, considering a total garbage generation of 100 MT (depicted in **Table 3**).

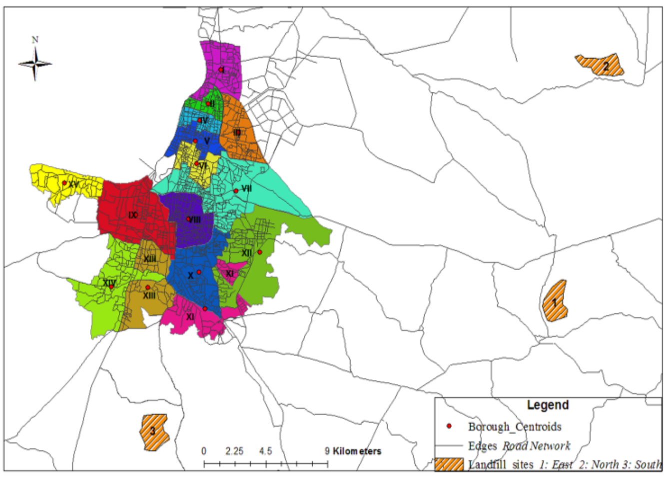

Fig. 3 Figure showing KMC borough divisions with their centers, the three proposed dumpsites and road network. 1, 2 and 3 are the dumpsites at East, North and South respectively.

Table 2. Proportion of recyclable materials in garbage in Kolkata at present

Materials	Original Composition	Recyclable portion at source and at landfill site
Paper	6.07	5.00 (82%)
Plastic	4.88	3.38 (70%)
Glass	0.34	0.27 (80%)
Metal	0.19	0.15 (80%)
From others:		
Rubber & leather	0.68	0.41 (60%)
Total	**12.16**	**9.21***

*Out of this 9.21%, about 5% is recycled at household level and 4.21% is recycled by ragpickers in the existing system

Table 3. Quantity of garbage entering different processing plants for each 100MT garbage generation

Operations	**Quantity (T)**
Sorter (ICS)	95
Total recyclable (including recyclables from pre-sorters)	10.75
Input for thermal processing	16
Input for composting processing	65
Total inerts	29.6

The LP model simulating the SWM system in a city was validated using Kolkata Municipal Corporation 2007 actual datasets. The optimisation problem was solved on a computer (Intel Pentium Dual-Core processor having 1.86 GHz processor speed, Windows XP OS) using LINGO v 9.0 optimisation software package. The present paper integrates the effect of transfer station as well, and endeavours to locate the transfer station in such a way that the overall waste management cost is optimised.

SOLVING THE MODEL FOR A FUTURISTIC SCENARIO

Data on MSW management in India is not easily available; also costs of the various functional elements of MSW tend to vary across municipalities over the country. We have calculated values of cost-related decisions variables and parameters taking into account our experience of present day (2015) costs in KMC, literature pertaining to other municipalities in India, government reports, DPR (detailed project reports) of proposed SWM projects, etc. The basis of these calculations are detailed in Paul (2018). We now propose certain optimised waste management options (referred below as 'cases') which Kolkata city can imbibe in near future.

Case 1: No capacity constraints on processing plants and landfill site

In this case, we have considered all the six types of vehicles run by KMC at present, and considered all the three dumpsites open. We have fixed minimum capacity of all sorters, incinerators, composting plants, landfill as zero, while assuming sufficient high values for their maximum capacity — thus encouraging the model to run without any constraint. Under such circumstances, the total cost of model-optimised SWM system came out as Rs. 22,88,205 /day and the total transportation cost (CTRANSP) was Rs. 25,77,367/day.

Analysis results of waste quantity (garbage + silt) transported to different dumpsites and subsequently subjected to different processing techniques (garbage) is shown in **Fig. 4**. It has been observed in Case 1 that, 97.79% waste is directed to the South dumpsite, and the rest 2.2% to the North dumpsite — this happens because the South dumpsite is the nearest.

