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Network Optimization of Solid Wastes Management in Chennai, India: case study

Sanjeevi V [a*], Shahabudeen P [b]

[a]*Director, Vellore Institute of Technology (VIT), Katpadi Road, Vellore, Tamil Nadu, 632014. India*
[b] *Department of Industrial Engineering, College of Engineering, Anna University, Sardar Patel Road, Guindy, Chennai 600025. India*

Abstract: *The purpose of this research is to present the current status of solid wastes flow in Chennai and optimize the cost of handling solid wastes. The city limits was extended form 175 km^2 to 426 km^2 in 2011, leading to sub optimum levels in solid waste management of 4840 tons per day. There is also pressure on city managers to reduce the cost of transport of solid wastes, due to shrinking budgetary allocations. In the changed scenario, there is need to examine the need for the current 12 transfer stations (TS) and also routing of solid waste transport vehicles. The existing TSs was set up historically without taking into account optimality. A linear programming model was developed to arrive at eight optimal transfer stations. The implementation of the proposal will bring in an annual saving of US$ 3.52 Million, about 33.1 percent of the analyzed transport, space and handling cost.*

Keywords: *integrated solid waste management, transfer stations, optimal locations, handling costs, linear programming and Chennai Optimal Transfer Stations for Integrated Solid Wastes Management in Chennai Metropolitan Area, India*

I. Introduction

Worldwide, 120 to 130 billion tons of natural resources are consumed every year and 4 billion tons of municipal solid wastes (MSW) are generated as well (Chalmin and Gaillochet, 2009). An amount of US$ 410 billion per year is spent from collection to recycling of solid waste (SW). The SW per year in India is likely to reach 260 million tons by 2047, which is more than 5 times of the current level (Essaku et al., 2007). With shrinking budgets for various city managements across the world, the mission is to increase the collection of waste with least cost (Rogoff et al., 2004). Currently most of the Solid Waste management (SWM) is being carried out using open cycle waste management systems, instead of closed cycle systems (Hina Zia and Devadas, 2008). Rapid paced and unplanned industrialization, population growth, increase in the living standards of the population, and technological developments been adding to the woes of solid wastes management issues in cities across the world. The urban population in India is up from 300 million in 2001 to 395 million in 2011 (Katkar, 2012). The trend is almost the same in all developing countries. According to the State of the World Cities Report of the UN-HABITAT (UN-HABITAT, 2010a, 2010b), more than 70 per cent of the global GDP comes from cities.Failure of the Integrated Solid Waste Management (ISWM) could jeopardize public health. Solid wastes contaminate groundwater as well as surface water and increases air pollutants, leading to miserable living conditions. This put enormous pressure on the research, academic and administrative systems of city managements. There is an urgent need to look in to the issues of ISWM and also improve the ability of city administrators to manage ISWM with the least cost. Transport cost alone comes to more than 50 per cent of the total costs incurred in ISWM in major cities of the developed world. However, in the developing countries (Ghose et al., 2006), about 85 per cent of the total costs is being spent on collection and transport. In Corporation of Chennai, the SW collection and road sweeping cost (mostly manual) comes to 62 percent and transport cost is 22 per cent of the total SWM costs (Annual Budget of the Corporation of Chennai, 2014-15).In the present research, for minimizing the transport and handling costs of SWM, the authors apply Linear Programming for optimization of the number of transfer stations for the entire city.

II. Research on optimization models

According to Komilis (2008), there are fundamentally three nodes in SWM systems, namely, the generation node, the intermediate node and the sink node. As per the USEPA (1977), the setting up of intermediate nodes or Transfer Stations (TS) become viable when the distance between the generation nodes (City Wards) and the sink nodes or the Dumping Yards (DY) ranges from 24 km to 32 km. However, the optimum distance may differ from city to city, depending on the local topology and transport economics. In such systems, the collected solid wastes are delivered at the transfer stations and then high capacity haulers or multi-axle vehicles haul the solid wastes to the dumping yards.

Optimization for the handling of SWM was first applied in California (Andersen, 1968). As per Abou Najm et al (2002) and Abou Najm and El-Fadel (2004) with increasing complexity in solid wastes management in the cities of the developing world, selection or setting up of an optimum solid waste management system becomes difficult for technical and operation research professionals. This led to the use of various mathematical models and systems analysis techniques to develop integrated solid wastes management systems. These models fall into categories such as linear and non-linear programming, multi-criteria decision analysis using Geographical Information Systems (GIS), and simulation optimization models (Chang and Wang, 1996). The solid wastes management models developed over the last five decades are with different goals and methodologies. Of these, most of researchers focused on the use of linear and non-linear programming models for MSWM. And with increasing pressure on city managements to minimize the cost of MSWM, cost reduction exercises become vary crucial. Barlishen and Baetz (1996) developed an optimization study using mixed integer linear Programming for facility location. Nema and Modak (1998) developed an Integer Linear Programming model to minimize total costs in handling hazardous waste management systems. Bhat (1996)focused on allocation of trucks in the handling of MSW using simulation models. Karagiannidis et al (2003) developed a simulation based GIS for optimally locating Solid waste management facilities. Paily (2006) applied a Linear Programming model to optimally locate transfer stations given various disposal sites. Yeomans (2007), Sarika Rathi (2007), Rodionov and Nakata (2011), Bernd Noche et al. (2010) and Markovic et al. (2010),used Linear programming models for designing an optimal and sustainable Solid Waste Management Systems for various cities such as Ontario (Canada), Mumbai (India), St. Petersburg (Russia), Duisburg (Germany), and City of Nis (Serbia) respectively. A very useful review on the development of various decision support systems for cost reduction in MSWM, using various optimization systems are presented by Ohri and Singh (2010). The review article by Rajendra K. Kaushal et al. (2010) brought out the current challenges in terms of cost reduction needs in India. In the opinion of Chatzouridis and Komilis (2012), however, only limited research work appears to exist, on the methods to optimally locate and allocate transfer stations, when the available data are only on the generation and on the sink nodes.

