Waste Management 43 (2015) 9–18

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Optimization of municipal solid waste collection and transportation routes

Swapan Das *, Bidyut Kr. Bhattacharyya

Department of Mechanical Engineering, Indian Institute of Engineering Science and Technology, Shibpur, Howrah 711103, India

ARTICLE INFO

Article history:
Received 31 March 2015
Revised 8 June 2015
Accepted 17 June 2015
Available online 4 July 2015

Keywords:
Solid waste
Collection
Transfer
Transportation
Route optimization

ABSTRACT

Optimization of municipal solid waste (MSW) collection and transportation through source separation becomes one of the major concerns in the MSW management system design, due to the fact that the existing MSW management systems suffer by the high collection and transportation cost. Generally, in a city different waste sources scatter throughout the city in heterogeneous way that increase waste collection and transportation cost in the waste management system. Therefore, a shortest waste collection and transportation strategy can effectively reduce waste collection and transportation cost. In this paper, we propose an optimal MSW collection and transportation scheme that focus on the problem of minimizing the length of each waste collection and transportation route. We first formulize the MSW collection and transportation problem into a mixed integer program. Moreover, we propose a heuristic solution for the waste collection and transportation problem that can provide an optimal way for waste collection and transportation. Extensive simulations and real testbed results show that the proposed solution can significantly improve the MSW performance. Results show that the proposed scheme is able to reduce more than 30% of the total waste collection path length.

1. Introduction

The rapid and constant growth in urban population led to a dramatic increase in municipal solid waste (MSW) generation, with a crucial socioeconomic and environmental impact. Municipal solid waste management is a multidisciplinary activity that includes generation, source separation, storage, collection, transfer and transportation, processing and recovery, and, last but not least, disposal (Rada et al., 2013; Bovea et al., 2010; Gallardo et al., 2015; Rada, 2014; Minoglou and Komilis, 2013; Wagner and Bilitewski, 2009). In order to develop a sound material-cycle society, cost-effective integrated municipal solid waste management system is required for the municipalities (Weng and Fujiwara, 2011; Consonni et al., 2011; Massarutto et al., 2011; Ionescu et al., 2013; Eriksson et al., 2014). Solid waste collection is widely recognized across the globe to account for a majority of expenditure on solid waste management (Jacobsen et al., 2013). Typically, collection costs represent 80–90% and 50–80% of municipal solid waste management budget in low income and middle income countries respectively (Aremu, 2013). Therefore, waste collection and transportation problems are one of the most difficult operational problems to develop an integrated waste management system (Nuortio et al., 2006). In a bid to reduce collection costs as well as transportation cost, municipal authorities have been motivated to develop new strategies for the collection and transportation of solid wastes, particularly in urban centres (Khan and Samadder, 2014; Kanchanabhan et al., 2011; Rada et al., 2010).

Generally, collection and transportation are the most important and costly aspect of the process because of the labour intensity of the work and the massive use of vehicles in the collection and transportation process (Amponsah and Salhi, 2004). In India, waste collectors start the journey from a collection centre for collection of segregated waste and visit the various sources with containerized tri-cycle (hand cart). The containerized tri-cycle having six buckets of 40–50 L capacity. After the full fill the capacity of tri-cycle bar, they conveyed the garbage to the collection centre. Similarly, a vehicle starts from the depot, visits a number of collection centre/transfer station and ends at the depot (Kim et al., 2006). Depending on the complexity of the problem and different waste characteristics, different types of vehicles are used for collection and transportation (Wy et al., 2013). An integrated waste management system can improve the vehicle routing, dispatching, maintenance and management (Sahoo et al., 2005; Xu et al., 2015; Li et al., 2014; Ionescu and Stefani, 2014; Rabbani et al., 2014) and in this paper, in order to improve the road compactness and workload balancing, a scheme is developed for municipal solid waste

* Corresponding author.
E-mail addresses: swapan2009sajal@gmail.com (S. Das), bidyut53@yahoo.co.in (B.Kr. Bhattacharyya).

http://dx.doi.org/10.1016/j.wasman.2015.06.033
0956-053X/

collection and transportation: an optimization scheme is needed to reduce waste collection and transportation route length.

This paper mainly focuses on the collection, transfer and transportation of solid waste from any waste generation sources (households, markets, institutions and offices) to the processing plant or landfill site. The factor influencing the municipal solid waste collection and transportation are: (i) quantity of municipal solid waste generation; (ii) number of waste collectors and their deployment to cover the whole city; (iii) vehicles to run to and from various transfer stations where garbage is gathered to the respective processing plant. In this paper a scheme is proposed for optimizing municipal solid waste collection and transportation routes using the Travelling Salesman Problem (TSP). The proposed scheme design an optimized municipal solid waste management (MSWM) system with respect to transportation route length. The TSP is one of the most prominent problems in combinatorial optimization, and at the same time a quintessential applied spatial-analytic challenge. The well-known travelling salesman problem is the following: a salesman is required to visit once and only once each of n number of different cities starting from a base city, and returning to this city. The task is to find a shortest possible tour that visits each city exactly once by the salesman (Dumitrescu et al., 2009; Renaud et al., 2002).

2. Problem formulation

In waste management system, n number of sources are available in different municipalities under a city. Each source point generates some waste material in each day. The waste management system collects these waste form the different sources and process it through different plants. Therefore, total waste management cost ($W_{management}$(Cost)) for n number of sources is

$$W_{management}(\text{Cost}) = \sum_{i=1}^{n} C^c + \sum_{i=1}^{n} C^t + \sum_{i=1}^{n} C^p + \sum_{i=1}^{k} C^d + C \qquad (1)$$

where C^c is the collection cost, C^t is the transportation cost, C^p is the processing cost, C^d is the disposal cost for k number of unused or produced waste material after processing and C is the constant cost that are depending on other parameter such as accident, maintenance of collection centre, transfer station and vehicle. The profit gain by the n number of sources is

$$W_{management}(\text{profit}) = \sum_{i=1}^{f} P(\text{Revenue}) - W_{management}(\text{Cost}) \qquad (2)$$

where P(Revenue) is mainly achieved from the sales of recyclable materials, sales of compost product and the sales of electricity. A waste management system always tries to develop a mechanism that increases the profit ($W_{management}$(profit)). Therefore, the objective of any waste management scheme is how to reduce waste collection cost and waste processing cost. In this paper, we increase $W_{management}$(profit) to reduce $\sum_{i=1}^{n} C^c$ and $\sum_{i=1}^{n} C^t$.

Therefore, our main objective is to identify optimal waste collection and transportation routes for reduction of waste collection and transportation cost in the waste management system design.

3. Proposed scheme

The proposed scheme divides whole integrated waste management system into four different parts (shown in Fig. 1). (i) Collection of segregated solid waste from various sources (households, markets, offices and institutes) and conveyed waste to the nearest collection centre; (ii) transfer accumulate solid waste from collection centre to the adjoining transfer station; (iii) transport the segregated solid waste from the transfer station to nearby categorized waste processing plant; (iv) transfer the produced waste from processing plant to the nearest landfill site. Each part contents huge amount of cost for waste collection or waste material transportation. The proposed scheme optimizes transportation cost of each part of the system. Therefore, the total waste management cost for the whole system is optimized. The optimization process for each waste management part is described in Fig. 1.

