Sustainable multi-trip periodic redesign-routing model for municipal solid waste collection network: The case study of Tehran

Leila Mahdavi¹. Saeed Mansour¹. Mohsen Sheikh Sajadieh¹

✉ Saeed Mansour  
s.mansour@aut.ac.ir  
¹ Department of Industrial Engineering, Amirkabir University of Technology (Tehran Polytechnic), No. 424, Hafez Ave, Valiasr Square, Tehran, Iran  
Tel: +98 21 64540
Abstract

Daily transportation of vehicles is one of the most important challenges in municipal solid waste management systems in developing countries related to environmental aspects in different areas, financial issues, and social factors. The location of transfer stations as intermediate nodes in municipal solid waste management network affects optimal collection frequency. Here a sustainable multi-period and multi-trip mixed-integer linear programming model was developed to redesign the intermediate transfer stations and find optimal routes for vehicles and the best collection frequency for each municipal solid waste generation point. Regarding the social aspect of sustainability, an extended social life cycle assessment methodology is developed for impact assessment of redesign and routing operations. The model is applied to a real-world case study with no cooperative perspective, which could result in total cost reduction by a 66% that occurred by a 86% reduction in weekly traveled distance and a 12% decrease in routing social score.

Keywords

Municipal solid waste, periodic location routing, multi-trip vehicle routing, sustainability, redesign routing model, strategic decisions, tactical and operational issues.
Introduction

Currently, atmospheric CO$_2$ is about 412 ppm with an increasing pattern of 2 ppm per year (Hannan et al. 2018). The most important source that increases CO$_2$ is transportation. According to the U.S. Environmental Protection Agency (EPA), the transportation sector generates the largest share (about 29%) of Green House Gas (GHG) emissions. Besides 5% of the global GHG emissions refereed to the perishable part of solid waste (Edalatpour et al. 2018). Daily transportation for collecting municipal solid waste (MSW) is one of the major parts of the municipal solid waste management system (MSWMS) in most developing countries. As there are many limitations in these countries including inadequate financial resources, any stages of the MSW management process should be done as efficient as possible (Moghadam et al. 2009). Also, environmental and health-related issues, increasing waste generation, and resource limitations make designing an efficient system for collecting MSW paramount important (Mirdar Harijani et al. 2017). In the Brundtland Report, sustainability is defined as “the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs”. For referring to the sustainable systems, three dimensions of sustainability – economic, environmental, and social – need to be considered (Ramos et al. 2014).

Municipal solid waste management (MSWM) involves several of strategic, tactical, and operational decisions. Addressing two or three groups of them simultaneously will increase the accuracy of resultant decisions. To make some efficient MSWM policy, many challenging questions may arise such as: What is the best policy for redesigning an existing intermediate transfer station (ITrS) in MSWMS? How to allocate waste generation points to each of these ITrSs? In a certain period, what is the best collection frequency for generation points? What is the best route for each vehicle? How to minimize costs for such a system? How to achieve a sustainable MSWMS? For addressing the questions, a sustainable MSWM network has been
introduced and a mixed-integer linear programming (MILP) model was developed to find an optimal solution with regard to the economic, environmental, and social dimensions of sustainability.

**Literature review**

This section provides brief literature on relocation, sustainability, and some variants of Vehicle Routing Problem (VRP) containing Location Routing Problem (LRP), Multi-trip, and Multi-period which are essential for making routing decisions of MSWMS. Decisions are categorized into two main group namely strategic/ tactical and operational decisions. Redesign/ relocation optimization literature in the field of MSWM is devoid of any in-depth research. Regarding redesign/relocation in other logistic networks, restructuring a warehouse network could lead to an annual saving of 5–10% of total logistics costs (Ballou 2007). The redesign of the distribution network of an actual electronics company examined by formulating a MILP for three-echelon multi-commodity of LRP (P. Sanghatawatana 2019). The consolidation of strategic and tactical decision levels could organize LRP (Prodhon 2011) for MSW (Asefi et al. 2015; Asefi and Lim 2017; Erfani et al. 2017; Farrokhi-Asl et al. 2017; Rabbani et al. 2017; Asefi et al. 2019).

To detect the optimal locations of MSWMS’s facilities consisting of ITrSs, treatment, recycling, and disposal centers and to determine the optimum routing strategy, a model of MSWM was organized (Asefi et al. 2015). For reducing daily collection tours, bin location problem and capacitated vehicle routing problem (CVRP) separately using GIS was solved for a real case and reached a suboptimal solution (Erfani et al. 2017). The choice of location of depots and disposal facilities from potential points was decided for the waste collection problem by solving with metaheuristic algorithms (Farrokhi-Asl et al. 2017). Choosing treatment facility potential locations and designing routes with multi-compartment vehicles assumption reached by developing an NSGA-II metaheuristic (Rabbani et al. 2017).
In many developing countries, there is a problem in collecting wastes where trucks are fully utilized only in certain days when demand is in its maximum level, while they are partially loaded on other days. This would generate additional costs for operational collection stages (Ghiani et al. 2014).

In waste management papers, there are some research works for the examination of periodic vehicle routing problem (PVRP) which is an extension of the classical VRP that customers are serviced with different frequencies over a time horizon (Beltrami and Bodin 1974). A mathematical model for the infectious hospital waste collection problem through a two phases PVRP was proposed (Shih and Chang 2001). The collection of recycling paper containers in Portugal in the context of the period vehicle routing system was studied (Baptista et al. 2002). An algorithm for a waste collection system involving 202 locations in the municipality of Viseu, Portugal was developed (Matos and Oliveira 2004). Recently, a MILP model for urban waste collection with considering multi-trip VRP with time windows and SA algorithm for solving the model in small and medium sizes was developed (Babaee Tirkolaee et al. 2019).

The summary of the literature in Table 1 shows that different types of optimization models in strategic, tactical, and operational issues have been developed in the field of MSWM. The surveyed articles did not simultaneously consider three dimensions of sustainability with strategic, tactical, and operational issues in MSWM. Authors believe that there is a gap in MSWM literature about the absence of an optimization model for considering three dimensions of sustainability aggregated with three aspects of strategic, tactical, and operational issues in MSWM literature.