In the present paper, the authors analyze the status of waste management in the Chennai Metropolitan Area (CMA) and developedtwo methods, one, a linear programming methodology to optimize the cost of managing the Municipal Solid Wastes Management (MSWM) network, and the other ArcGIS application for optimal routing. The purpose of this research is to optimize the cost of handling and transport of solid wastes from the 200 city wards to 12 transfer stations and to the two dumping yards in the CMA. As the city wards and dumping yards are 'fixed', and the available space within the Corporation is limited to the existing transfer stations, there is need to optimize the number of transfer stations and determine their ideal locations.

The discussion in the paper is in four commissioned parts, namely, (a) the study area and the solid wastes, inclusive of solid waste flows and the current network for collection, transport and disposal, (b) the linear programming model for optimizing transfer stations and reducing cost of handling, (c) the optimal locations for transfer stations and discussion on the model results, and (d) recommendations towards an integrated solid wastes management system for the CMA.

III. Chennai and Solid Wastes

Chennai earlier called as Madras, established as a Corporation in the year 1688 by the East India Company, is one of the oldest municipal corporations in India. Thepresent research has been conducted in the area governed by the Corporation of Chennai(CoC) or,administratively, called as CMA. Chennai is the fourth largest metropolitan city in India. It is the capital of the State of Tamil Nadu and is located on the eastern coast (12° 85' N 80° 13' E and13° 23' N 80° 34' E),and covers an area of 426 km^2 with a current population of 7.1 million (Census 2011). As per the Annual Report of the CoC, CMA has about 1.4 million households and about 1,136 notified slums. Chennai is divided into 15 administrative zones and 200 city wards(Figure 1).Tables 1 provide the names of the various zones and the wards attached to each zone.The map giving details of Zones , Transfer stations, Dumping yards, Ward- Centroids of CMA are given in Figure 2 and the list of zones along with the wards attached to each zone is given in Table 1.

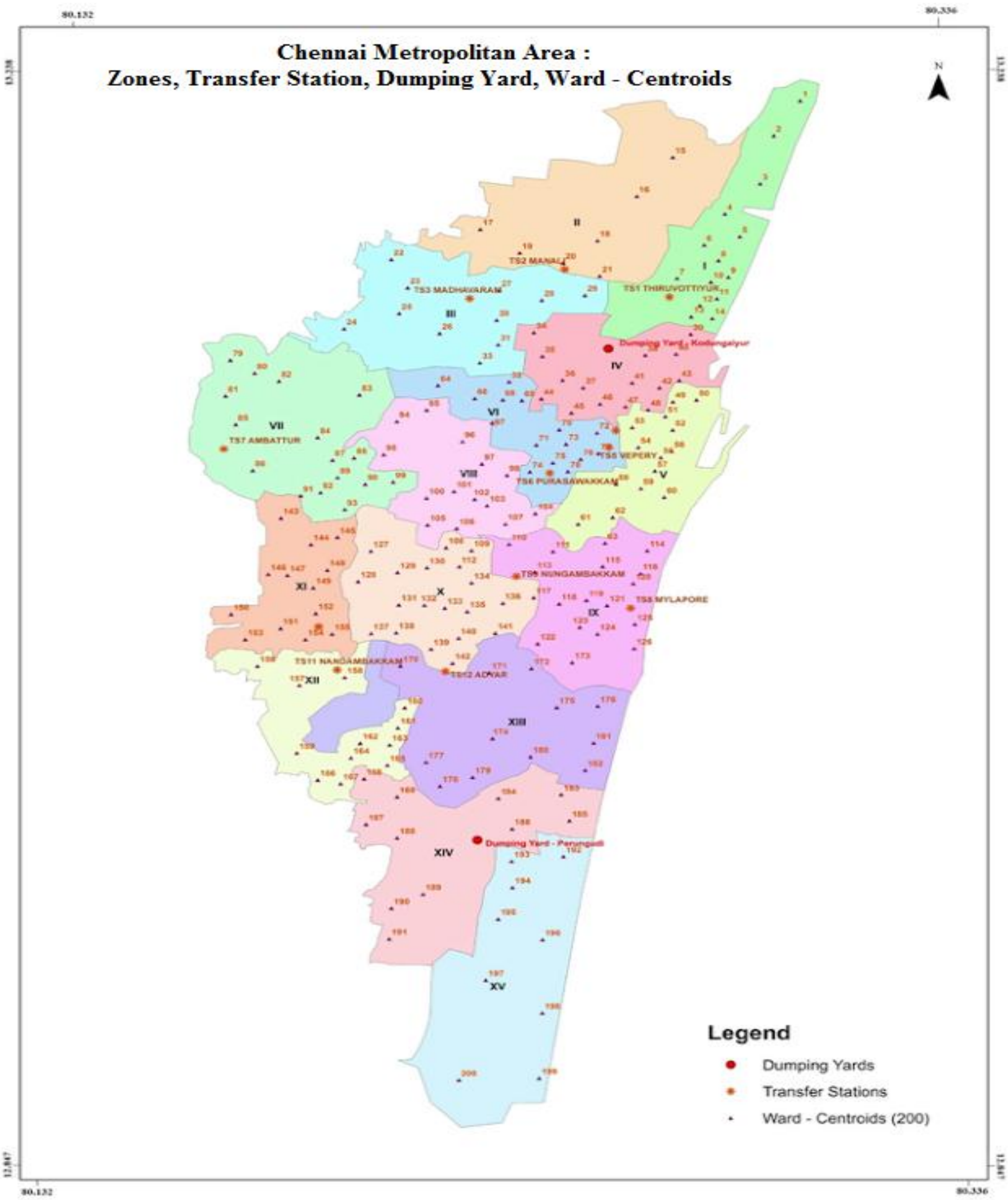


Figure 1 Chennai Metropolitan Area
Zones, Transfer stations, Dumping yards, Ward- Centroids