3.1. Optimal waste collection from source to collection centre

In phase 1, waste collectors collect waste from different sources in different areas and transfer to a collection centre (shown in Fig. 2). Here, we find optimize route between each collection centre and its sources. The optimal route between the collection centre and its sources, reduces waste collection cost in phases one. We represent waste collection point through a connected graph $G(V, E)$, where $V = \{v_1, v_2, \ldots, v_n\}$ $(n \neq 0)$ is the number of sources point and $E = \{e_1, e_2, \ldots, e_n\}$ $(n \neq 0)$ is the number of edges that connect all source points.

In phase 1 optimization, m number of waste collectors visit each v_i centre where $v_i \in V$ through optimal path sequence, where $e_i \in E$. Our optimal waste collection path calculation problem is related to travelling salesman problem (TSP). Therefore, our objective function for optimal waste collection path calculation is

$$\text{Minimize} \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} v_{ij} x_{ij} \qquad (3)$$

Subject to

$$\sum_{j=2}^{n} x_{ij} = m \qquad (4)$$

$$\sum_{i=2}^{n} x_{i1} = m \qquad (5)$$

$$\sum_{i=1, i \neq j}^{n} x_{ij} = 1, \forall j = 2, \ldots, n \qquad (6)$$

$$\sum_{j=1, i \neq j}^{n} x_{ij} = 1, \forall i = 2, \ldots, n \qquad (7)$$

$$x_{ij} \in \{0, 1\}, \forall i, j = 1, \ldots, n, i \neq j \qquad (8)$$

$$x_{ij} = \begin{cases} 1, & \text{if source } i \text{ directly procedes source } j \text{ on any tour} \\ 0, & \text{otherwise}, \ \forall i, j = 1, \ldots, n, \ i \neq j, \end{cases}$$

Our main objective is to minimize waste collection path cost in the lower level where each waste collector collects waste from different sources. Constraints (4) and (5) insure that m number of waste collector starting from a source points and visits each source point and return to starting point. Constraint (6) and (7) are the classical assessment restriction that each source point in the set $\{v_1, v_2, \ldots, v_n\}$ to be visited by at least one waste collector and at one connection has been existed between the neighbour source point. The logical representation of the decision variables are represented in (8).

3.2. Optimal waste transfer from collection centre to transfer station

In phase 2, collected waste is transferred from the collection centre to transfer station through different small vehicle (shown in Fig. 3). The optimized route between collection centre and transfer station minimize waste transportation cost. Transfer stations and collection centres are represented by an undirected connected graph $T(C, D)$ where, $C = \{c_1, c_2, \ldots, c_n\}$ $(n \neq 0)$ are all points that vehicles are visited for waste transportation and $D = \{d_1, d_2, \ldots, d_n\}$ $(n \neq 0)$ are the double way route between them.

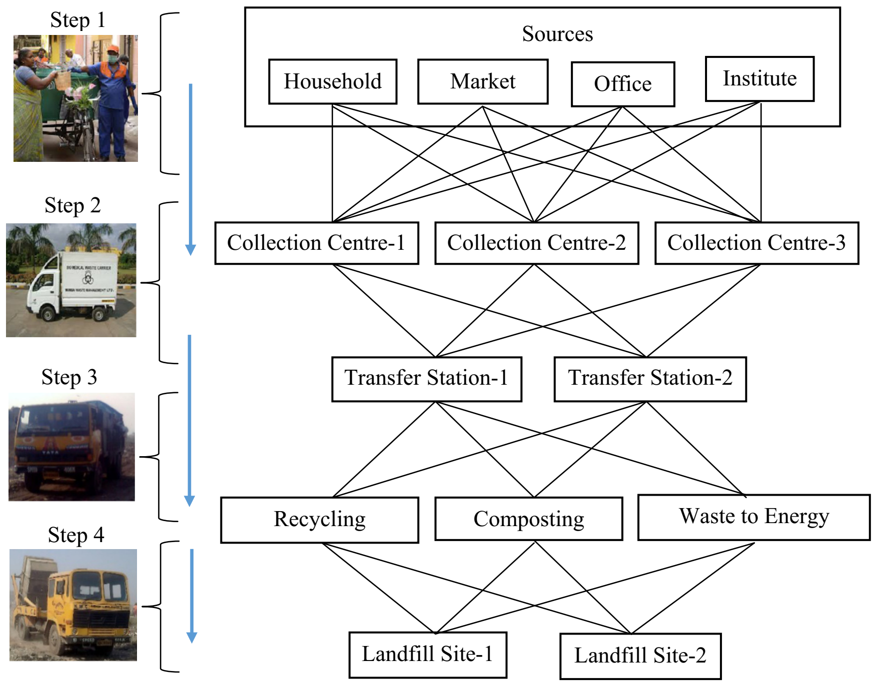

Fig. 1. Architectural view for MSW collection and transportation.

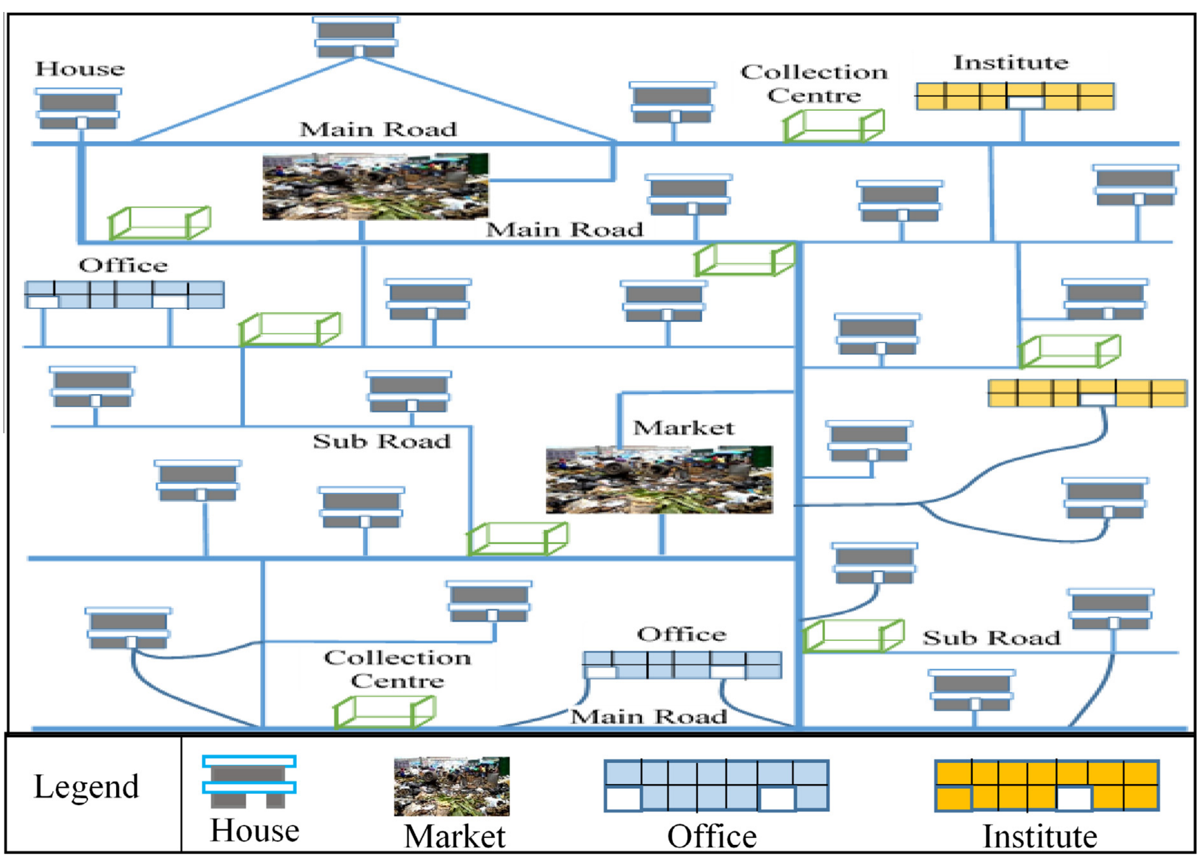

Fig. 2. Different road between sources and collection centres.