This study proposes a MILP model to optimize the design and operations of the MSW collection network through a sustainable, multi-trip, and periodic redesign-routing problem (SMTP-reLRP) for MSWMS.
Table 1 Summary of related literature

| Research(s) | Waste management | Economic | Environment | Social | Location optimization | Redesign | LRP | Multi-period VRP | Multi-trip VRP |
|-------------|------------------|----------|-------------|--------|-----------------------|----------|-----|-----------------|----------------|
| (P. Sanghatawatana 2019) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| (Asefi et al. 2019) | ✓ | ✓ | ✓ | ✓ | ✓ |
| (Erfani et al. 2017) | ✓ | ✓ | ✓ | ✓ | ✓ |
| (Farrokhi-Asl et al. 2017) | ✓ | ✓ | ✓ | ✓ | ✓ |
| (Rabbani et al. 2017) | ✓ | ✓ | ✓ | ✓ | ✓ |
| (Shih and Chang 2001) | ✓ | ✓ |
| (Baptista et al. 2002) | ✓ | ✓ |
| (Matos and Oliveira 2004) | ✓ | ✓ |
| (Babaee Tirkolaee et al. 2019) | ✓ | ✓ |
| Current study | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

The SMTP-reLRP is to minimize economic and environmental costs subject to social constraints and other adapted constraints. The proposed SMTP-reLRP simultaneously decides the customers, vehicles, and the trips of a vehicle that should be serviced each day of a certain time horizon with considering redesign decisions of ITrSs.

Major contributions are: (1) it introduces a MILP optimization model to consider the sustainability of MSWMSs with strategic, tactical, and operational issues simultaneously, (2) it extends the social life cycle assessment (SLCA) methodology to model the social impacts of the network and (3) it considers the city.
of Tehran as a real case study to show the applicability of the proposed model and it can be a solution to the stated problems related to waste collection in Tehran.

**Problem definition and mathematical model**

Graphical representation for MSW collection VRP is provided in Fig.1(a) where the MSW collecting process starts from ITrSs as vehicles’ depots and will continue until the vehicle’s capacity complete. The destination of the vehicles will be the starting ITrS. This process is called a trip. In classic VRP, it is assumed that each vehicle only makes one trip, but this is not possible due to the scarcity of vehicles. For this reason, a sequence of trips must be performed by each vehicle called a journey. The network consists of two-echelon with two main different fleets, small and lightweight vehicles for the first part, and heavyweight semitrailers for the second part of the network. The lightweight vehicles and heavyweight semitrailers are referred to as vehicles and semitrailers respectively. In the first echelon, transportation costs for waste collection are considered. In contrast, in the second echelon only waste transferring costs are addressed. An example of the SMTP-reLRP solution is given in Fig.1(b). Cooperating municipal solid
waste collection demonstrated in Fig.1(c) is considered as the next generation of the MSW collection networks.
Fig. 1 a) Graphical representation for the current MSW collection problem, b) An illustration of the SMTP-reLRP solution in a week, c) Cooperating municipal solid waste collection scheme

Routing and redesign social scores

Multi-disciplinary and multi-stakeholders’ attributes of systems make measurement and controlling all aspects of social issues impossible (Hosseinijou et al. 2014; Mirdar Harijani et al. 2017).

For social impact assessment of redesign and routing operations in the proposed model, the first guidelines for SLCA of UNEP/SETAC (UNEP/SETAC 2009) is used with some modifications. The details of extended SLCA methodology are shown in Fig. 2.

The developed SLCA methodology includes four main steps: Goal and scope definition, Life cycle inventory analysis, Life cycle impact assessment and Life cycle interpretation.
About the first step, the goal is to assess the social scores of the routing and redesign system and the scope is the whole stages of MSW collection network from generation nodes to treatment, recycling, disposal facilities.

In the second step, the result should be some inventory indicators in order to reach the goal mentioned in previous step. The guidelines of UNEP/SETAC (UNEP/SETAC 2009) includes five stakeholder groups and further 31 assessment subcategories introduced through international consensus and presented to the experts including managers, engineers, workers, consumers and local communities. The goal and scope are explained and based on their opinions selected impact subcategories by stakeholders and experts who have more influence on stakeholders are presented in Table 2 in routing and redesign section respectively. In order to measure the score of facilities, 21 and 16 inventory indicators are developed for routing and redesign section respectively (see Table 2).
Fig. 2 Steps of the proposed SLCA methodology for calculating the social score of routing and redesign system

The third step calculates the social score of routing and redesign section using a characterization model which is based on a scoring system. For each subcategory, there are inventory indicators and measurement guidelines to assess life cycle impacts. Scoring system assigns a value of \{1, 2, ..., m_i\} for inventory indicator i for fulfillment degree of the social criteria, respectively, the lowest level to highest fulfillment level. Answers given by each stakeholder interviewed regarding fulfillment will be transformed into these values. The number of all the interviewed stakeholders is n. By considering that \(s_{ij}\) is the selected score of stakeholder j to indicator i average score for each indicator can be calculated by Equation (1):

\[
\bar{s}_i = \frac{\sum_{j=1}^{n} s_{ij}}{m_i/n}
\]  (1)
The social score for the indicator $i$ ($\bar{s}_i$) will be a decimal number between 0 and 1. For calculating the final social score of routing it is necessary to normalize all average scores of 21 indicators as presented in Equation (2):

$$S_{scr} = \sum_{i=1}^{21} \alpha_i \bar{s}_i$$

(2)

The $\alpha_i$ coefficients show the importance weight of indicator $i$ and their summation is equal to one. In addition, the selected impact subcategories and 16 developed inventory indicators for the redesign system are presented in Table 2. Similarly, redesign social score is calculated over the above procedure.

The Fourth step is life cycle interpretation. The results indicate that the routing system have higher positive social impacts than redesign system.
Table 2: Selected impact subcategories and developed inventory indicators for the routing and redesign system (Aparcana and Salhofer 2013)

| Stakeholder    | Selected subcategories | Inventory indicators                                                                 | routing system | redesign system |
|----------------|-------------------------|--------------------------------------------------------------------------------------|----------------|----------------|
| Worker         | Health and safety       | Absence of working accidents                                                        | ✓              | ✓              |
|                |                         | Vaccination for workers                                                              | ✓              | ✓              |
|                |                         | Training programs regarding preventive measures                                      | ✓              | ✓              |
|                |                         | Formal policy about health and safety for workers                                     | ✓              | ✓              |
|                |                         | Access to medical centers for workers                                                | ✓              | ✓              |
|                |                         | Access to preventive equipment for workers in prevalence situation                   | ✓              |                 |
|                |                         | Absence of disease for workers                                                       | ✓              | ✓              |
|                | Child labor             | Absence of child labor                                                                | ✓              | ✓              |
|                | Fair salary             | Regular payment for workers                                                           | ✓              | ✓              |
|                |                         | Absence of non-agreed income deductions                                               | ✓              | ✓              |
|                | Working hour            | Doing of overtime agreed in working contracts                                          | ✓              |                 |
|                |                         | Overtime balance between workers                                                      | ✓              |                 |
|                | Social security         | Existence of social security                                                          |                 | ✓              |
| Customer       | Health and safety       | Satisfaction of cleaning of containers                                               | ✓              |                 |
|                |                         | Satisfaction about pollution                                                          | ✓              |                 |
|                |                         | Satisfaction of collection frequency                                                 | ✓              |                 |
|                | Feedback mechanism      | Existence of a reporting system for suggestions                                        |                 | ✓              |
| Local community| Local employment        | Creating job opportunities                                                            | ✓              | ✓              |
|                | Delocalization          | Reduce in housing prices                                                              |                 | ✓              |
|                | Safe and healthy living conditions | Willingness to continue living in the district                                      |                 | ✓              |
|                | Contribution to economic development | Progress of annual redesign cost /annual revenue index                               |                 | ✓              |
|                | Access to material resources | Accessibility to containers                                                          |                 | ✓              |
| Society        | Economic development    | Progress of annual cost /annual revenue index                                         | ✓              | ✓              |
| Prevention of armed conflicts | Reduce in number of dissatisfaction calls | ✓ |
|-------------------------------|-----------------------------------------|---|
| Value chain actors           | Fair competition                        | ✓ |
|                              | Formal policy for selecting contractors |   |
**Problem assumptions and formulation**