Table 1 name of the zones with attached ward numbers

Serial No.	Zone	Name of the Zone	Ward Numbers
1	I	Thiruvottiyur	1 to 14
2	II	Manali	15 to 21
3	III	Madhavaram	22 to 33
4	IV	Tondaiarpet	34 to 48
5	V	Royapuram	49 to 63
6	VI	Thiru-Vi-Ka Nagar	64 to 78
7	VII	Ambattur	79 to 93
8	VIII	Anna Nagar	94 to 108
9	IX	Teynampet	109 to 126
10	X	Kodambakkam	127 to 142
11	XI	Valasaravakkam	143 to 153
12	XII	Alandur	154 to 167
13	XIII	Adyar	170 to 182
14	XIV	Perungudi	168,169, and 183 to 191
15	XV	Sholinganallur	192 to 200

Solid waste management is the one of the major activities of the CoC. This process is however very tedious as it involves collection of garbage generated at every house through various means and then moving the wastes to the two disposal sites or the dumping yards, geographically located at the northern most and southern most points of the CMA.All of the 200 city wards are estimated to generate about 4,840 tons of garbage a day.The cost of handling garbage is increasing year after year, while the budgetary allocations were kept the same. This put pressure on the city engineers to optimize the cost of handling and transporting the solid waste. The composition of solid wastes generated is given in Table 2. Note that the inert and the organic together comprise 67 per cent of all the wastes.

Table 2: Composition of Solid Wastes in Metropolitan Chennai

Type of Wastes	Percent
Inerts	34.90
Organic	32.57
Food	8.10
Wood/timber	7.00
Paper	6.50
Consumable plastic	5.10
Rags and textile	3.10
Rubber/leather	1.50
Industrial plastic	1.20
Others	0.03

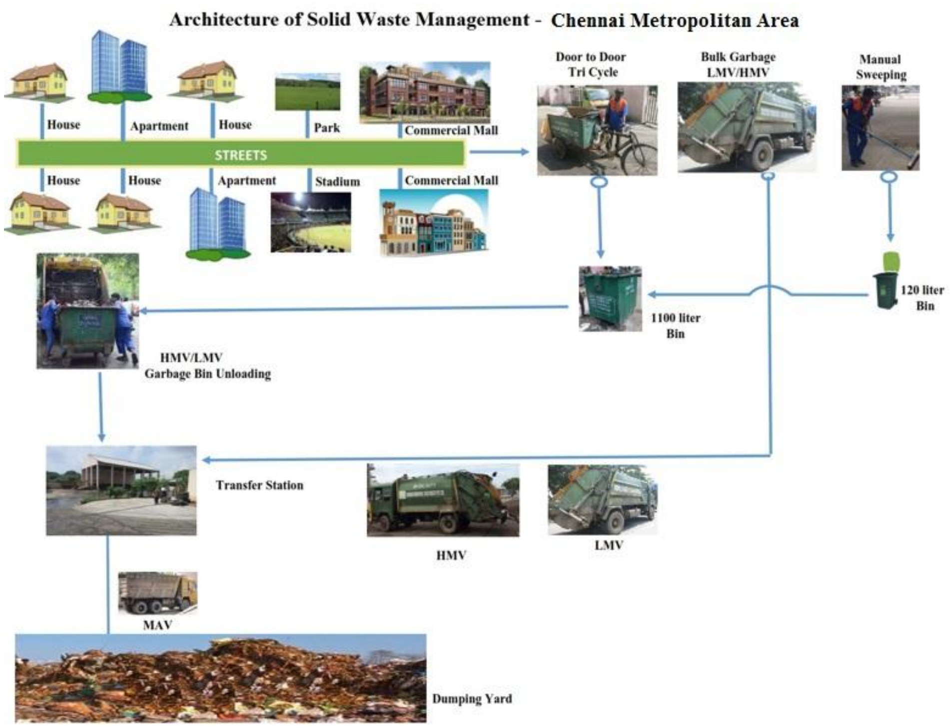
Source: Corporation of Chennai 2013.

The high moisture content in the solid wastes of 27.6 percent compared to the global average of about 10 percent leads to complicated handling of garbage in Chennai.

3.1 The Solid Waste Flow and Current Network

Over 19,390 workers are engaged in the sweeping, collection of wastes, managing and operating the transport operations in the MSWM of the CMA. The Corporation employees are engaged in sweeping the streets of the areaat least once a day, using brooms, brushes, wheel bins, wheelbarrows and also long brooms. The collected wastes are dropped into the waste bins along the streets, placed at regular intervals and according to the needs of the city households.

The solid wastes are collected by workers in each of the 200 wards and then transported to transfer stations (the storage points for garbage) and then to the dumping yards. The wastes from the wards closer to the dumping yards are moved directly to the dumping yards. The architecture of current flow of solid wastes from households and streets are shown pictorially in Figure 2.