In phase 2, we calculate the optimal path between the collection centre and transfer station. In the second level optimization, g number of the transfer vehicles, visit each c_i collection centre where $c_i \in C$ through the optimal path sequence and $d_i \in D$. In this optimization problem we consider the number of visits in each collection centre must be once. In second waste collection tour, each collection centre may be visited k number of times, if the amount of waste is more than the capacity of a transfer vehicle. We relate

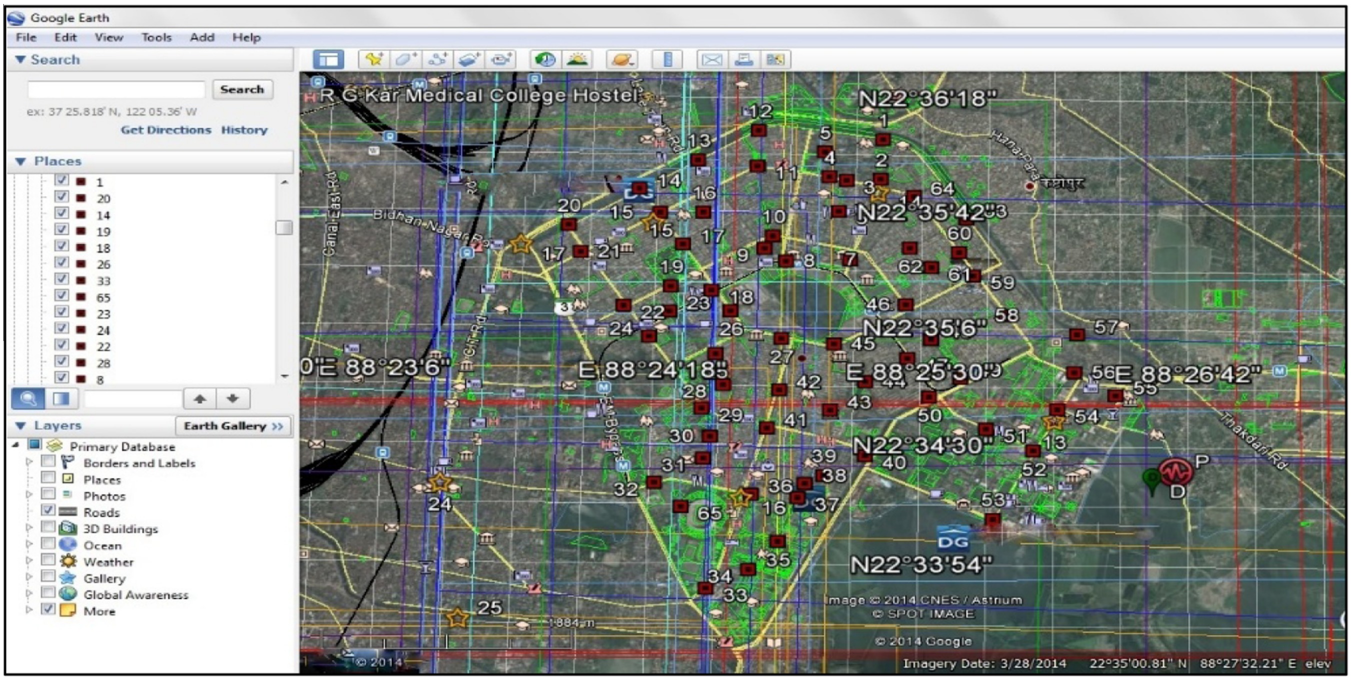

Fig. 3. Road between collection centres (red mark) to transfer stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

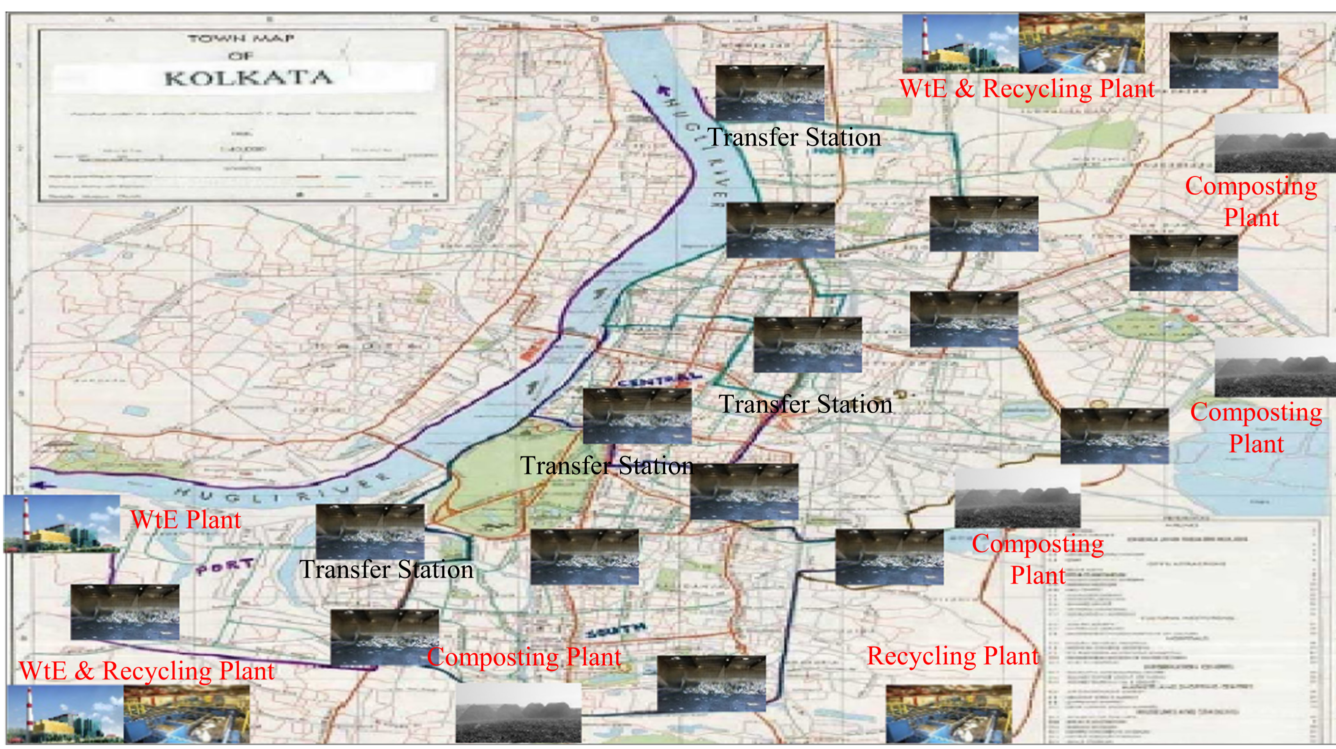

Fig. 4. The optimal transportation of waste material from transfer stations to processing plants.