Introducing Transfer Station in the ISWM

Transfer stations have been introduced in between the route from borough collection points to the dumpsite. Three transfer stations are located, each transfer station associated with a particular dumpsite. It is assumed that along with the transfer station, there will be sorter, incinerator and composting plant; the landfill sites will, however, be located at the original dumpsites. No extra land cost for setting up of incinerator and composting plant need to be accounted for, since land cost is already incorporated in the operational costs of incinerator and composting plant — only their locations have shifted from dumpsite to transfer station. Garbage portion from the city will enter the processing plants and then the disposable waste (includes process rejects/residues, ash, inert, etc) will be transferred from transfer station to dumpsites (landfill sites) for landfilling by Heavy Duty trucks. Silt/inert/rubbish may be directly loaded to the Heavy Duty trucks and transferred to landfill site. Due to the introduction of the transfer station, the modeling equations need to be modified, since fuel cost, fixed running and fixed idle cost of the Heavy Duty Trucks have to be taken into account. Cost of transfer station is ignored, since no equipment or processing is expected inside the transfer station. It has also been assumed that waste entering transfer station attached to dumpsite *d* will proceed to that particular dumpsite *d* only, after processing.

Total cost of transportation of wastes, CTRANSP can be found out from:

$$CTRANSP - ctchh - \sum_{dd=1}^{DD} ctcdd_{dd} - ctctrucks = 0 \quad (2)$$

ctctrucks is the total cost of transporting disposable waste from transfer station to the dumpsite landfills by the heavy duty trucks.

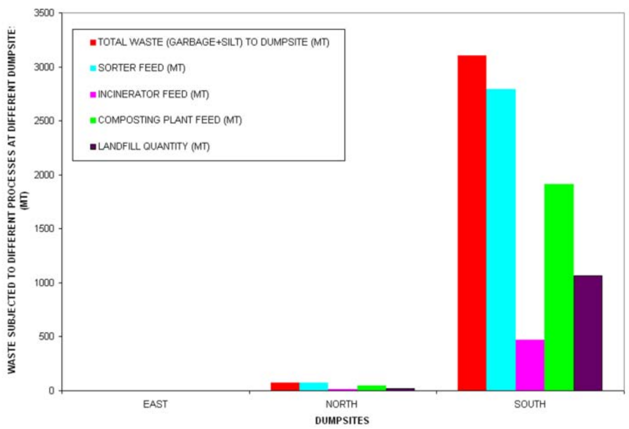

Fig. 4 Waste quantity entering different dumpsites and processing plants (Case 1).

The following equations need to be appended: Total cost of transporting waste from transfer station to the respective dumpsite (landfill) *d* by the heavy duty trucks:

$$ctctrucks - cfueltruckstot - cfxdrtruckstot - cfxditruckstot = 0 \tag{3}$$

cfueltruckstot is the fuel cost of the heavy duty trucks used for transporting disposable waste from transfer station to dumpsite landfills. Similarly, *cfxdrtruckstot* and *cfxditruckstot* are the fixed running cost and idle cost respectively of the heavy duty trucks.
Total fuel cost of the heavy duty trucks:

$$cfueltruckstot - \sum_{d=1}^{D} xf_d \times fc\_t_d = 0 \tag{4}$$

fc_t_d is the fuel cost per ton of waste transported by heavy duty trucks from transfer station associated with dumpsite *d* to dumpsite (landfill) *d* (Rs/MT).
Total fixed running cost of heavy duty trucks:

$$cfxdrtruckstot - t\_na \times t\_rc = 0 \tag{5}$$

t_na is the number of heavy duty trucks actually running considering all the three dumpsites. t_rc is the fixed running cost per truck.
Total fixed idle cost of heavy duty trucks:

$$cfxditruckstot - (t\_no - t\_na) \times t\_ic = 0 \tag{6}$$

t_no is the total number of heavy duty trucks considering all the three dumpsites. t_ic is the fixed idle cost per truck.
Number of trips per day for each heavy duty truck associated with dumpsite *d*:

$$xf_d \le trips\_truck_d \times no\_trucks_d \times cap\_truck \quad \forall d = 1, 2, ..., D \tag{7}$$