Legend:
LMV – Light Motor Vehicles
HMV- Heavy Motor Vehicles
MAV – Multi Axle Vehicles

Figure 2Architecture of Solid waste management –CMAThe diagram is self-explanatory. The architecture of MSWM show clearly the four components of the SWM system, namely, generation, collection, transport and disposal. While the generation is at the residences, commercial establishments and streets, the collection is also from the same locations; the transport of the municipal wastes is first to the garbage bins using tricycles and wheel barrows, to transfer stations using bulk-garbage open tippers (light and heavy motor vehicles) and then from there to dumping sites using multi-axle vehicles, both light and heavy. The disposal is by open dumping, although some part of the collection is composted at select points in CMA. The current network design is given below in Figure 3.

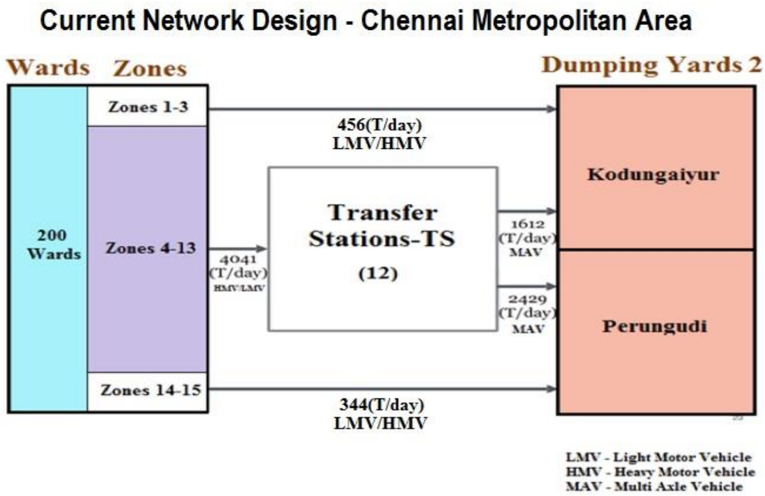


Figure 3

Current network design –CMA

The network design outlines the fact as to how the wastes from the 200 wards of Corporation in the 15 administrative zones are collected and transported, on a daily tonnage basis, to the 12 transfer stations and then disposed of at the two dumping sites with different types of vehicles. Note the solid wastes from zones 1-3 (456 tons / day) and zones 14-15 (344 tons / day) are directly dumped at the dumping yards at Kodungaiyur and Perungudi, respectively. A total of 4,041 tons / day is transferred to 12 transfer stations from zones 4-13 and then disposed of at 1,612 tons / day at Kodungaiyur dumping site and at 2,429 tons / day at Perungudi dumping site. Thus, a total of 4,841 tons of solid wastes are collected, transported and disposed of in the metropolitan city of Chennai every day. Low capacity vehicles are used to haul the garbage collected from the households and street bins.

IV. Need and objective for the study

Presently, there are 12transfer stations in use in CMA and theywere created over the last 30 years, without any optimization study. The elected representativesof wards generally apply pressure on the city management for cleaning up the garbage in a speedy way and to carry out the same, new transfer stations were opened up, without any optimization study. There were added reasons such as: one, to store and ensure movement through large capacity vehicles to reduce the cost of transportation and to store the fluctuating, day-to-day generation of the wastes in the city.The solid wastes collected from the 200 wards are transferred through the 12 transfer stations to the two dumping yards. With multiple transfer stations, which were created over a period of time in the CMA, there was a felt need to identify the most optimal operation, to minimize the cost of handling garbage.As no optimization study was done in the past, City managers and Engineers requested for a study to identify the optimal number of Transfer stations, given the current annual garbage generation at various wards and the existing dumping yards.

The objective for the study is defined as

- To optimize the cost of handling solid wastes from the generation points (households and institutions) to transfer stations and the dumping yards in CMA using a model of Linear Programming for optimization.

V. Data, Model and Methods

The data required for the project were collected from the available real data in the web site of CoC. The datasets collected for the research reported hereinclude the following:

- Gravity locations (centroids) for generation of solid wastes for each of the 200 wards.
- Daily generation of solid wastes by wards (there are no appreciable seasonal changes in the generation and collection of solid waste in Chennai city)
- Locations of current transfer stations (12) and current wards covered by each of the transfer stations.
- Locations of dumpingyards (DY) and transfer stations covered by each of the dumping yards.
- Cost of managing each of the transfer stations.
- Current costs of running light motor vehicles (LMV), heavy motor vehicles (HMV) and multi-axle vehicles(MAV).
- LMV, HMV and MAV in operation.
- Distance calculations based on latitude and longitude information.

The latitude-longitude distances are converted into actual distances (km),by verifying and comparing sample calculations between Google map distances and latitude-longitude based distances.It was found that the map distance is 1.62 times of the latitude-longitude distances on the average. Hence this factor 1.62 is used to convert the latitude-longitude distance into actual distance. The maps showing ward boundaries and centroids with x, y coordinates (latitudes and longitudes) are shown in Figure 6. The maps have been essential in the computation of distances between ward-centroids and transfer stations and transfer stations and dumping yards. Solid wastes from transfer stations 1 to 6 are disposed of at Kodungaiyur and the wastes from the remaining transfer stations 7 to 12 are moved to Perungudi.

5.1 Linear Programming Model

The key elements of optimization model adopted for study is as shown in the following paragraphs.