Problem assumptions are as follows: Customer’s demand for waste collecting is deterministic and known. Potential location for establishing new ITrS or aggregation with existing ITrS is given. Each customer is serviced at most once during the day and at least once in a week. The vehicles are homogeneous with maximum time and capacity of service. The semitrailers are homogeneous maximum capacity of service. Each vehicle may have multiple trips. ITrSs are origins and destinations of the trips. Each trip has the same origin and destination.

**Sets**

$Ex$  Set of existing ITrSs in existing network

$N$  Candidate nodes establishing a probable new ITrS

$I$  Union of $Ex$ and $N$ sets, $I = Ex \cup N$

$J$  Set of customers for collecting services

$T$  Set of days in planning period

$R$  Set of trips, $R = \{1, \ldots, w\}$

$K_1$  Set of vehicles, $K_1 = \{1, \ldots, NV\}$

$K_2$  Set of Semitrailers, $K_2 = \{1, \ldots, k\}$

$P$  Set of treatment, recycling and disposal facilities, $P = \{1, \ldots, p\}$
\( M \) Set of types of emission to air, \( M = \{1, \ldots, m\} \)

**Parameters**

- \( f_{re_i} \) Relocation cost (USD) of existing ITrS \( e \) to the aggregated location \( i, e \in Ex, i \in I \)
- \( f_{m_i} \) Fixed storage cost (USD) of existing ITrS \( i \) independent of its capacity, \( i \in I \)
- \( f_{s_e} \) Saving cost (USD) from closure of ITrS \( e, e \in Ex \)
- \( f_c \) Unit overhead costs (USD/year) of vehicles
- \( c_{k_1} \) Unit traveling costs (USD/(m*Kg)) of vehicles, \( k_1 \in K_1 \)
- \( c_{k_2} \) Unit transferring costs with collected MSW (USD/(m*Kg)) of semitrailer, \( k_2 \in K_2 \)
- \( d_{ij} \) Distance (m) between node \( i \) and \( j, i \in I \cup J, j \in I \cup J \)
- \( t_{ij} \) Traveling time (min) between node \( i \) and \( j, i \in I \cup J, j \in I \cup J \)
- \( D_{k_1} \) Maximum operating time (min) of vehicles, \( k_1 \in K_1 \)
- \( W \) An upper bound for number of vehicle trips, \( k_1 \in K_1 \)
- \( q_j \) Daily demand (kg) of customer \( j \)
- \( Q_{k_1} \) Vehicle’s capacity (kg), \( k_1 \in K_1 \)
- \( Q_{k_2} \) Semitrailer’s capacity (kg), \( k_2 \in K_2 \)
- \( FTL^m \) Coefficient of increase in emission \( m \) when semitrailers travel Full-Truck-Load (FTL)
\(\Psi^m\)  Amount (kg/m) of emission of type \(m\) from MSW transportation by vehicles

\(\Omega^m\)  Amount (kg/(kg* m)) of emission of type \(m\) from MSW transferring by semitrailers semitrailer

\(ec_m\)  Unit environmental cost (USD/kg emissions) of emissions of type \(m\), \(meM\)

\(E_{scr}^{j,k,r,t}\)  Normalized weight of social criteria for routing which vehicle \(k\) during trip \(r\) of day \(t\) visits customer \(j\)

\(E_{sei}^{sel}\)  Normalized weight of social criteria for establishment of \(i\)

\(E_{sei}^{sel}\)  Normalized weight of social criteria for relocating \(e\) to \(i\)

\(S^{scr}\)  Social score for routing

\(S^{sci}\)  Social score for redesign

\(\Delta\)  The minimum acceptable rate for social score of the network

**Variables**

\(x_{ij}^{k,r,t}\)  1 if vehicle \(k\) passes edge \((i,j)\) in trip \(r\) and day \(t\), 0 otherwise, \(k \in K_1, i,j \in I \cup J, r \in R, t \in T\)

\(y_{j}^{k,r,t}\)  1 if vehicle \(k\) collects demand of customer \(j\) in trip \(r\) and day \(t\), 0 otherwise, \(k \in K_1, i,j \in I \cup J, r \in R, t \in T\)

\(t \in T\)

\(\alpha_{pi}^{kt}\)  Amount of MSW (kg) transferred from IT\(i\)S \(i\) to treatment, recycling, disposal facilities \(p\) in day \(t\), \(i \in I, p \in P, t \in T, k \in k_2\)
\(Tak^k_{er}\) Amount of MSW (kg) collected and disposed in ITrS \(e\) by vehicle \(k\) in trip \(r\) and day \(t\)

\(s_i\) Number of vehicles assigned to the ITrS \(i\), \(i \in I\)

\(s_i^t\) Number of vehicles assigned to the ITrS \(i\) in day \(t\), \(i \in I\), \(t \in T\)

\(z_{ei}\) 1 if an existing ITrS \((eeEx)\) is relocated to the location \(i\) \((i \neq e)\) or an existing ITrS \(e\) \((eeEx, i = e)\) be open, 0 otherwise

\(w_i\) 1 if a new ITrS is establish in candidate location for ITrS \(i\), 0 otherwise, \(i \in N\)

**Objective function**

Minimize \(COST = \sum_{j \in J, j \in J} \sum_{k \in K_1} \sum_{r \in R} \sum_{t \in T} \sum_{d_{ij}} c_{k_1} q_{j} x_{ij}^{krt}\) \(+ \sum_{t \in T} \sum_{k \in K_2} \sum_{i \in I} \sum_{p \in P} d_{ip} c_{k_2} (\alpha_{ip}^{kt} + 1)\)

\(+ \sum_{e \in Ex} \sum_{i \in I} f r e_{ei} z_{ei}\)

\(+ \sum_{i \in Ex} f m_{i} z_{it} \sum_{l \in N} f m_{i} w_{i}\)

\(+ \sum_{j \in E} (f s_{j} (1 - \sum_{i \in I} z_{ji}) + f m_{j} \sum_{(e \in Ex, i \neq j)} z_{ji})\)

\(+ \sum_{i \in I} f c \times s_{i}\)

\(+ \sum_{m \in M} c m \times\)