our optimal path problem with covering salesman problem (CSP). The objective function for optimal path calculation is computed as follows:

$$a_{ij} = \begin{cases} 1, & \text{if collection centre } j \text{ can cover collection centre } i, \\ 0, & \text{otherwise} \end{cases}$$

We introduce the decision variables:

$$w_i = \begin{cases} 1, & \text{if collection centre } i \text{ is on the tour}, \\ 0, & \text{otherwise} \end{cases}$$

$$x_{ij} = \begin{cases} 1, & \text{if arc } (i,j) \text{ is chosen to be in the solution}, \\ 0, & \text{otherwise} \end{cases}$$

The integer programming model can be now stated as

$$\text{Minimize} \sum_{(i,j)\in A} c_{ij}x_{ij} + \sum_{i\in N} F_i w_i \tag{9}$$

Subject to

$$\sum_{j:(j,i)\in A} x_{ji} = \sum_{j:(i,j)\in A} x_{ij} = w_i \quad \forall i \in N \tag{10}$$

$$\sum_{j\in N} a_{ij} w_i \geq k_i \quad \forall i \in N \tag{11}$$

$$\sum_{l\in S}\sum_{k\in N\setminus S} x_{lk} + \sum_{k\in N\setminus S}\sum_{l\in S} x_{kl} \geq 2(w_i + w_j - 1) S \subset N,$$

$$2 \leq |S| \leq n-2, \quad i \in S, j \in N \setminus S \tag{12}$$

$$x_{ij} \in \{0,1\} \quad \forall i,j \in A \tag{13}$$

$$w_i \in \{0,1\} \quad \forall i \in N. \tag{14}$$

The objective is to minimize the sum of the tour costs and collection centre visiting costs. Constraint set (10) ensures that for each on-tour collection centre, we have one incoming and one outgoing route. Constraint set (11) specifies that the demand of each collection centre must be covered. Constraint set (12) is a connectivity constraints that ensures there are no sub tours. Note that there are an exponential number of connectivity constraints. Constraints (13) and (14) define the variable as binary.

3.3. Optimal waste transportation form transfer station to processing plant

In a practical scenario, processing plants is setup at outside of the city (shown in Fig. 4). Therefore, we use heavy vehicle to transfer segregated waste to their respective processing plants. The optimal road length minimizes the transportation cost between the transfer stations to processing plants. Transfer stations and processing plants are represented by $P(K, L)$, where, $K = \{k_1, k_2, \ldots, k_n\}$ $(n \neq 0)$ and $L = \{l_1, l_2, \ldots, l_n\}$ $(n \neq 0)$ are represented transfer stations and processing plants and connection route between them.

In the third stage, we minimize path length between the transfer station and processing plant. At third level, optimization h number of transport vehicle visit each k_i transfer station where $k_i \in K$ through optimal path sequence, where $l_i \in L$. Our optimal waste transportation path calculation problem is related to Integer Covering Salesman Problem without Overnights (ICSP).

In this stage, any vehicle may visit more than one time to a transfer station, because of in high population density city's transfer station may contain the more amount of waste. Therefore, our objective function is

y_i = number of times that transfer station i is visited by the tour, and z_{ij} = number of times road (i, j) is traversed by the tour.

The integer programming model can now be stated as:

$$\text{Minimize} \sum_{(i,j)\in A} c_{ij}z_{ij} + \sum_{i\in N} F_i y_i \tag{15}$$

Subject to

$$\sum_{j:(j,i)\in A} z_{ji} = \sum_{j:(i,j)\in A} z_{ij} = y_i \quad \forall i \in N \tag{16}$$

$$\sum_{j\in N} a_{ij} y_j \geq k_i \quad \forall i \in N \tag{17}$$

$$y_i \leq L w_i \quad \forall i \in N \tag{18}$$

$$z_{ij} \leq L x_{ij} \quad \forall (i,j) \in A \tag{19}$$

$$\sum_{l\in S}\sum_{k\in N\setminus S} x_{lk} + \sum_{k\in N\setminus S}\sum_{l\in S} x_{kl} \geq 2(w_i + w_j - 1) S \subset N,$$

$$2 \leq |S| \leq n-2, i \in S, j \in N \setminus S \tag{20}$$

$$x_{ij} \in \{0,1\}, z_{ij} \in Z^+ \quad \forall (i,j) \in A \tag{21}$$

$$w_i \in \{0,1\}, y_i \in Z^+ \quad \forall i \in N \tag{22}$$

where L is the connecting route between transfer stations and processing plants. The objective is to minimize the sum of the tour costs and transfer visiting costs. Constraint set (16) ensures that if transfer station i is visited y_i times, then we have y_i incoming and y_i outgoing arcs. Constraint set (17) specifies the demand of each transfer station must be covered. Constraints set (18) and (19) are linking constraints, ensuring that w_i and x_{ij} are 1 if y_i or z_{ij} are greater than 0 (i.e. if a transfer station is visited or an arc is traversed). Note that it suffices to set $L = \max_{i\in N}\{k_i\}$. Constraint set (20) is a connectivity constraint that ensures that there are no sub tours.

Note again, that there are an exponential number of connectivity constraints. Finally, constraints set (21) and (22) define the variables as binary an integer as appropriate. For the ICSP with overniths, the above integer programming model is valid if we augment the arc set A with a self-loops. Specially, we add to A the arc set $\{(i, i): i \in N\}$ or $(A = A \cup \{(i, i): i \in N\})$ with c_{ii} the cost of self-loop arcs (i, i) set to 0.

3.4. Optimal waste transportation from processing plant to landfill site

In this phase we have not used any standard optimization technique for transporting of producing waste from processing plant to landfill sites because in real life scenarios the produced waste material is used as road construction material by the third party or sent to landfills. Therefore, different third party contractors carry this material from the plants. Therefore, we only set our processing plant in the nearby a landfill site for despatching produced (inert) waste usually. Therefore, unused materials are disposed without any cost.

4. Methodology

In waste management system, waste collection, transfer and transportation are a complex problem where three different processes are going on sequentially in three different levels. Each level uses individual collection or transportation strategy to collect and transport wastes from sources to processing plants. For this complex problem a local optimization problem is more cost effective. Therefore, we have used local optimization technique for each individual part that give better results for each particular real life problem.

Fig. 5 shows a schematic representation of the phases of the methodology proposed. The first phase of the methodology consists of number of sources, which are scattered throughout the city by heterogeneous way. Each of the source is connected to its neighbour sources by at least one route or more than one route. In the first phase, we have pointed out all sources and all possible connecting routes between them according to existing map. Then we apply our proposed route optimization technique to find out the optimal routes for waste collection. In the second phase, our main objective is to transport waste from collection centres to transfer stations through optimal routes. Therefore, the location of the collection centres and routes have been selected according to the existing map. Then we apply our proposed scheme for second phase optimization. In the third phase, the location of the transfer stations and routes between them has been identified through the detail existing map study. Then we found out the optimal route between the transfer stations by applying our third phase optimization process. The combination of these three phase output shows the optimal way of waste collection, transfer and transportation.