5.1.1 Model Assumptions

The model assumptions are:

- Each ward has a single loading point.(Centroid, details given in Table 3)
- Distance between ward and transfer station / dumping yard and between transfer stations and dumping yards are taken to be 162 per cent of the latitude-longitude distance.(Details of the coordinates of Transfer Stations and Dumping Yards are given in Table 4)
- The loaded vehicles move from transfer stations to dumping yards and return empty. As the vehicles return empty to the starting points, after consulting the CoC engineers, it has been estimated that one trip equals 1.8 times the distance between two points, say between ward and transfer station and from transfer station and dumping yard. Similar is the case with LMVs and HMVs.
- Each transfer station owns a fleet of LMVs and HMVs.
- Each dumping yard owns a fleet of MAVs.
- Solid wastes from a ward can be transferred only to a single transfer station or to a single dumping yard.
- Routes considered in the study are the haul routesthat connect wards to transfer station / dumping yard directly and transfer station to dumping yard directly.
- Wards are not connected to each other. Transfer stations are not connected to each other, and dumping yards are not connected to each other.
- Only 12 transfer stations and 2 dumping yards are the available entities. Distances are calculated from each of the 200 wards to these 14 entities.

5.1.2 Basic Constraints

The basic constraints of the model in the study are:

- Each of the dumping yards can receive a maximum of 1000 tonsa day from the wards. This is due to constraints in compactor unloading delays at dumping yards and loading delays at wards in regard to multi-axle vehicles.
- A given ward can dispatch garbage only to one receiving point, that is, it could be either a dumping yard or a transfer station.
- The maximum a transfer station can handle is about 600 tonsof solid wastes a day and the capacity of the transfer station could be either 300 or 600 tons.

The trucking and other costs incurred in the collection and transport of solid wastes in the CMA are in respect of:

- Solid waste flow from the city wards to transfer stations, transported by the compactors in HMVs and LMVs and the solid waste flow from transfer stations to dumping yards, transported using the MAVs.
- Wherever the solid waste is transported directly to dumping yards form the wards only HMVs and LMVs are used.

Table 3 Chennai Metro Area: Ward-Centroids(Latitudes and Longitudes - x, ycoordinates)

Ward No	Latitude	Longitude	Ward No	Latitude	Longitude	Ward No	Latitude	Longitude	Ward No	Latitude	Longitude
1	13.2275	80.3273	51	13.1113	80.2858	101	13.0837	80.2209	151	13.0333	80.1676
2	13.2146	80.3192	52	13.1063	80.2881	102	13.0808	80.2273	152	13.0388	80.1784
3	13.1969	80.3150	53	13.1072	80.2756	103	13.0785	80.2311	153	13.0292	80.1568
4	13.1858	80.3041	54	13.1000	80.2775	104	13.0756	80.2459	154	13.0292	80.1753
5	13.1775	80.3088	55	13.0962	80.2844	105	13.0714	80.2128	155	13.0312	80.1835
6	13.1744	80.2978	56	13.0985	80.2878	106	13.0701	80.2217	156	13.0194	80.1605
7	13.1621	80.2894	57	13.0912	80.2826	107	13.0717	80.2367	157	13.0124	80.1734
8	13.1687	80.3022	58	13.0864	80.2707	108	13.0630	80.2184	158	13.0153	80.1873
9	13.1626	80.3052	59	13.0848	80.2784	109	13.0620	80.2263	159	12.9909	80.1717
10	13.1607	80.2998	60	13.0815	80.2855	110	13.0643	80.2379	160	13.0041	80.2058
11	13.1546	80.3017	61	13.0717	80.2590	111	13.0616	80.2514	161	12.9967	80.2037
12	13.1521	80.2965	62	13.0742	80.2697	112	13.0560	80.2225	162	12.9911	80.1921
13	13.1480	80.2938	63	13.0647	80.2673	113	13.0540	80.2456	163	12.9904	80.2012
14	13.1474	80.3003	64	13.1227	80.2160	114	13.0619	80.2803	164	12.9857	80.1893
15	13.2066	80.2882	65	13.1136	80.2125	115	13.0560	80.2666	165	12.9830	80.2005
16	13.1923	80.2771	66	13.1179	80.2273	116	13.0534	80.2782	166	12.9775	80.1790
17	13.1801	80.2290	67	13.1089	80.2326	117	13.0446	80.2454	167	12.9762	80.1861
18	13.1760	80.2650	68	13.1174	80.2359	118	13.0423	80.2533	168	12.9779	80.1933
19	13.1715	80.2411	69	13.1172	80.2418	119	13.0436	80.2616	169	12.9713	80.2034
20	13.1677	80.2545	70	13.1064	80.2533	120	13.0498	80.2759	170	13.0195	80.2045
21	13.1629	80.2657	71	13.1008	80.2462	121	13.0417	80.2680	171	13.0170	80.2317
22	13.1690	80.2017	72	13.1053	80.2648	122	13.0277	80.2466	172	13.0185	80.2447
23	13.1586	80.2067	73	13.1011	80.2553	123	13.0337	80.2595	173	13.0207	80.2572
24	13.1435	80.1872	74	13.0909	80.2442	124	13.0312	80.2650	174	12.9928	80.2327
25	13.1492	80.2041	75	13.0942	80.2513	125	13.0348	80.2765	175	13.0042	80.2525
26	13.1419	80.2165	76	13.0955	80.2599	126	13.0259	80.2763	176	13.0046	80.2651
27	13.1576	80.2348	77	13.0977	80.2653	127	13.0617	80.1954	177	12.9840	80.2123
28	13.1540	80.2479	78	13.0910	80.2559	128	13.0505	80.1914	178	12.9753	80.2166
29	13.1559	80.2611	79	13.1320	80.1522	129	13.0539	80.2036	179	12.9785	80.2266
30	13.1467	80.2340	80	13.1272	80.1597	130	13.0556	80.2126	180	12.9860	80.2444
31	13.1377	80.2345	81	13.1188	80.1507	131	13.0419	80.2040	181	12.9912	80.2638
32	13.1240	80.2379	82	13.1243	80.1671	132	13.0418	80.2119	182	12.9811	80.2612
33	13.1310	80.2289	83	13.1192	80.1918	133	13.0408	80.2181	183	12.9721	80.2539
34	13.1422	80.2454	84	13.1035	80.1790	134	13.0501	80.2263	184	12.9708	80.2345
35	13.1334	80.2481	85	13.1083	80.1538	135	13.0395	80.2250	185	12.9625	80.2564
36	13.1246	80.2543	86	13.0914	80.1591	136	13.0426	80.2359	186	12.9595	80.2389
37	13.1219	80.2606	87	13.0952	80.1836	137	13.0314	80.1954	187	12.9612	80.1939
38	13.1338	80.2797	88	13.0960	80.1902	138	13.0317	80.2032	188	12.9562	80.2034
39	13.1416	80.2937	89	13.0888	80.1851	139	13.0257	80.2139	189	12.9355	80.2114
40	13.1342	80.2891	90	13.0863	80.1936	140	13.0297	80.2223	190	12.9303	80.2017
41	13.1236	80.2756	91	13.0821	80.1739	141	13.0316	80.2336	191	12.9191	80.2010
42	13.1219	80.2840	92	13.0833	80.1799	142	13.0205	80.2204	192	12.9494	80.2545
43	13.1246	80.2901	93	13.0770	80.1874	143	13.0739	80.1677	193	12.9476	80.2387
44	13.1178	80.2477	94	13.1094	80.2034	144	13.0642	80.1770	194	12.9380	80.2389
45	13.1126	80.2570	95	13.0972	80.1993	145	13.0668	80.1851	195	12.9264	80.2345
46	13.1159	80.2658	96	13.1020	80.2235	146	13.0532	80.1638	196	12.9187	80.2481
47	13.1148	80.2736	97	13.0938	80.2295	147	13.0528	80.1698	197	12.9039	80.2307
48	13.1137	80.2806	98	13.0897	80.2372	148	13.0548	80.1820	198	12.8918	80.2480
49	13.1167	80.2882	99	13.0872	80.2022	149	13.0482	80.1777	199	12.8678	80.2471
50	13.1174	80.2955	100	13.0812	80.2125	150	13.0385	80.1524	200	12.8671	80.2224