\(\left(\sum_{j \in J, j \in J} \sum_{k \in K_1} \sum_{r \in R} \sum_{t \in T} d_{ij} \alpha_{ij}^{krt}\right)\)

\(+ \sum_{t \in T} \sum_{k \in K_2} \sum_{i \in I} \sum_{p \in P} \Omega^{m} d_{ip} \times FTL^m \times \alpha_{ip}^{kt}\)

\(+ \sum_{t \in T} \sum_{k \in K_2} \sum_{i \in I} \sum_{p \in P} \Omega^{m} d_{ip} \alpha_{ip}^{kt}\)
The objective function is to minimize the cost \((COST)\) as described by Eq. (4). It consists of two parts to tackle two dimensions of sustainability.

\[
\text{Minimize } COST = ECOCOST + ENVCOST \tag{4}
\]

\(ECOCOST\) is presented in Eq. (5).

\[
ECOCOST = TPCOST + TFCOST + RCOST + MCOST - SCOST + FVCOST \tag{5}
\]

\(TPCOST\) or the routing cost is calculated based on the distance matrix, as Eq. (6). Additional information on how to calculate \(q_{jt}\) is provided in appendix A.

\[
TPCOST = \sum_{i \epsilon I} \sum_{l \epsilon (I,J)} \sum_{k \epsilon K_1} \sum_{r \epsilon R} \sum_{t \epsilon T} d_{ij} c_{k1} q_{jt} x_{ij}{krt} \tag{6}
\]

\(TFCOST\) is waste transferring costs between ITrSs and treatment, recycling, and disposal facilities, as shown in Eq. (7). The coefficient is referred to as returning cost from treatment, recycling disposal facilities to ITrSs when the semitrailers are empty.

\[
TFCOST = \sum_{t \epsilon T} \sum_{k \epsilon K_2} \sum_{l \epsilon (I,J)} \sum_{p \epsilon P} d_{ip} c_{k2} (\alpha_{ip}^{kt} + 1) \tag{7}
\]

\(RCOST\) is given by Eq. (8). The equation represents the relocation cost of an existing ITrS to a new or another existing ITrS.

\[
RCOST = \sum_{i \epsilon I} \sum_{l \epsilon (I,J)} f_{ri} a_{li} \tag{8}
\]

\(MCOST\) is fixed maintenance costs of a new or an existing ITrS including insurance, taxes, and renting costs, as described in Eq. (9).
\[ MCOST = \sum_{i \in Ex} fm_i z_{ii} + \sum_{i \in N} fm_i w_i \]  

(9)

SCOST is cost savings resulted from the closure of existing ITrS, as Eq. (10).

\[ SCOST = \sum_{j \in Ex} [fs_j (1 - \sum_{i \in I} z_{ji}) + fm_j \sum_{(i \in Ex, j \neq i)} z_{ji}] \]  

(10)

FVCOST is the fixed cost of vehicles paid to the contractors as shown in Eq. (11).

\[ FVCOST = \sum_{i \in I} fc \times s_i \]  

(11)

ENVCOST is the total environmental cost caused by waste transportation by vehicles and semitrailers. As shown in Eq. (12) it consists of three parts. Transportation and transferring wastes could result in GHG emissions. GHG emissions associated with the collection routes and the second echelon of the network produced by semitrailers are measured through ENVCOST. The environmental cost of emission \( m \) through the collection phase is calculated by the first term in Eq. (12). Moreover, the environmental cost of emission \( m \) from waste transportation by semitrailers when they are traveling FTL is calculated by the second term. The last term is the environmental cost of emission \( m \) when the semitrailers are empty during their trip back to the ITrSs.

\[ ENVCOST = \sum_{m \in M} ec_m \times \left[ \sum_{j \in I \cup J} \sum_{i \in I \cup J} \sum_{k \in K} \sum_{t \in T} \sum_{r \in R} d_{ij} \mu m x_{ij} \right]  

+ \sum_{t \in T} \sum_{k \in K} \sum_{i \in I} \sum_{p \in P} \Omega m d_{ip} \times FTL m \times \alpha_{tp}^k  

+ \sum_{t \in T} \sum_{k \in K} \sum_{i \in I} \sum_{p \in P} \Omega m d_{ip} \alpha_{tp}^k \]  

(12)

Constraints
The constraints are divided into four main components which are related to the generation nodes, vehicles, tours and ITrSs. In the following the connection among the components are provided:

**Generation node’s constraints**

\[ \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} y_{j}^{krt} \geq 1 \quad \text{for } j \in J \] (13)

Constraints (13) ensure that every generation node is served at least once in a given period.

\[ \sum_{k \in K} \sum_{r \in R} y_{j}^{krt} \leq 1 \quad \text{for } j \in J \text{ and } t \in T \] (14)

In contrast, Constraints (14) emphasize that every generation node must be served at most once in each day of a certain period.

\[ \sum_{i \in I \cup J} x_{ij}^{krt} = y_{j}^{krt} \quad \text{for } j \in J \text{ and } k \in K \text{ and } r \in R \text{ and } t \in T \] (15)

Constraints (15) consider the relation between \( x_{ij}^{krt} \) and \( y_{j}^{krt} \) variables.

\[ \sum_{i \in I \cup J} x_{i}^{krt} = \sum_{j \in J} x_{e}^{krt} \quad \text{for } e \in I \cup J \text{ and } k \in K \text{ and } r \in R \text{ and } t \in T \] (16)

Constraints (16) ensure the flow conservation for generation node and ITrS.

\[ \sum_{k \in K} \sum_{r \in R} y_{j}^{krt} \leq \sum_{k \in K} \sum_{r \in R} y_{j}^{krt} \quad \text{for } j \in J \text{ and } t \in T \text{ and } 1 \leq t < i \] (17)

Constraints (17) indicate that the demands are met for the entire planned period.

**Vehicle’s constraints**

\[ \sum_{j \in J} q_{jt} y_{j}^{krt} \leq Q_{k1} \quad \text{for } k \in K \text{ and } r \in R \text{ and } t \in T \] (18)

Constraints (18) ensure the total MSW collected during a trip should not exceed the vehicle's maximum capacity.
Constraints (19) are limitation on collection operation time.