$trips\_truck_d$ is the number of trips per day each heavy duty truck associated with dumpsite (and transfer station) *d* is required to make. no_trucks_d is the number of heavy duty trucks associated with dumpsite (and transfer station) *d*. cap_truck is the payload capacity of a heavy duty truck (MT). Total number of running heavy duty trucks:

$$\sum_{d=1}^{D} no\_trucks_d - t\_na = 0 \tag{8}$$

Case 2: Transfer stations at midway between boroughs and dumpsite

With the help of Google Earth suitable places for the construction of three transfer stations associated with the three dumpsites were located. The East transfer station is located at Bhatipota (22°30´27" N, 88°32´00"E) on Kolkata-Malancha Road, North transfer station at New Town, Rajarhat (22°37´59" N, 88°27´56"E) on SRCM Road and South transfer station at Kabardanga, Ramchandrapur (22°27´39" N, 88°20´01"E) on Nepalgunje-Julpia Road respectively. The locations of these three transfer stations at East, North and South are shown in **Figs 5–7** respectively. The shortest route and distances between the borough centres and transfer stations were re-calculated using Network Analyst of ArcGIS.

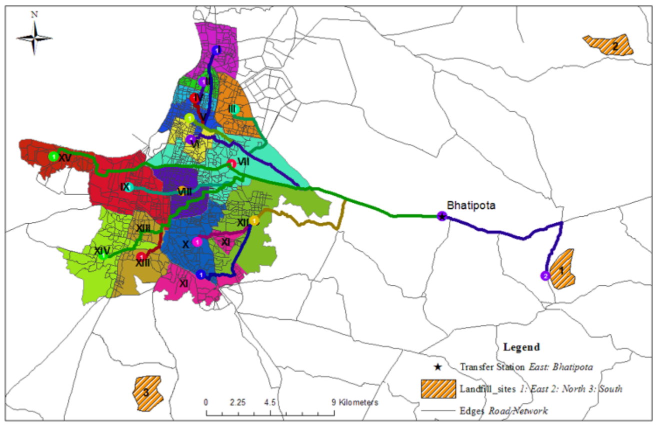

Fig. 5 Figure showing location of East transfer station along with shortest route from borough centres to transfer station and from transfer station to East dumpsite (landfill).

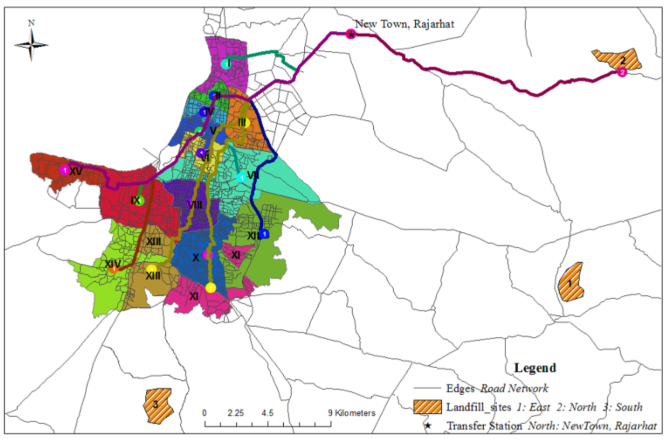

Fig. 6 Figure showing location of North transfer station along with shortest route from borough centres to transfer station and from transfer station to North dumpsite (landfill).

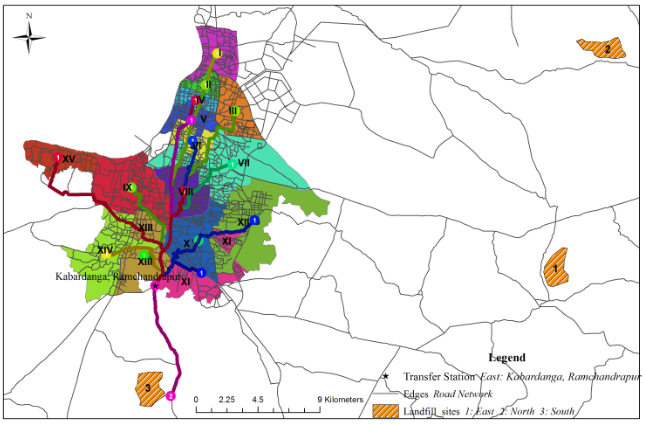

Fig. 7 Figure showing location of South transfer station along with shortest route from borough centres to transfer station and from transfer station to South dumpsite (landfill).