Table 4: Chennai Metro Area: Transfer Stations and Dumping Yards with coordinates

No.of TS	Zone	Zone number	Wards Covered	Address	Latitude	Longitude
TS1	Collection Point	1	1 to 14	Manali High Road, Sathangadu	13.155	80.287
TS2	Collection Point	2	15 to 22	KamarajSalai, Manali	13.165	80.254
TS3	Collection Point	3	23 to 33	Omakkulam, Kilburn Nagar	13.154	80.225
TS4	Modern Transfer Station	4	34 to 48	Basin Bridge Road	13.106	80.270
TS5	Modern Transfer Station	5 and 8	49 to 63 and 94 to 108	Basin Elephant Gate Bridge Road	13.094	80.268
TS6	Modern Transfer Station	6	64 to 78	1st Main Road, S.S. Puram, 'A' Block	13.090	80.250
TS7	Modern Transfer Station	7	79 to 93	Vanakaram Road, Athipattu	13.099	80.150
TS8	Modern Transfer Station	9	109 to 196	Karaneeswara Pakoda St.,	13.040	80.275
TS9	Modern Transfer Station	10	127 to 142	12, Kodambakkam High Road	13.052	80.240
TS10	Modern Transfer Station	11	143 to 155	Bharathi Salai	13.033	80.179
TS11	Modern Transfer Station	12	156 to 167	Nandambakkam Service Road, M.G.R. Nagar	13.017	80.185
TS12	Modern Transfer Station	13	170 to 182	Alandur Salai, Saidapet, Chennai 600015	13.017	80.218
Direct dumping	Zones 14 and 15.	14 and 15	183 to 200 and 168,169	Directly dumped at Perungudi dumping yard	12.955	80.228
Dumping yard				Kodungaiyur	13.136	80.268
Dumping yard				Perungudi	12.955	80.228

Source: Corporation of Chennai and Google Map

The HMV, LMV and MAV details and the costs incurred to the CMAare given in Tables 5below.

Table 5: Haul transport (HMV, LMY, MAV), loads, trips and costs

Parameters	Compactor HMV- ***LHMV***	Compactor LMV- ***CLMV***	MAVs ***-CMAV***
Total numbers	190	126	84
Loadability (tons)	9	5	14
Trips per day (NOs)	2	3	3
Transport cost (INR)	66	40	82
Monthly Cost to The Company (CTC) for driver per trip in INR	12500 *SHMV*	8333 *SLMV*	9000 *SMA*

Source: Corporation of Chennai 2013.(INR- Indian Rupees, the local currency)

The details of staff at eachtransfer stationand the total cost per month in INR to the CoCare given table 6.

Table 6: Staffs and costs of each transfer station

Post –Staff (Cost To Company per month per post in INR)	Number	Total Cost / month inINR
Superintendent (26000)	1	26000
Data entry operator (15000)	2	30000
Sweeper (9000)	3	27000

Source: Corporation of Chennai 2013

Note: Each transfer station has the following staffsand the total cost per month in INR to the CoC, for each position is given in brackets.

The transfer station costs per month work out to: Salaries and others:INR 83,000; Space cost: INR 117,000; and Total Cost(Fixed Costs):INR 200,000. In addition to the fixed costs, one JCB dumper operates on variable cost basis for lifting the garbage and loading the same on to the MAVs. As per available data, JCB dumpers handle only 25 percent (Q) of the garbage.The balance is unloaded directly from HMVs/LMVs to MAVs through gravity method. The hiring costs for a JCB (variable) isINR 24 (R) per ton of solid wastes handled.The current cost component that is optimizedis INR 367.2 per ton.