**ITrS’s constraints**

\[
\sum_{i \in I} \sum_{j \in J} \sum_{r \in R} t_{ij} x_{ij}^{krt} = D_{k1} \quad k \in \mathcal{K}, t \in T
\]  

(19)

Constraints (20) and (21) ensure that the inlet flow to each ITrS (total daily waste collected) and the outlet flow to the ITrSs (to processing plants) must be equal.

\[
\sum_{j \in J} q_{jt} x_{ij}^{krt} + \sum_{i \in I} q_{jt} x_{ij}^{krt} = T a_{e}^{krt} \quad e \in \mathcal{E}, t \in T, r \in \mathcal{R}, k \in \mathcal{K}
\]  

(20)

\[
\sum_{k \in K_1} \sum_{r \in R} T a_{k}^{krt} = \sum_{k \in K_2} \sum_{p \in P} a_{ip}^{krt} \quad i \in \mathcal{I}, t \in T
\]  

(21)

**Constraints (22), (23), and (24) are related to the redesign and relocation of ITrSs. Constraints (22) state that the capacity of an existing ITrS cannot be relocated to the capacity of another existing ITrS unless that ITrS remains open. Constraints (23) state that the capacity of an existing ITrS cannot be relocated to another new ITrS unless that new ITrS has been established. In Constraints (24), all options for an existing ITrS include (Keeping it open, integration with another existing ITrS, moving to another new ITrS, or closing the existing ITrS) are examined.**

\[
\sum_{e \in \mathcal{E}} z_{e1} \leq |\mathcal{E}| z_{ii} \quad i \in \mathcal{E}
\]  

(22)

\[
\sum_{e \in \mathcal{E}} z_{e1} \leq |\mathcal{E}| w_{i} \quad i \in \mathcal{N}
\]  

(23)

\[
\sum_{i \in \mathcal{E} \cup \mathcal{N}} z_{ei} \leq 1 \quad e \in \mathcal{E}
\]  

(24)

**Constraints (25) indicate that if an existing and a new ITrS wish to be integrated into a new ITrS site, the existing ITrS must be pre-established.**

\[
s_{i}^{l} \leq w_{i} \quad i \in \mathcal{N}, t \in T
\]  

(26)
Constraints (26) and (27) denote that prior to allocating the vehicles to any ITrSs, it must be pre-established. Constraints (28) and (29) indicate the relation between the number of vehicles that should be allocated to ITrSs and the number of total existing vehicles.

**Tours constraints**

\[ s_i^t \leq z_{it} \quad \text{for } i \in \text{Ex}, t \in T \]  
(27)

\[ s_i^t \leq s_i \quad \text{for } i \in \text{el}, t \in T \]  
(28)

\[ \sum_{i \in \text{el}} s_i = NV \]  
(29)

Constraints (28) and (29) are subtour elimination constraints.

**Connection among vehicles and generation nodes constraints**

\[ \sum_{i \in \text{el} \subseteq S} \sum_{j \in \text{el} \subseteq S} x_{ij}^{krt} \leq |S| - 1 \quad \text{for } k \in \text{el}, t \in T, w \in I \cup J; |S| \geq 2 \]  
(30)

Constraints (30) are subtour elimination constraints.

\[ \sum_{j \in \text{el}} x_{ij}^{krt} \leq 1 \quad \text{for } i \in \text{el}, k \in \text{el}, t \in T \]  
(31)

\[ \sum_{i \in \text{el}} x_{ij}^{krt} \leq 1 \quad \text{for } j \in \text{el}, k \in \text{el}, t \in T \]  
(32)

After leaving the ITrS, each vehicle could only visit a generation node on its trip and the return trip to the ITrS should be from a generation node addressed in Constraints (31) and (32).

**Connection among vehicles, generation nodes and ITrSs constraints**

\[ x_{ij}^{krt} \leq \sum_{e \in \text{Ex}, j \in \text{el}} z_{ei} \quad \text{for } e \in \text{Ex}, j \in \text{el}, k \in \text{el}, t \in T \]  
(33)

\[ x_{ij}^{krt} \leq w_{ij} \quad \text{for } i \in \text{el}, j \in \text{el}, k \in \text{el}, t \in T \]  
(34)

Similarly, Constraints (33) and (34) emphasize that before the collection operation commences, the origin of these flows must establish.
Constraints (35) indicate that if the vehicle wishes to have a trip that serves more than one customer or in the network there is an edge connecting two customers, the vehicle must begin its trip from ITrS.

\[
\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} x_{ij}^{krt} \leq \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} x_{ij}^{krt} \quad \text{for } i \in I, j \in J, k \in K, r \in R, t \in T
\]  

Finally, Constraints (36) consider the social dimension of sustainability in routing and redesign of the network. The social score of the network should be greater or equal than a specific value calculated based on trial and error method with considering the local governments and the responsible organizations for MSWMSs.

\[
\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} S_{sca} \times x_{ij}^{krt} \times y_{ij}^{krt} + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} S_{scl} \times x_{ij}^{krt} \times y_{ij}^{krt} + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} S_{scl} \times x_{ij}^{krt} \times y_{ij}^{krt} \geq \Delta
\]  

Constraints (37) – (44) include the binary and non-negative requirements for the variables.
Case study description

To represent the applicability of the SMTP-reLRP model, a real case study is used, related to Tehran, the capital of Iran. Tehran waste management organization (TWMO) is responsible for collecting, separating, and processing MSW of all 22 districts but the collection operation is outsourced to 58 contractors (TWMO 2020). Here the case is related to the contractor who collects the MSW of district 8, region 2, Haft Howz neighborhood, which discharges the collected MSW in Beyhaghi ITrS. Currently, MSW collection of this area is done by two vehicles during the day. The approximate location of MSW containers (The main version of TMWO can be seen in appendix B) and the current collection route of the vehicles are shown in Fig.3(b) and Fig.3(c). Each vehicle performs some trips every day and the patterns of routes in all trips are similar for each vehicle. The drivers repeat their trips at least twice in 24 hours. The MSW container numbers in Fig.3(a) indicates the order of visits and Fig.3(b) and Fig.3(c) demonstrate current vehicle 1 and 2 route patterns implemented by the contractor respectively.

The number of MSW containers in the considered region is 69 with a maximum capacity of 55 kg. About the daily demand parameter in the SMTP-reLRP model, the data is derived from the weighing system located in Beyhaghi ITrS. By examining daily generated MSW in 2018, the average daily demands for the route of vehicles 1 and 2 are 664 kg and 456 kg respectively.

As the containers are located in a region with the same geographical, historical, cultural, and economic characteristics, it is realistic to assume the daily demands of customers in a route are equal. Therefore, daily demand of MSW containers in the route of vehicle 1 and 2 is 40 kg and 41 kg respectively. Both vehicles are similar and have 6 tons of capacity. Weekly fixed and variable cost are 148.79 UC or Unit Cost (Because the costs of the contractors are confidential, the exact unit is not provided) and 4.6* 10e-7 UC per meter and per kg respectively (TWMO 2020). The maximum daily working time for them is 300 minutes.
For obtaining the exact solution, NEOS solver for optimization is used online (Gropp and Moré 1997; Czyzyk et al. 1998; Dolan 2001). Within the NEOS server, IBM ILOG CPLEX Optimizer is applied. CPLEX uses a branch and cut algorithm which solves a series of LP sub problems and can obtain the exact solution for the problem with maximum of 1000 variables and 1000 constraints. Here with 69 customers, there are one million constraints. For solving this problem, square adjacency matrix $A$ [[customers]] is defined. It is a zero-one matrix with zeros on its diagonal since edges from a customer node to itself are not allowed. Other elements of $A_{ij}$ are one when there is just one choice for continuing the trip which is an edge from customer node $i$ to customer node $j$. In the streets, it is usual to have just one choice for servicing other MSW containers from a fixed container. The adjacency matrix could help to omit the MSW container nodes that do not determine the optimal route. For example, for the route of vehicle 1, as the container nodes 1 to 12 are located in a one-way street, if node 2 is selected then there is no other choice for completing the trip unless reaching node 12. The 26 key MSW container nodes for the region are shown in Fig.3(d). Therefore, the daily demand for key MSW containers are achieved by aggregating the daily demand of non-key MSW containers to the nearest key MSW container.
Fig. 3 a) Current approximate MSW container location, b, c) daily route pattern by vehicles, d) 26 key MSW container nodes