5. Performance evaluation

This section shows the simulation result with respect to real life data that have been gathered in the Kolkata metropolitan city (In-

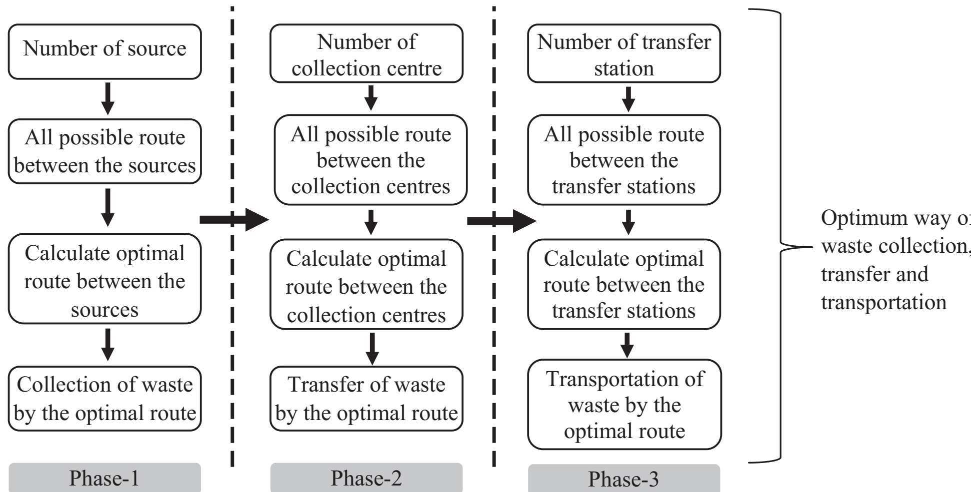

Fig. 5. Schematic representation of the phases of the methodology proposed.

dia). The factors related to this proposed scheme are the Kolkata metropolitan city area comprising about 1886.67 km^2, having population of 1,41,12,536 as per the 2011 census, density of 7480 per square km, quantity of waste generation 4837 tonne/day, per capita waste generation 0.35 kg/capita/day. Also considered the collection centres capacity 2 tonne, transfer vehicle capacity 1 tonne, transfer stations capacity 15–18 tonne and the transportation vehicle capacity 4–5 tonne. In the performance evaluation process, the optimal path shows between the sources and waste collection centre, second we show the optimal path between the waste collection centre and transfer station. After that, we describe the optimal path between the transfer station to processing plant also shown in the figure.

5.1. Optimal waste collection between the sources and waste collection centre

Fig. 6(a) shows all possible paths between the source points. The position of the sources and path between the sources has been identified according to 'BF' block of the Bidhan nagar municipal corporation area (under Kolkata metropolitan city).

Initially, we have taken 100 number of source points for our experiment, we have identified distances between these sources according to their position. The source position has been identified through GPS like devices. For simulation, we have imported the real life data to the MATLAB simulation software. We calculated the optimal path between the 100 sources points through MATLAB with the help of the proposed scheme.

Table 1 shows the distance of each path between the sources. According to these distances we calculated the optimal waste collection path between the sources and collection centres. In real life, Table 1 distance originally shows the each road length that has been present between the sources.

Fig. 6(b) shows the optimal path between the 100 source points. The optimal path has been simulated in the MATLAB software according to the real life data which are collected from 'BF' block of the Bidhan Nagar municipal corporation area. The optimal path reduces the tour length for waste collection. The path has been shown by the sequence of the sources that will be followed by the waste collector. The sequence of the sources is following: 99 → 100 → 95 → 94 → 93 → 92 → 89 → 90 → 89 → 88 → 87 → 86 → 85 → 84 → 83 → 82 → 81 → 80 → 57 → 80 → 79 → 78 → 77 → 76 → 75 → 74 → 91 → 74 → 73 → 96 → 97 → 98 → 71 → 72 → 66 → 65 →64 → 63 → 62 → 61 → 60 → 59 → 58 → 56 → 55 → 54 → 53 → 50 → 49 → 48 → 47 → 43 → 42 → 43 → 68 → 69 → 70 → 39 → 40 → 41 → 35 → 36 → 37 → 38 → 12 → 13 → 14 → 11 → 10 → 17 → 16 → 15 →16 → 17 → 18 → 19 → 34 → 46 → 45 → 44 → 33 → 32 → 31 → 30 →51 → 52

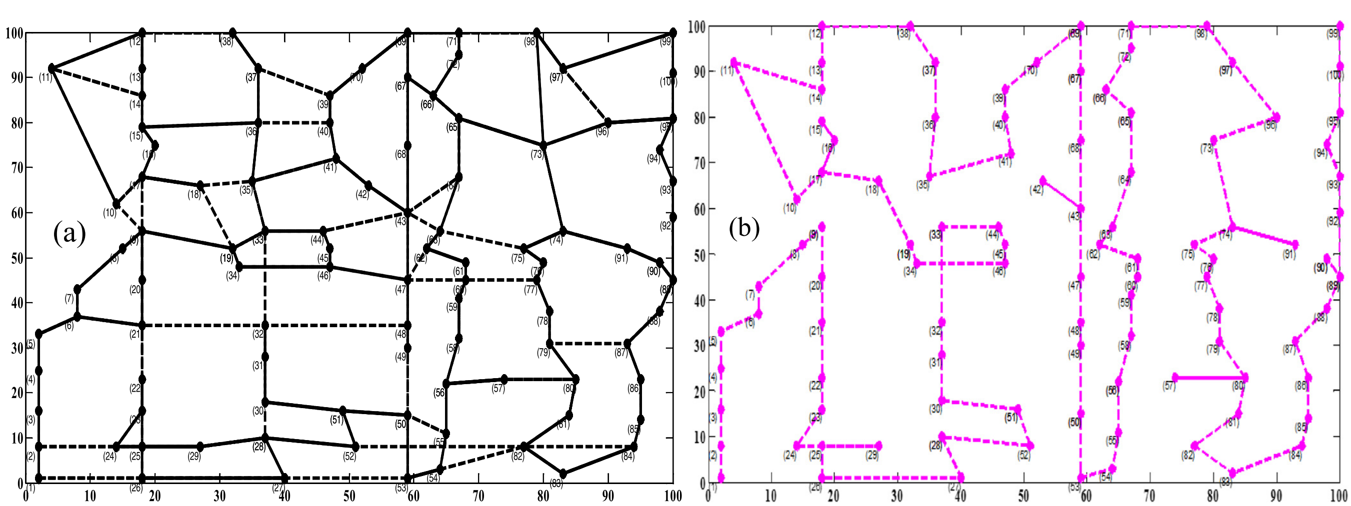

Fig. 6. (a) All possible path between the sources. (b) Optimal path between the sources.

Table 1
Path distance (m) between the sources.