In the case of transfer station at midway, it was decided that each Heavy Duty truck will operate maximum 4 trips at East, 4 trips at North and 5 trips at South. The total number of such trucks operating is the input data, while the program is free to choose the number of trucks required in the East, North and South direction — so as to optimise the total cost for a particular input of total number of trucks. Operation and maintenance cost of composting and incineration includes the loading charge of process reject and inert waste to the Heavy Duty trucks for transportation from transfer station to landfill site. Under such circumstances, the total cost of model-optimised SWM system came out as Rs. 18,33,638 /day and the total transportation cost (CTRANSP) was Rs. 21,44,603/day. An examination of the output results reveals that out of the 12 running Heavy Duty trucks, 3 trucks are required in the North while remaining 9 are required in the South but no trucks are needed in the East.

Analysis results of waste quantity (garbage + silt) transported to different dumpsites and subsequently subjected to different processing techniques (garbage) is shown in **Fig. 8**. 78.37% of waste enters South transfer station/dumpsite, since for most of the boroughs, it is the nearest.

Case 3: Transfer stations located very near/within KMC boundary

In this case, the North and East transfer stations are taken close to the KMC boundary or even inside the KMC area to analyse its effect on SWM cost. The East transfer station is located at UttarpanchannaGram (22°32′02" N, 88°23′50"E), near Science City, North transfer station at Ghughudanga-Pearabagan (22°37′11" N, 88°23′38"E) and South transfer station at Kabardanga, Ramchandrapur (22°27′39" N, 88°20′01"E) on Nepalgunje-Julpia Road, respectively. The location of the South transfer station is kept same as that in the earlier case, since it is already on the KMC boundary. The locations of these three transfer stations are shown in **Fig. 9**, **Fig. 10** and **Fig. 11**.

In the case of transfer station near/within KMC boundary, it was decided that each Heavy Duty truck will operate maximum 4 trips at East, 3 trips at North and 5 trips at South. Under such circumstances, the total

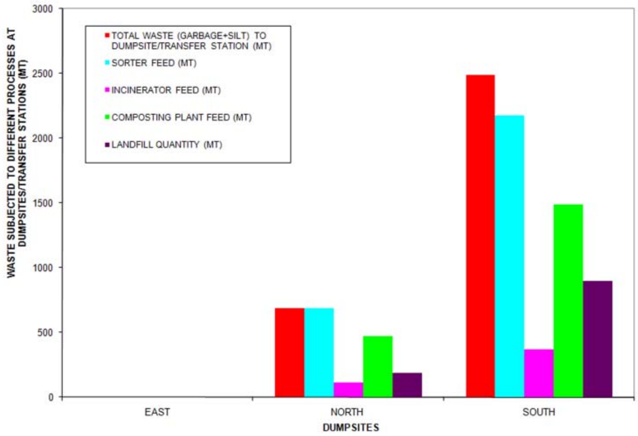

Fig. 8 Waste quantity entering different transfer stations/dumpsites and processing plants (transfer station midway).

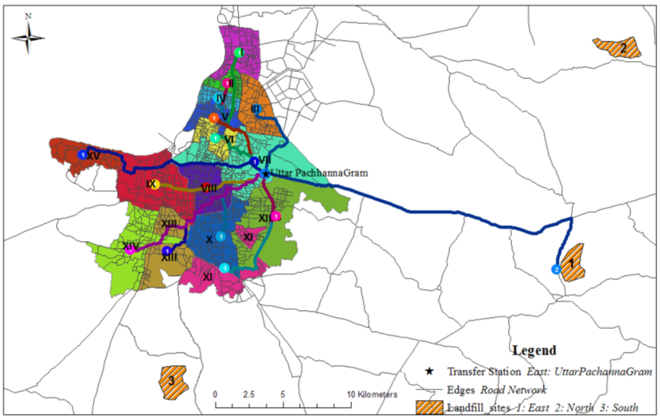

Fig. 9 Figure showing location of East transfer station along with shortest route from borough centres to transfer station and from transfer station to East dumpsite (landfill).