Semitrailer capacities for transferring MSWs from ITrSs to the processing plants are 22 tons with $5.6 \times 10^{-7}$ UC variable cost per kg and per meter. The candidate ITrS for considering the redesigning options is Banihashem ITrS. The saving cost of Beyhaghi ITrS closure is considered 7474 UC.

Aradkooh waste processing plant which is the biggest one in Tehran is considered a processing plant in the model and has the distance 47 and 51 (km) with Beyhaghi and Banihashem ITrS respectively. The distances
between nodes are obtained from Google Maps. All the parameters are uploaded on given link: (Dropboxlink).

For solving the problem presented of a real case study, some main parameters of the SMTP-reLRP model should be set. For the case study, the environmental and social parameters setting process are provided in next sections respectively.

**Environmental parameters**

About environmental costs, four main types of emissions are considered, i.e., CO\(_2\), SO\(_2\), NO\(_x\), and VOC emissions. The unit environmental cost and the amount of emissions caused by transportation and transferring operations is considered based on recent researches (Mirdar Harijani et al. 2017). As the MSW is transported and transferred by diesel-fueled trucks named vehicles and semitrailers it is supposed that GHG emissions (kg emissions/kg of MSW) for them are equal.

**Social parameters**

About social constraints, at first, the inventory indicators for the social score of routing and redesign operation were scored by 43 people, including employees of TWMO and contractors in charge of waste collection. Secondly, for routing and redesign operation, the summation of normalized weight is 0.6 and 0.4 respectively. Thirdly, the minimum acceptable rate for the total social score of the network is chosen via sensitivity analysis. Considering that all participants choose the worst and the best score for each indicator, the social score of the routing section will be equal to 0.25 and 1 respectively. It is the same for
the social score of the redesigning. Considering economic and environmental function \( \text{Fig.4(a)} \) indicates the minimum acceptable rate for the total social score of the network should be between 0.0001 and 0.4 because for the other values the solver has an infeasible solution. Here \( \Delta \) parameter is considered 0.004.

Finally, about the social score for routing and relocation, \( \text{Fig.4(a)} \) indicates that the diagram related to \( S^{scr} \). \( S^{sel} = 1 \) has the most feasible solutions. In other words, the higher the scores provided by experts, the higher probability of finding the optimal solution. These values are \( S^{scr} = 0.63 \) and \( S^{sel} = 0.62 \) with considering the scores of employees of TWMO and contractors in charge of waste collection.

**Results and discussion**

\( \text{Fig.4(b)} \) shows the results of solving the \( SMTP-reLRP \) model for the case study. As the real distances between ITrSs and demand nodes are long, the location of ITrSs is considered symbolically.
Fig. 4 a) Acceptable range of $\Delta$ parameter via economic and environmental function consideration, b) Optimal routing and redesign for the case study

Daily trips of vehicles and tour duration for the optimal solution are provided in Table 3. Optimal solution indicates that vehicles should begin their trips from Beyhaghi and vehicles 1 and 2 can cover all weekly requirements for waste collection with 3 and 2 trips respectively.

The results show that for the first research question, there is no need to relocate Beyhaghi ITrS for the case. As stated before, for Tehran case, TWMO is responsible for collecting, separating, and processing MSW of all 22 districts but the collection operation is outsourced to 58 contractors. The results of solving the case are related to one of these contractors and for this contractor Beyhaghi is the best choice of being ITrS.
Table 3 Results of solving the SMTP-reLRP model for the Haft Howz district of Tehran

| Tour | Day | Vehicle | Optimal route | Traveled distance (km) | Tour duration (min) |
|------|-----|---------|---------------|------------------------|---------------------|
| 1    | 7   | 1       | Beyhaghi-(22-21-20-19-18-17-16-15-14)(green)-12-11-10-9-8-7-6-5-4-3-2-1-23-22-21-20-19-18-17-16-15-14-13-Beyhaghi | 26                      | 49                  |
| 2    | 7   | 1       | Beyhaghi-30-32-31-29-28-27-26-24-25-34-33-Beyhaghi | 17                      | 28                  |
| 3    | 7   | 1       | Beyhaghi-(8-9-10-11-12-13) green-Beyhaghi | 13                      | 26                  |
| 1    | 7   | 2       | Beyhaghi-(1-2-3-4-5-6-7) green-35-36-Beyhaghi | 17                      | 27                  |
| 2    | 7   | 2       | Beyhaghi-47-46-45-44-43-42-41-40-39-38-37-Beyhaghi | 18                      | 30                  |

Optimal total traveled distance (km) 91
Current total traveled distance (km) 672
Weekly CO₂ Emission reduction from transportation (kg) 447
Optimal total transferring distance (km) 94
Current total transferring distance (km) 685
Weekly CO₂ Emission reduction from transferring (kg) 660

It seems that by considering some/all of these contractors or changing system boundaries and solving the problem from a general perspective, the relocation of Beyhaghi ITsS will not be unexpected. Moreover, in current Tehran ITsSs’ structure there is no cooperative perspective between ITsSs as value chain actors. Cooperating municipal solid waste collection scheme demonstrated in Fig.1(c) could result in changing ITsSs’ structure. In other words, if the ITsSs as value chain actors work with cooperation, the result of relocation of them is expected. It could be considered as a direction for future researches.

Besides, the comparison of the annual capacity of the ITsSs and the average annual amount of Tehran MSW generation rate indicates that the redesign of ITsSs will be more probable. The average daily amount of Tehran MSW generation rate is about 9000 tons which equals 328*e10+4 tons in a year. According to the annual capacity of an ITs which is 175*e10+4 tons, it seems that the existence of 11 ITsSs is not cost-
effective and revision in ITrS's numbers and locations could help to reduce the municipality operation costs (TWMO 2020).

It should be noted the solution of the model is obtained with this assumption that only the revenues from the equipment sale are included in the saving cost from the closure of Beyhaghi ITrS (7474 UC). However, if the profit from the ITrS's estate sale is taken into account, this number will increase to 1257474 UC.