5.1.3 Variables

Counter: *i* - two hundred wards; *j* - twelve transfer stations and two dumping yards;m - twelve transfer stations, *l* - two dump yards; *DPij* - distance between ward *i* and transfer stations/dumping yards *j*; *DSml*- distance between transfer stations and dumping yards

i – source – wards (200)

j – transfer stations and dumping yards (14)

m – transfer stations (12)

l – dump yards (2)

DPij – distance between ward i and transfer station or dump yard *j*

DSml – distance between transfer stations m and dumping yards *l*

wi–solid waste quantity (weight) from wards *i*

NLMV- number of available Light Motor Vehicles

NHMV - number of available Heavy Motor Vehicles

NMAV - number of available Multi Axle Vehicles

5.1.4 Decision variables

Cij– Connectivity between wards*i* and transfer stations/dumping yards *j* (type: binary);

Hij - number of trips of HMV vehicles between ward *i*and transfer stations/dumping yards *j*(type: non-negative integer);

Lij- number of trips of LMV vehicles between wards*i* and transfer stations/dumping yards *j* (type: non-negative integer);

Mml - number of trips of MAV vehicles between transfer stations*m* and dumping yards*l* (type: non-negative integer); and

Km - type of transfer stations *m* (type: non-negative integer; upper limit: 2).

5.1.5 Objective of the model

The objective is to minimize the total transport cost in the network from generating nodes to sink nodes, fixed cost of managing a TS and handling cost at TS. The cost elements taken for this study are the transport cost for all the three types of vehicles, and separately the cost of Drivers and Helpers for the vehicles, the space cost at TSs, the administrative cost of TSs.

$$\min_{C_{ij},H_{ij},L_{ij},M_{ml},K_m} HMVtripcost + LMVtripcost + MAVtripcost + TSfixedcost + Forkliftcost$$

where,

$$HMVtripcost = \sum_{i=1}^{200}\sum_{j=1}^{14} H_{ij}\,(DP_{ij} \times t \times C_{HMV} \times 30 + S_{HMV})$$

$$LMVtripcost = \sum_{i=1}^{200}\sum_{j=1}^{14} L_{ij}\left(DP_{ij} \times t \times C_{LMV} \times 30 + S_{LMV}\right)$$

$$MAVtripcost = \sum_{i=1}^{12}\sum_{j=1}^{2} M_{ml}\,(DS_{ml} \times t \times C_{MAV} \times 30 + S_{MAV})$$

$$TSfixedcost = \sum_{m=1}^{12} K_m \times FC$$

$$Forkliftcost = \sum_{i=1}^{200}\sum_{m=1}^{14} C_{im} \times w_i \times Q \times R \times 30 \;(1)$$

5.1.6 Constraints

Following constraints restricts the number of connections for any ward to be one.

$$\sum_{j=1}^{14} C_{ij} = 1 \quad \forall_{i,j} \;(2)$$

Above constraints and variable *Cij* are not required if there is no upper limit on capacity of transfer stations (variables *Hij* and *Lij* are sufficient to denote connections). With the upper limit in place, load from a ward might be split and sent to two or more transfer stations. Further, for trips and connections between wards and transfer stations to be consistent following constraints are added.

$$L_{HMV} \times H_{ij} + L_{LMV} \times L_{ij} \geq C_{ij} \times w_i \forall_{i,j} \quad (3)$$

To minimize the trip cost, solver decreases *Hij a*nd *Lij*. If a connection between ward *i* and transfer station/dump yard *j* exists (i.e. *Cij* equals one) number of *Hij* and *Lij* cannot be lesser than required to transfer load from ward *i*. At optimum, when a particular *Cij* = 0, *Hij* and *Lij* will be zero as unnecessary presence of trip results in excess cost. Intuitively, a connection and corresponding trips between *i* and *j* either coexist or become zero together at optimum. To restrict the feasible solution space, following constraints are added,

$$L\_HMV \times H\_ij + L\_LMV \times L\_ij \leq C\_ij \times w\_i + L\_LMV \;\forall\_(i,j) \quad (4)$$

Both number of HMV and LMV can be included as vector variables (single variable per ward) instead of matrices. However, cost function will become quadratic as Cij needs to be multiplied with number of HMV's and LMV's to estimate optimal trip distance.

Type of transfer stations (0,1,2) and capacity of transfer stations (600 ton as maximum) are limited by following constraint

$$K\_m \leq 2 \;\forall\_m \quad (5)$$

$$300 \times K_m \leq \sum_{i=1}^{200} C_{im} \times w_i \forall_m \;(6)$$

Above constraint is applied for each of the twelve transfer stations (i.e. for all k). It identifies whether the transfer station is present (Km > 0) or not (Km = 0) and if present whether it is of 300 (Km = 1) or 600 (Km = 2) ton capacity.

In the case of load transfer from Transfer station to dump yard, no connectivity variable is used, as there is no upper limit on capacities of dump yards is enforced. To estimate number of multi axial vehicles and limit the feasible solution space following constraints are enforced,

$$L_{MAV} \times M_{ml} \leq \sum_{i=1}^{200} C_{im} \times w_i \forall_{m,l} \;(7)$$

$$L_{MAV} \times M_{ml} \geq \sum_{i=1}^{200} C_{im} \times w_i + L_{MAV} \forall_{m,l} \quad (8)$$

Further, number of vehicles available for transport should more than or equal to the required number of trips. Assuming 3 trips per LMV, 2 trips per HMV and 4 trips per MAV. Following constraints are applied.