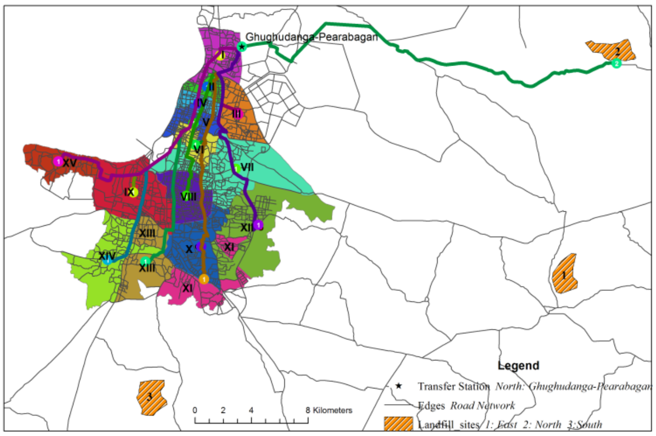

Fig. 10 Figure showing location of North transfer station along with shortest route from borough centres to transfer station and from transfer station to North dumpsite (landfill).

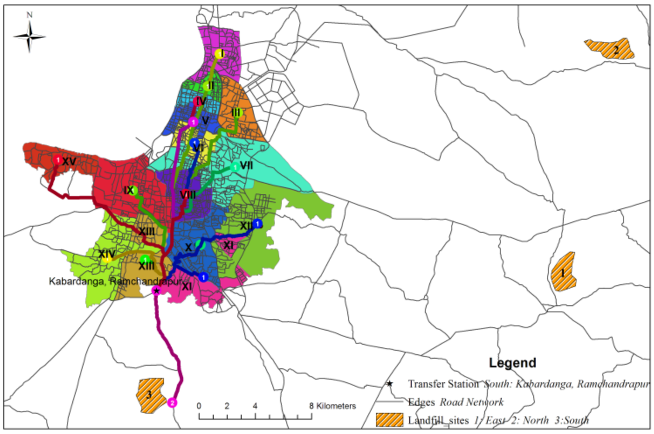

Fig. 11 Figure showing location of South transfer station along with shortest route from borough centres to transfer station and from transfer station to South dumpsite (landfill).

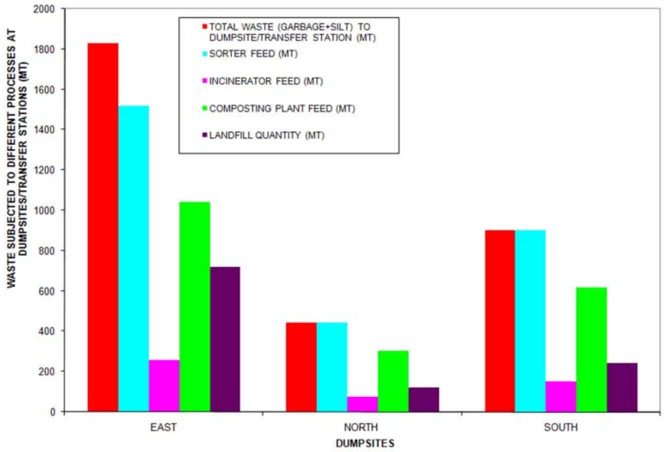

Fig. 12 Waste quantity entering different transfer stations/dumpsites and processing plants (transfer station near/within KMC boundary).

cost of model-optimised SWM system came out as Rs. 16,39,421/day and the total transportation cost (CTRANSP) was Rs. 19,48,341/day. An examination of the output results reveal that out of the 14 running Heavy Duty trucks, 9 trucks are running in the East while 2 trucks are running in the North and 3 in the South direction. **Fig. 12** illustrates that 57.62% of waste has entered East transfer station, while 13.99% and 28.3% of waste has entered North and South transfer station respectively.