Source	Destination source	Distance	Source	Destination source	Distance	Source	Destination source	Distance
1	2	7	31	32	7	63	64	12.37
1	26	16	32	33	21	63	75	13.6
2	3	8	32	48	22	64	65	13
2	24	12	33	35	11.18	65	66	6.4
3	4	9	33	44	9	65	73	14.32
4	5	8	34	46	14	66	67	5.66
5	6	7.21	35	36	13.04	66	72	9.85
6	7	6	35	41	13.93	67	68	15
6	21	10.2	36	37	12	67	69	10
7	8	11.4	36	40	11	69	70	10.63
8	9	5	37	38	8.94	69	71	8
9	10	7.21	37	39	12.53	71	72	5
9	17	12	39	40	6	71	98	12
9	19	14.56	39	70	7.81	73	74	19.24
9	20	11	40	41	8.06	73	96	11.18
10	11	31.62	41	42	7.81	73	98	25.02
10	17	7.21	42	43	8.49	74	75	7.21
11	12	16.12	43	44	13.6	74	91	10.77
11	14	15.23	43	47	15	75	76	4.24
12	13	8	43	63	6.4	76	77	4.12
12	38	14	43	64	11.31	77	78	7.28
13	14	6	43	68	15	78	79	7
14	15	7	44	45	4.12	79	80	8.94
15	16	4.47	45	46	4	79	87	12
15	36	18.03	46	47	12.37	80	81	8.06
16	17	7.28	47	48	10	81	82	9.9
17	18	9.22	47	60	9	82	83	8.49
18	19	14.87	47	62	7.62	82	84	17
18	35	8.06	48	49	5	83	84	12.53
19	33	6.4	49	50	15	84	85	6.08
19	34	4.12	50	51	10.05	85	86	9
20	21	10	50	53	14	86	87	8.25
21	22	12	50	55	7.21	87	88	8.6
21	32	19	51	52	8.25	88	89	7.28
22	23	7	52	82	26	89	90	4.47
23	24	8.94	53	54	5.39	89	92	14
23	25	8	54	55	8.06	90	91	5.83
24	25	4	54	82	13.93	92	93	8
25	26	7	55	56	11	93	94	7.28
25	29	9	56	57	9.06	94	95	7.28
26	27	22	56	58	10.2	95	96	10.05
27	28	9.49	57	80	11	95	100	10
27	53	19	58	59	9	96	97	13.89
28	29	10.2	59	60	4.12	97	98	8.94
28	30	8	60	61	4	97	99	18.79
28	52	14.14	60	77	11	99	100	9
30	31	10	61	62	6.71	–	–	–
30	51	12.17	62	63	4.47	–	–	–

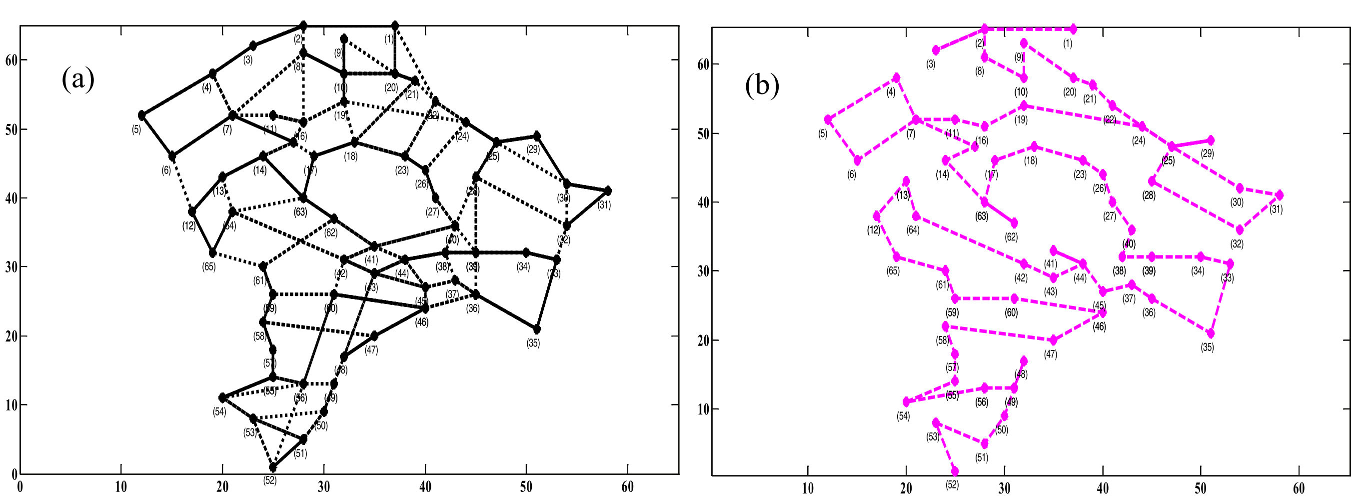

Fig. 7. (a) All possible path between the collection centres. (b) Optimal path between the collection centres.

Table 2
Path distance (km) between the collection centres.

Collection centre	Destination collection centre	Distance	Collection centre	Destination collection centre	Distance	Collection centre	Destination collection centre	Distance
1	2	9	21	22	3.61	42	60	5.1
1	20	7	22	23	8.54	42	64	13.04
1	22	11.7	22	24	4.24	43	44	3.61
2	3	5.83	23	26	2.83	43	45	5.39
2	8	4	24	25	4.24	43	48	12.37
3	4	5.66	24	26	8.06	44	45	4.47
4	5	9.22	25	28	5.39	45	46	3
4	7	6.32	25	29	4.12	46	47	6.4
5	6	6.71	25	30	9.22	46	60	9.22
6	7	8.49	26	27	4.12	47	48	4.24
6	12	8.25	27	40	4.47	47	58	11.18
7	8	11.4	28	32	11.4	48	49	4.12
7	11	4	28	39	11	49	50	4.12
7	15	7.21	28	40	7.28	49	56	3
8	10	5	29	30	7.62	50	51	4.47
8	16	10	30	31	4.12	50	53	7.07
9	10	5	30	32	6	51	52	5
9	20	7.07	31	32	6.4	51	53	5.83
10	19	4	32	33	5.1	52	53	7.28
10	20	5	33	34	3.16	52	56	12.37
11	16	3.16	33	35	10.2	53	54	4.24
12	13	5.83	34	39	5	54	55	5.83
12	65	6.32	35	36	7.81	54	56	8.25
13	14	5	36	37	2.83	55	56	3.16
13	64	5.1	36	39	6	55	57	4
14	15	3.61	36	46	5.39	56	60	13.34
14	63	7.21	37	38	4.12	57	58	4.12
15	16	3.16	37	45	3.16	58	59	4.12
15	17	2.83	38	39	3	59	60	6
16	19	5	38	40	4.12	59	61	4.12
17	18	4.47	38	44	4.12	61	62	9.9
17	63	6.08	39	40	4.47	61	65	5.39
18	19	6.08	40	41	8.54	62	63	4.24
18	21	10.82	41	42	3.61	63	64	7.28
18	23	5.39	41	44	3.61	64	65	6.32
19	24	12.37	41	62	5.66	–	–	–
20	21	2.24	42	43	3.61	–	–	–

→ 28 → 27 → 26 → 25 → 29 → 24 → 23 → 22 → 21 → 20 →9 → 8 → 7 → 6 → 5 → 4 → 3 → 2 → 1. The numbering of the sources given as per the planning of Municipality Corporation (Bidhan Nagar). The numbering of the sources are used to identify the sequence of the optimal visiting path. The total path length in the case study area is 2947 m and the optimal path length is 2009 m. The optimal waste collection path can reduce the number of waste collector if waste collection time is constant. On the other hand, if waste collectors are fixed, then waste collection time has been reduced. When waste collectors are fixed for a particular area, then these waste collectors collect the waste from that particular area within the minimum time period. Therefore, we have used this collectors for loading and unloading purposes in collection centres or transfer stations that can also reduce waste collection labour cost. Therefore, the proposed scheme reduces marginally the overall collection cost of municipal solid waste.