About the second research question or allocation rule of waste generation points to the Beyhaghi ITrS and with comparison to existing MSW collection operation, routing pattern switched from two dimensions for each vehicle. The first dimension is the number of generation nodes which are visited in a trip for the vehicles. The second dimension will be the number of trips assigned to each vehicle in a day.

The third research question is about the collection frequencies for the generation points. The results indicate that for any generation node the optimum solution is the visiting and servicing them just once in a week. For the other research questions, about the best routes Fig.4(b) is shown and as a result costs minimization representation is investigated through solving the model with scenarios in which social and environmental consideration are ignored. In other words, to evaluate the impact of sustainability the SMTP-reLRP model is compared with three other possible models in Table 4: I) only economic aspect of sustainability is considered, II) the economic and environmental dimensions of sustainability are considered, III) the economic and social dimensions of sustainability are considered. Table 4 shows the comparison between the key results of the SMTP-reLRP model and the models (I), (II) and (III). The economic dimension of the sustainability is considered in all of them. The comparison of the SMTP-reLRP and model (I) indicates that model (I) leads to less COST and less social benefits. This denotes that the omitting the social constraints might decrease costs from the collection network.
Model (I) and model (II) have same solution for collecting MSW network. As the environmental costs are considered in model (II) it’s calculated cost is more than the cost of model (I).

Similarly, comparison of the SMTP-reLRP model and model (III) shows that the solutions of both are same. For the case, involving the sustainability concept results in a sustainable solution with a higher social score and higher system costs in comparison with the solution of the model without considering the sustainability factors.
### Table 4: The key results of the SMTP-reLRP model and the models (I), (II) and (III)

| Model            | Sustainability | Objective function | Subject to the constraints set given by: | COST(UC)  | ECOCOST(UC) | ENVCOST(UC) | Relocation social score | Routing social score |
|------------------|----------------|--------------------|-------------------------------------------|-----------|-------------|--------------|------------------------|---------------------|
| Current          | Excluded       | -                  | -                                         | 3534941.42 | 794570.78   | 2740370.635  | 0.624                  | 0.715               |
| SMTP-reLRP model | Included       | Minimize ECOCOST and ENVOCOST | Eqs. (13) to (44)                         | 1186024.5  | 794536.64   | 391487.85    | 0.624                  | 0.626               |
| Model (I)        | Excluded       | Minimize ECOCOST   | Eqs. (13) to (35) and (37) to (44)        | 650324.12  | 650324.12   | -            | 0.624                  | 0.615               |
| Model (II)       | Excluded       | Minimize ECOCOST and ENVOCOST | Eqs. (13) to (44) and (37) to (44)        | 961199.22  | 650324.12   | 310875.1     | 0.624                  | 0.615               |
| Model (III)      | Excluded       | Minimize ECOCOST   | Eqs. (13) to (44)                         | 794536.64  | 794536.64   | -            | 0.624                  | 0.626               |
To compare the result with the existing situation, Table 4 is presented. The weekly cost function has decreased 2348916 UC which equals to 122143679 UC in a year. 66% saving cost is obtained via finding optimal weekly collection frequency and finding the best redesign. Objective function, total traveled distance of the current status and the Number of vehicle’s trip in a week are calculated with the current minimum collection frequency in 24 hours. Maximum daily working hour is reduced from 24 to 5 hours. Moreover, Number of involving days is decreased from seven days to one day.

Table 4 indicates that current collection operation suffers from a lot of inefficiency in terms of cost objectives. Generally, it should be noted that Tehran municipality outsourced the collection operation into the contractors and there are many inefficient rules for controlling the contractors, which led to inefficient collection operation.

The proposed model considers three dimension of sustainability including economic, environmental and social aspect of MSW collection simultaneously and the results indicate that there are many inefficiencies in current collection operation.

**Conclusion**

In this research, the SMTP-reLRP model for simultaneous consideration of three sustainability dimensions with strategic, tactical, and operational issues in MSWMSs is introduced. Given the literature, this is the first study that considers economic, environmental, and social concerns for two main parts of MSWMSs named MSW collection and ITrSs redesign. The SMTP-reLRP develops multi-trip PVRP by considering redesign strategies for ITrSs with regard to the sustainability concept. Regarding the social aspect of sustainability, an extended social life cycle assessment methodology is developed for impact assessment of
redesign and routing operations. To represent the SMTP-reLRP model applicability a real case study was investigated. For obtaining the exact solution of the problem CPLEX optimizer is used. It has been described that for the real case, the proposed model can result in total cost reduction by 66% that occurred by 86% reduction in weekly traveled distance and a 12% decrease in routing social score. The results indicate that there are many inefficiencies in current collection operation.

Furthermore, involving the sustainability concept results in a sustainable solution for the case with a higher social score and higher system costs in comparison with the solution of the model without considering the sustainability factors.

For future research, involving the environmental factors about different collection frequency options, for example, the effect of collection frequency on attracting pests and leakage of leachate is suggested.

Because of the limited real data for testing of the model, observation of some potential features of the model, such as, the closing or relocation of facilities was hard. Solving the model for investigating the reduction possibility of ITrSs numbers located in Tehran city is direction for future research. Moreover, cooperative perspective between ITrSs as value chain actors will be another direction for future researches.

In addition, extension of the model in stochastic form to accommodate the demand uncertainty is suggested.

**Declarations:**

**Ethics approval and consent to participate**

Not applicable.

**Consent for publication**

Not applicable.
Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Funding

Not applicable.

Authors’ contributions

Conceptualization, Methodology, Software: [Leila Mahdavi]. Data curation, Writing- Original draft preparation: [Leila Mahdavi]. Visualization, Investigation: [Leila Mahdavi, Mohsen Sajadieh:]. Supervision: [Saeed Mansour]. Software, Validation: [Leila Mahdavi]. Writing- Reviewing and editing: [Leila Mahdavi, Saeed Mansour, Mohsen Sajadieh:]. All authors read and approved the final manuscript.
References

Aparcana, S., & Salhofer, S. (2013). Development of a social impact assessment methodology for recycling systems in low-income countries. *The International Journal of Life Cycle Assessment, 18*(5), 1106-1115.

Asefi, H., & Lim, S. (2017). A novel multi-dimensional modeling approach to integrated municipal solid waste management. *Journal of cleaner production, 166*, 1131-1143.

Asefi, H., Lim, S., & Maghrebi, M. (2015). A mathematical model for the municipal solid waste location-routing problem with intermediate transfer stations. *Australasian Journal of Information Systems, 19*.

Asefi, H., Lim, S., Maghrebi, M., & Shahparvari, S. (2019). Mathematical modelling and heuristic approaches to the location-routing problem of a cost-effective integrated solid waste management. *Annals of Operations Research, 273*(1-2), 75-110.

Babaee Tirkolaee, E., Abbasian, P., Soltani, M., & Ghaffarian, S. A. (2019). Developing an applied algorithm for multi-trip vehicle routing problem with time windows in urban waste collection: A case study. *Waste Management & Research, 37*(1_suppl), 4-13.