DISCUSSION

The aim of this research is to provide comparisons between optimised ISWM solutions, vis-à-vis with and without transfer stations, with special emphasis in the context of the scenario in a developing country like India. The model presented below, is quite generic in nature, and can be applied to any city in a developing country after accommodating their datasets with small alternations and modification. It is readily applicable to any metro city in India, considering the fact that the pattern of MSW management system is almost similar throughout India. However, for validating and running the model and performing analysis, Kolkata Municipal Corporation (KMC) datasets are being used.

The model was first validated using 2007 KMC datasets. During 2007, there was only one dumpsite in Dhapa, while there were no sorting /incineration /engineered landfill facility; a composting plant occasionally processed 150 MT/day of waste. Overall SWM cost in 2007 as predicted by the model is Rs. 9,86,836.10/day (15,182 USD/day) while the actual cost was Rs. 10,66,867.93/day i.e. 16,413.35 USD/day (7.5% deviation).

The overall SWM cost is Rs. 22,88,205/day (35,203.15 USD/day) and the total cost of O & M (including land cost, construction cost) of the waste treatment plants (viz. sorter, composting plant, incinerator) is Rs. 11,68,935.4/day (17,983.62 USD/day) for Case 1. Although the cost of waste treatment is high yet, it is to be appreciated that the treatment plants are responsible for 66% of waste reduction. Such a huge amount of waste reduction increases lifespan of landfills and saves land resources; additionally the treatment processes along with recycling earns a revenue of Rs. 16,84,376.99 /day (25,913.49 USD/day). Since only process rejects, inert, incineration ash and silt are transported to the engineered landfill sites, chances of methane generation and leachate contamination will be less. Considering methane’s global warming potential and leachate’s polluting effect on water resources, the environmental cost benefit of proposed ISWM model added to the revenues earned will surpass the O & M costs of these treatment plants. For Case 1, almost the entire waste is transported to the South dumpsite, since it is the nearest and per MT waste transportation cost is the least. Also, 1960 MT (61.76%) of waste undergoes composting compared to 482 MT (15.2%) of waste which goes to the incinerator.

To further optimise the SWM cost, transfer stations have been introduced in between KMC area and dumpsites. The local transportation vehicles (DD1, DD2, DD3, DD4, DD5, DD6 and HH) will transport waste upto transfer station. From transfer station, inert, process rejects and silt will be transported to the landfill site by Heavy Duty trucks. Transfer stations set up midway between KMC area and dumpsites (Case 2) will decrease overall SWM cost by 19.86% and transportation cost (includes local vehicles transportation cost and long-haul vehicles transportation cost) by 16.79% as compared to Case 1. 78.37% of waste is transferred to the South transfer station while 21.62% waste enters North transfer station. Majority of the waste enters South transfer station, because for most of the boroughs, distance of borough centre to South transfer station is the least.

In Case 3, the transfer stations are shifted near/within KMC boundary; overall SWM cost (including transfer station cost) and transportation cost decreases by 25.26% and 24.4% respectively w.r.t Case 1. It can thus be concluded that the local transportation cost upto transfer station has a greater impact on SWM cost than long distance hauling cost — and hence it is more profitable to locate transfer stations close to the city boundary. Under such circumstances, 57.62% of waste has entered East transfer station, while 13.99% and 28.3% waste has been directed to North and South transfer stations respectively.

CONCLUSION

The overall objective of the present study was to develop a linear programming model that aids in planning an ISWM system and identifies the most cost-effective SWM option. The aim is to assist decision makers by providing an optimum waste management system given the available data and constraints. The model thus serves as decision support tool to evaluate various waste management alternatives and obtain the least-cost combination of technologies for handling, treatment and disposal of municipal solid waste. The paper specially dwells on the role of transfer stations in minimising overall SWM cost and underlines the importance of proper location of transfer stations in an ISWM system.

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