5.2. Optimal path between waste collection centres and transfer station

Fig. 7(a) shows the all possible paths between the 65 waste collection centres. In our simulation, we have considered initially 65 waste collection centres available within the Bidhan Nagar municipal corporation area (under Kolkata metropolitan city). In real life, each path between the waste collection centres indicates route between the waste collection centres. According to our proposed scheme, small size vehicles collects waste from the collection centres and conveyed it to transfer station. In this process, we optimize waste collection path between the collection centres and transfer stations. This optimized path not only optimized waste collection cost it also minimizes waste collection time.

The path cost between the collection centres are shown in Table 2. These costs indicate road distance between the collection centres.

Fig. 7(b) show the optimal path between the 65 collection centres. This optimal path has been calculated according to the optimization formula shows in Eq. (9). Small size vehicles, visit each waste collection centres through this optimal path and collects waste from the collection centres. After that collected waste has brought to the transfer station. Initially, all vehicles start from an initial waste collection centre and each vehicle visit at least one waste collection centre before going to transfer station. On the other hand optimal waste transfer, we also consider that all waste collection centres must be visited by at least one vehicle. The optimization waste transfer path is represented by the sequence of the collection centre. The sequence of the collection centres is following: 52 → 53 → 51 → 50 → 49 → 48 → 49 → 56 → 54 → 55 → 57 → 58 → 47 → 46 → 60 → 59 → 61 → 65 → 12 → 13 → 64 → 42 → 43 → 44 → 41 → 44 → 45 → 37 → 36 → 35 → 33 → 34 → 39 → 38 → 40 → 27 → 26 → 23 → 18 → 17 → 63 → 62 → 63 → 14 → 15 → 7 → 6 → 5 → 4 → 7 → 11 → 16 → 19 → 24 → 25 → 28 → 32 → 31 → 30 → 25 → 29 → 25 → 24 → 22 → 21 → 20 → 9 → 10 → 8 → 2 → 3 → 2 → 1. The total road length in the case study area is 19.89 km and the optimal road length in the case study area is 12 km. The optimal path length can reduce the number of waste transfer vehicles (small size vehicles) and also reduces the waste transfer time. Therefore, this optimization path marginally reduces the transfer cost of municipal solid waste.

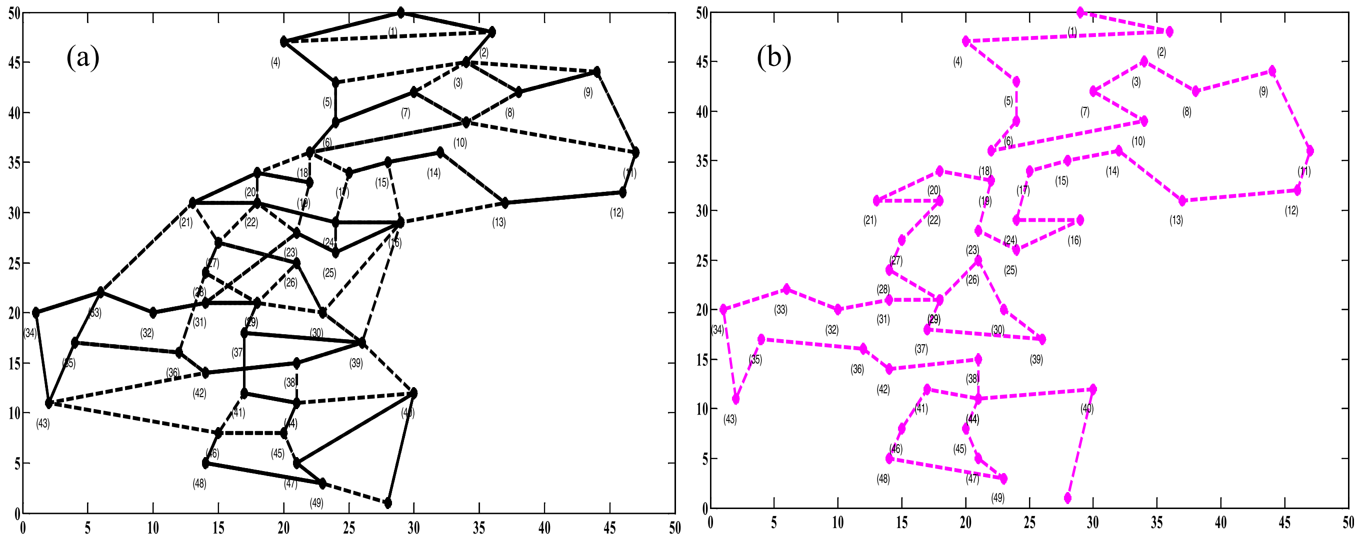

Fig. 8. (a) All possible path between the transfer stations. (b) Optimal path between the transfer stations.

Table 3
Path distance (km) between the transfer stations.

Transfer station	Destination transfer station	Distance	Transfer station	Destination transfer station	Distance	Transfer station	Destination transfer station	Distance
1	2	7.28	16	39	12.37	31	32	4.12
1	4	9.49	17	18	3.61	32	33	4.47
2	3	3.61	17	24	5.1	33	34	5.39
2	4	16.03	18	19	3	33	35	5.39
3	5	10.2	18	20	4.47	34	43	9.06
3	7	5	19	20	4.12	35	36	8.06
3	8	5	19	23	5.1	35	43	6.32
3	9	10.05	20	21	5.83	36	42	2.83
4	5	5.66	20	22	3	37	39	9.06
5	6	4	21	22	5	37	41	6
6	7	6.71	21	27	4.47	38	39	5.39
6	18	3.61	21	33	11.4	38	42	7.07
7	10	5	22	23	4.24	38	44	4
8	9	6.32	22	24	6.32	39	40	6.4
8	10	5	22	27	5	40	44	9.06
9	11	8.54	23	25	3.61	40	47	11.4
10	11	13.34	23	31	9.9	40	50	11.18
10	18	12.37	24	25	3	41	44	4.12
11	12	4.12	26	27	6.32	41	46	4.47
12	13	9.06	26	29	5	42	43	12.37
13	14	7.07	26	30	5.39	43	46	13.34
13	16	8.25	27	28	3.16	44	45	3.16
14	15	4.12	28	29	5	45	46	5
15	16	6.08	28	36	8.25	45	47	3.16
15	17	3.16	29	30	5.1	46	48	3.16
16	24	5	29	31	4	47	49	2.83
16	25	5.83	29	37	3.16	48	49	9.22
16	30	10.82	30	39	4.24	49	50	5.39

5.3. Optimal waste routing between the transfer stations and processing plants

In this process, we transfer waste from the transfer station to processing plants through minimum transportation cost. In our simulation, we consider 50 transfer stations within the Kolkata metropolitan city (shown in Fig. 8(a)). In real life scenario, each path between the transfer station indicates route between the transfer station and processing plants. Different wastes are transferred from the transfer station to categorize processing plant using heavy vehicles. The proposed optimization scheme, minimized transportation cost for categorize waste.

Table 3 shows all possible paths and their distances. We calculate the optimal path according to these costs. The route between the transfer station and processing plants are capable to carry the heavy vehicle.

Fig. 8(b) shows the optimal waste transportation path between the transfer stations to the categorized processing plants. The optimal path reduces transportation cost and time according to Eq. (15). In our optimization problem, we compute an optimal path for categorize waste transportation between the transfer station to processing plants. In this optimization, we consider that vehicle must visit at least one transfer station before visiting processing plant. On the other hand, we consider all transfer station must be visited by the vehicle at least one time.