$\sum_{i=1}^{200} \sum_{i=1}^{14} H_{ij} \leq 2 \times N_{HMV}$ (9)

$\sum_{i=1}^{200} \sum_{i=1}^{14} L_{ij} \leq 3 \times N_{LMV}$ (10)

$\sum_{m=1}^{12} \sum_{l=1}^{2} M_{ml} \leq 4 \times N_{MAV}$ (11)

The above LP was run using LINDO (Linear,Interactive, and Discrete Optimizer).All the data needed for running the model were prepared in the required format. All data were also validated with the engineers of CMA.

IV. Results

The LINDO model was run with the actual field data ofCMA in terms of 200 wards, solid wastes handled by each ward, totaling to 4,840 tons a day, 12 transfer stations, 2 dumping yards, and the details on transport vehicles (HMV, LMV, MAV) availability. For the given objective function of optimum transfer cost and the constraints given above, the Linear Programming model was run with the following logic.

As a first step, each ward identifies the nearest located entity of dumping yard or transfer station. Variable Cij indicates the Connectivity between wards and transfer station/ dumping yard. If it is DY after verifying the available capacity (permitted capacity minus allocated tonnage to the DY) and checking the sum of the tonnage of the new ward under consideration and the already allocated tonnage do not exceed the permitted capacity, allow the ward to send the solid waste to the DY.

But if it is nearer a transfer station then the tonnage that is checked is the permitted capacity of TS. This process is repeated until all the solid waste from all the wards are allocated either to DY or TS. For any individual TS or DY, Cij values indicate the wards connected to it. Optimum allocation of tonnages for each TS or DY is computed by adding Tonnages generated in the wards connected to respective TS/DY. Capacity of the transfer station is optimally chosen by the LP model either 300 or 600 tons and indicated by the variable K_m.

Presence of TS and DY are denoted by binary variables in the problem formulation. That is 1 if a TS/DY is present and 0 if a TS/DY is not present. The Lindo Solver has chosen in addition to two Dys, only eight transfer stations to be the optimal number transfer stations , required for the process. Further, sensitivity analysis also shows that increase in number of transfer station leads to increase in operating cost. Tonnages to be handled by the optimal (suggested) transfer stations, which are by the designations from the existing transfer stations are given in Table 7.

Table 7 Suggested Transfer stations and respective volumes

Transfer Station number	Transfer Station code	Recommended (Tons /day)	Maximum daily tonnage permitted
1	TS1	277.4	600
2	TS3	311.6	600
3	TS4	281.1	600
4	TS5	293.8	600
5	TS6	598.7	600
6	TS10	279.2	600
7	TS11	294.5	600
8	TS12	511.2	600
	Direct to DY1	999.5	1000
	Direct to DY2	993.0	1000
	Total	4840.0	

Thus the optimum number of Transfer Stations comes to eight.

At optimum level , the cost (INR per Tonne) is 245.60 compared to the current cost of INR 367.20 per tonne .Thus there is considerable savings of INR 121.60 per tonne (33.1 percent of current cost levels)

Chatzouridis and Komilis,(2012) have carried out Similar study for a region consisting of 53 Municipalities in Greece by using Linear Programming and the optimal solution suggested that from 47 candidate TSs , 12 transfer stations will meet the needs . In this study, the authors have taken a large city with fixed locations of TSs and then optimized the low cost locations in terms of how many TSs are needed and what are the tonnages that will be handled by each TS and Dumping yard. Here the authors have analyzed a live issue. The choice of relocating the TSs is not feasible as with in the limits of CMA, there is no space to accommodate TS and even if it is available the fixed cost of acquiring the space is abnormally high.

6.1 Scenario Analysis

In order to test the various scenarios of the model, the optimization model was run without any TS, meaning all the 200 wards would transfer directly to the DYs. The theoretical minimum cost came to INR 227.6 per ton. This option is impractical due to number of issues such as high unloading time at DYs, extended collection time for multi axle vehicles, available vehicle capacities, increase in number of vehicles and operating staff etc.

Table 8 Number of transfer stations vs. cost

Transfer stations (Numbers)	Total cost (INR / Ton)
5	231.1
6	234.7
8	245.6
9	273.4
10	302.8
11	334.5
12	367.2

Source: Linear Programming computations

The model was run repeatedly by increasing the number of TSs from one to 12.The feasible solution was available only when the number of transfer stations reached five. Then,by increasing the number of available transfer stations to 6, 7, 8, 9,10,11, and 12, the cost per ton were arrived. The details are given in Table 8.

V. Conclusion and Recommendations

Based on this study, it is concluded that CMA has to operate with eight TSs and close the balance four namely TS2, TS7, TS8, and TS9. The implementation of the recommendations will bring in a saving of INR 214.8 Million per year (US$ 3.52 Million) to CoC.

As CMA has no free space available, the choice of relocating the TSs is not feasible. However the City has developed a master Plan 2026, as per which the area covered by CMAwill be increased to 1189 km2 from the present 426. Taking into account the increase in population to 12.58 million by the year 2026 and the increase in standard of living of citizens the Solid waste is expected to touch 8950 tons per day.

With the availability of free space in expanded areas of the city, and with availability of technologically superior vehicles to transport the SW, further study need to be carried out to decide on the optimum location and number of TSs desired by 2026. As per USEPA (1977), the threshold one-way distance between a city and the DY area is about 24 to 32 km. This break-even distance need to be studied keeping in mind the increase in fuel price, the available transportation technology, the quantity of available SW, and the sensitivity of local citizens for having DY.

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