Ballou, R. H. (2007). The evolution and future of logistics and supply chain management. *European business review*.

Baptista, S., Oliveira, R. C., & Zúquete, E. (2002). A period vehicle routing case study. *European Journal of Operational Research, 139*(2), 220-229.

Beltrami, E. J., & Bodin, L. D. (1974). Networks and vehicle routing for municipal waste collection. *Networks, 4*(1), 65-94.

Czyzyk, J., Mesnier, M. P., & Moré, J. J. (1998). The NEOS server. *IEEE Computational Science and Engineering, 5*(3), 68-75.

Dolan, E. D. (2001). NEOS Server 4.0 administrative guide. *arXiv preprint cs/0107034.*

Edalatpour, M., Mirzapour Al-e-hashem, S., Karimi, B., & Bahlil, B. (2018). Investigation on a novel sustainable model for waste management in megacities: A case study in tehran municipality. *Sustainable cities and society, 36*, 286-301.

Erfani, S. M. H., Danesh, S., Karrabi, S. M., & Shad, R. (2017). A novel approach to find and optimize bin locations and collection routes using a geographic information system. *Waste Management & Research, 35*(7), 776-785.

Farrokhi-Asl, H., Tavakkoli-Moghaddam, R., Asgarian, B., & Sangari, E. (2017). Metaheuristics for a bi-objective location-routing-problem in waste collection management. *Journal of Industrial and Production Engineering, 34*(4), 239-252.

Ghiani, G., Laganà, D., Manni, E., Musmanno, R., & Vigo, D. (2014). Operations research in solid waste management: A survey of strategic and tactical issues. *Computers & Operations Research, 44*, 22-32.
Gropp, W., & Moré, J. (1997). Optimization Environments and the NEOS Server in MD Buhmann and A. Iserles (eds.), Approximation Theory and Optimization. Cambridge University Press.

Hannan, M., Akhtar, M., Begum, R., Basri, H., Hussain, A., & Scavino, E. (2018). Capacitated vehicle-routing problem model for scheduled solid waste collection and route optimization using PSO algorithm. Waste management, 71, 31-41.

Hosseini-Jou, S. A., Mansour, S., & Shirazi, M. A. (2014). Social life cycle assessment for material selection: a case study of building materials. The International Journal of Life Cycle Assessment, 19(3), 620-645.

Matos, A. C., & Oliveira, R. C. An experimental study of the ant colony system for the period vehicle routing problem. In International Workshop on Ant Colony Optimization and Swarm Intelligence, 2004 (pp. 286-293): Springer.

Mirdar Harijani, A., Mansour, S., & Karimi, B. (2017). A multi-objective model for sustainable recycling of municipal solid waste. Waste Management & Research, 35(4), 387-399.

Moghadam, M. A., Mokhtarani, N., & Mokhtarani, B. (2009). Municipal solid waste management in Rasht City, Iran. Waste management, 29(1), 485-489.

P. Sanghatawatana, P. P., and M. Lohatepanont (2019). Redesign of Three-Echelon Multi-Commodity Distribution Network. Eng. J, 23(1), 49-74.

Prodhon, C. (2011). A hybrid evolutionary algorithm for the periodic location-routing problem. European Journal of Operational Research, 210(2), 204-212.

Rabbani, M., Farrokh-Asl, H., & Asgarian, B. (2017). Solving a bi-objective location routing problem by a NSGA-II combined with clustering approach: application in waste collection problem. Journal of Industrial Engineering International, 13(1), 13-27.

Ramos, T. R. P., Gomes, M. I., & Barbosa-Póvoa, A. P. (2014). Planning a sustainable reverse logistics system: Balancing costs with environmental and social concerns. Omega, 48, 60-74.

Shih, L.-H., & Chang, H.-C. (2001). A routing and scheduling system for infectious waste collection. Environmental Modeling & Assessment, 6(4), 261-269.

TWMO (2020). Statistics report on 2019. Tehran Waste Management Organization, Tehran municipality, Iran. http://pasmand.tehran.ir/.

UNEP/SETAC (2009). Guidelines for Social Life Cycle Assessment of Products. United Nations Environment Programme and the Society of Environmental Toxicology and Chemistry, Belgium.
Appendix A

In Constraints (18), (20), and Objective function, \( q_{jt} \) is the demand of customer \( j \) on day \( t \), which depends on whether or not the vehicles have been served to customer \( i \) in previous days. In fact, every day that the customer is not served, the demand for the day will be aggregated and the same customer’s demand must be met on the first service day. So the value \( q_{jt} \) can be rewritten in Eq. (45):

\[
q_{jt} = q_j[t - \max \left( \sum_{r \in R} \sum_{k \in K_1} y_{jkr}^{krl} \right)]
\]

\[
= q_j[t - \phi_{jt}]
\]

Then the model will be nonlinear and must be linearized:

\[
\phi_{jt} = \max \left( \sum_{r \in R} \sum_{k \in K_1} y_{jkr}^{krl} \right)
\]

\[
\phi_{jt} \geq \sum_{r \in R} \sum_{k \in K_1} y_{jkr}^{krl}
\]

Note Constraints (47) and \( \phi_{jt} \in N \) will be added to the main constraints. Constraints (30) greatly influence solving time which is a classic subtour elimination constraint for VRPs. Here a replaced formulation to overcome the limitations (Miller, Tucker et al. 1960) is derived and Equations (48), (49), and \( \mu_j \geq 0 \) is added to the model.

\[
q_j[t - \phi_{jt}] \leq \mu_j \leq Q_{k_1} \quad j \in J, t \in T
\]

\[
\mu_{it} - \mu_j + Q_{k_1} \sum_{k \in K_1} \sum_{r=1}^w x_{ijr}^{krt} - (Q_{k_1} - q_i[t - \phi_{it}] - q_j[t - \phi_{jt}]) \times \sum_{k \in K_1} \sum_{r=1}^w x_{ijr}^{krt}
\]

\[
i \neq j \in I \cup J, t \in T
\]
\[ \leq Q_k - q_j[t - \phi_{jt}] \]

It can be seen that Objective function and Constraints (18), (49) and (20) will be nonlinear. The following constraints must be considered in model for the linearization.

\[
\phi_{jt} x_{ij}^{krt} = w_{ij}^{krt} \tag{50}
\]

\[
w_{ij}^{krt} \leq \emptyset_{jt} \tag{51}
\]

\[
w_{ij}^{krt} \leq M x_{ij}^{krt} \tag{52}
\]

\[
w_{ij}^{krt} \geq \emptyset_{jt} - (1 - x_{ij}^{krt}) \times M \tag{53}
\]

\[
w_{ij}^{krt} \geq 0 \tag{54}
\]
Appendix B

Fig. 5 MSW container’s location map of Haft Howz neighborhood (TWMO 2020)