After applying the TSP in this section, we got the sequence of transfer stations for optimal collection of the solid waste. The sequence of transfer stations in the case study is: 1 → 2 → 4 → 5

→ 6 → 18 → 10 → 7 → 3 → 8 → 9 → 11 → 12 → 13 → 14 → 15 → 17 → 24 → 16 → 25 → 23 → 19 → 20 → 21 → 22 → 27 → 28 → 29 → 26 → 30 → 39 → 37 → 29 → 31 → 32 → 33 → 34 → 43 → 35 → 36 → 42 → 38 → 44 → 41 → 46 → 48 → 49 → 47 → 45 → 44 → 40 → 50. The total road length in the case study area is 106.26 km and the optimal road length 58.33 km. Therefore, the optimal road length can reduce the number of transport vehicles (heavy). Analysing of this section, we can see that this program marginally reduces the transportation cost for segregated solid waste.

6. Conclusions

In this paper, we have faced waste collection and transportation problem arising when planning an effective waste management system. In particular, we have studied the problem of waste collection in a city where sources are scattered by heterogeneous way. In this paper, we have also studied waste transportation problem for time and cost effective waste management system design. For this problem, in this paper, we have divided the entire waste management system into three stages. Each stage has been optimized with the aid of TSP. We have proposed heuristic solution for optimal waste collection and transportation problem. The proposed scheme computes optimal waste collection and transportation path at each stage. Computational results and real life experiment have been shown the effectiveness of the proposed scheme. Results show that the proposed scheme is able to reduce more than 30% of the total waste collection path length. This reduction of path length in waste collection and transportation determine consistent monetary saving in the waste management operations.

Acknowledgements

The authors wish to thank the Kolkata as well as Bidhan Nagar municipal corporation administrative authority and their staff for helping to collect practical data and improve the quality of the work.

References

Amponsah, S.K., Salhi, S., 2004. The investigation of a class of capacitated arc routing problems: the collection of garbage in developing countries. Waste Manage. 24 (7), 711–721.
Aremu, A.S., 2013. In-town tour optimization of conventional mode for municipal solid waste collection. Nigerian J. Technol. 32 (3), 443–449.
Bovea, M.D., Ibanez-Fores, V., Gallardo, A., Colomer-Mendoza, F.J., 2010. Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study. Waste Manage. 30 (11), 2383–2395.
Consonni, S., Giugliano, M., Massarutto, A., Ragazzi, M., Saccani, C., 2011. Material and energy recovery in integrated waste management systems: project overview and main results. Waste Manage. 31 (9–10), 2057–2065.
Dumitrescu, I., Ropke, S., Cordeau, J.F., Laporte, G., 2009. The travelling salesman problem with pickup and delivery: polyhedral results and a branch and cut algorithm. Math. Programm. 121 (2), 269–305.
Eriksson, O., Bisaillon, M., Haraldsson, M., Sundberg, J., 2014. Integrated waste management as a mean to promote renewable energy. Renew. Energy 61, 38–42.
Gallardo, A., Carlos, M., Peris, M., Colomer, F.J., 2015. Methodology to design a municipal solid waste pre-collection system. A case study. Waste Manage. 36, 1–11.
Ionescu, G., Stefani, P., 2014. Environmental assessment of waste transport and treatment: a case study. WIT Trans. Ecol. Environ. 180, 175–185.
Ionescu, G., Rada, E.C., Ragazzi, M., Marculescu, C., Badea, A., Apostol, T., 2013. Integrated municipal solid waste scenario model using advanced pretreatment and waste to energy processes. Energy Convers. Manage. 76, 1083–1092.
Jacobsen, R., Buysse, J., Gellynck, X., 2013. Cost comparison between private and public collection of residual household waste: multiple case studies in the Flemish region of Belgium. Waste Manage. 33 (1), 3–11.
Kanchanabhan, T.E., Abbas Mohaideen, J., Srinivasan, S., Kalyana Sundaram, V.L., 2011. Optimum municipal solid waste collection using geographical information system (GIS) and vehicle tracking for Pallavapuram municipality. Waste Manage. Res. 29 (3), 323–339.
Khan, D., Samadder, S.R., 2014. Municipal solid waste management using geographical information system aided methods: a mini review. Waste Manage. Res. 32 (11), 1049–1062.
Kim, B.I., Kim, S., Sahoo, S., 2006. Waste collection vehicle routing problem with time windows. Comput. Oper. Res. 33 (11), 3624–3642.
Li, C.-Z., Zhang, Y., Liu, Z.-H., Meng, X., Du, J., 2014. Optimization of MSW collection routing system to reduce fuel consumption and pollutant emissions. Nat. Environ. Pollut. Technol. 13 (1), 177–184.
Massarutto, A., Carli, A.D., Graffi, M., 2011. Material and energy recovery in integrated waste management systems: a life-cycle costing approach. Waste Manage. 31 (9–10), 2102–2111.
Minoglou, M., Komilis, D., 2013. Optimizing the treatment and disposal of municipal solid wastes using mathematical programming – a case study in a Greek region. Resour., Conserv. Recycl. 80 (1), 46–57.
Nuortio, T., Kytojoki, J., Niska, H., Braysy, O., 2006. Improved route planning and scheduling of waste collection and transport. Expert Syst. Appl. 30 (2), 223–232.
Rabbani, M., Sadri, Sh., Rafiei, H., 2014. Vehicle-routing in a multimodal transportation system used in waste collection. In: IMSS 2014 – 9th International Symposium on Intelligent Manufacturing and Service Systems, pp. 203–212.
Rada, E.C., 2014. Energy from municipal solid waste. WIT Trans. Ecol. Environ. 190, 945–958.
Rada, E.C., Grigoriu, M., Ragazzi, M., Fedrizzi, P., 2010. Web oriented technologies and equipments for MSW collection. In: Proceedings of International Conference Risk Management, Assessment and Mitigation – RIMA'10, pp. 150–153.
Rada, E.C., Ragazzi, M., Fedrizzi, P., 2013. Web-GIS oriented systems viability for municipal solid waste selective collection optimization in developed and transient economies. Waste Manage. 33 (4), 785–792.
Renaud, J., Boctor, F.F., Laporte, G., 2002. Perturbation heuristic for the pickup and delivery travelling salesman problem. Comput. Oper. Res. 29 (9), 1129–1141.
Sahoo, S., Kim, S., Kim, B.I., 2005. Routing optimization for waste management. Interfaces 35 (1), 24–36.
Wagner, J., Bilitewski, B., 2009. The temporary storage of municipal solid waste – recommendations for a safe operation of interim storage facilities. Waste Manage. 29 (5), 1693–1701.
Weng, Y.C., Fujiwara, T., 2011. Examining the effectiveness of municipal solid waste management systems: an integrated cost–benefit analysis perspective with a financial cost modelling in Taiwan. Waste Manage. 31 (6), 1393–1406.
Wy, J., Kim, B.I., Kim, S., 2013. The rollon–rolloff waste collection vehicle routing problem with time windows. Eur. J. Oper. Res. 224 (3), 466–476.
Xu, S., Li, G., Ou, H., Wu, W., 2015. Research and demonstration of dynamic intelligent logistics system of the collection and transportation process of giant municipal garbage. Lect. Notes Electr. Eng. 286, 39–50.