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

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Abstract	16
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.	17 18 19 20 21 22 23 24 25 26
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Municipal solid waste, periodic location routing, multi-trip vehicle routing, sustainability, redesign routing model, strategic decisions, tactical and operational issues.	28 29 30 31 32 33 34 35 36 37 38 39

Introduction	40
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).	41 42 43 44 45 46 47 48 49 50 51 52 53 54
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	55 56 57 58 59 60 61

introduced and a mixed-integer linear programming (MILP) model was developed to find an optimal	62
solution with regard to the economic, environmental, and social dimensions of sustainability.	63
	64
Literature review	65
This section provides brief literature on relocation, sustainability, and some variants of Vehicle Routing	66
Problem (VRP) containing Location Routing Problem (LRP), Multi-trip, and Multi-period which are	67
essential for making routing decisions of MSWMS. Decisions are categorized into two main group namely	68
strategic/ tactical and operational decisions. Redesign/ relocation optimization literature in the field of	69
MSWM is devoid of any in-depth research. Regarding redesign/relocation in other logistic networks,	70
restructuring a warehouse network could lead to an annual saving of 5–10% of total logistics costs (Ballou	71
2007). The redesign of the distribution network of an actual electronics company examined by formulating	72
a MILP for three-echelon multi-commodity of LRP (P. Sanghatawatana 2019). The consolidation of	73
strategic and tactical decision levels could organize LRP (Prodhon 2011) for MSW (Asefi et al. 2015; Asefi	74
and Lim 2017; Erfani et al. 2017; Farrokhi-Asl et al. 2017; Rabbani et al. 2017; Asefi et al. 2019).	75
To detect the optimal locations of MSWMS's facilities consisting of ITrSs, treatment, recycling, and	76
disposal centers and to determine the optimum routing strategy, a model of MSWM was organized (Asefi	77
et al. 2015). For reducing daily collection tours, bin location problem and capacitated vehicle routing	78
problem (CVRP) separately using GIS was solved for a real case and reached a suboptimal solution (Erfani	79
et al. 2017). The choice of location of depots and disposal facilities from potential points was decided for	80
the waste collection problem by solving with metaheuristic algorithms (Farrokhi-Asl et al. 2017). Choosing	81
treatment facility potential locations and designing routes with multi-compartment vehicles assumption	82
reached by developing an NSGA-II metaheuristic (Rabbani et al. 2017).	83

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 (Babaei 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

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Research(s)	Sustainability				Strategic/		Tactical/	
	Waste management	Economic	Environment	Social	Location optimization	Redesign	LRP	Operational issues
(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)		✓						✓
(Babae 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. 126

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(c)

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	139
is the whole stages of MSW collection network from generation nodes to treatment, recycling, disposal	140
facilities.	141
In the second step, the result should be some inventory indicators in order to reach the goal mentioned in	142
previous step. The guidelines of UNEP/SETAC (UNEP/SETAC 2009) includes five stakeholder groups	143
and further 31 assessment subcategories introduced through international consensus and presented to the	144
experts including managers, engineers, workers, consumers and local communities. The goal and scope are	145
explained and based on their opinions selected impact subcategories by stakeholders and experts who have	146
more influence on stakeholders are presented in Table 2 in routing and redesign section respectively. In	147
order to measure the score of facilities, 21 and 16 inventory indicators are developed for routing and	148
redesign section respectively (see Table 2).	149

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Fig.2 Steps of the proposed SLCA methodology for calculating the social score of routing and redesign system

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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 $\{1, 2, \dots, m_i\}$ 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 \(1\)](#):

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$$\bar{s}_i = \frac{\sum_{j=1}^n s_{ij} / n}{m_i} \quad (1)$$

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):

$$S^{scr} = \sum_{i=1}^{21} \alpha_i \bar{s}_i \quad (2)$$

The α_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)

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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		✓
		Willingness to continue living in the district		✓
	Safe and healthy living conditions	Living satisfaction		✓
	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	✓	

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Problem assumptions and formulation	172
Problem assumptions are as follows: Customer's demand for waste collecting is deterministic and known.	173
Potential location for establishing new ITrS or aggregation with existing ITrS is given. Each customer is	174
served at most once during the day and at least once in a week. The vehicles are homogeneous with	175
maximum time and capacity of service. The semitrailers are homogeneous maximum capacity of service.	176
Each vehicle may have multiple trips. ITrSs are origins and destinations of the trips. Each trip has the same	177
origin and destination.	178
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Sets	180
<i>Ex</i> Set of existing ITrSs in existing network	181
<i>N</i> Candidate nodes establishing a probable new ITrS	182
<i>I</i> Union of <i>Ex</i> and <i>N</i> sets, $I = Ex \cup N$	183
<i>J</i> Set of customers for collecting services	184
<i>T</i> Set of days in planning period	185
<i>R</i> Set of trips, $R = \{1. w\}$	186
K_1 Set of vehicles, $K_1 = \{1. NV\}$	187
K_2 Set of Semitrailers, $K_2 = \{1. k'\}$	188
<i>P</i> Set of treatment, recycling and disposal facilities, $P = \{1. p\}$	189

M	Set of types of emission to air, $M = \{1. \dots m\}$	190
		191
Parameters		192
fr_{ei}	Relocation cost (USD) of existing ITrS e to the aggregated location i , $e \in Ex$, $i \in I$	193
fm_i	Fixed storage cost (USD) of existing ITrS i independent of its capacity, $i \in I$	194
fs_e	Saving cost (USD) from closure of ITrS e , $e \in Ex$	195
fc	Unit overhead costs (USD/year) of vehicles	196
c_{k1}	Unit traveling costs (USD/(m*Kg)) of vehicles, $k_1 \in K_1$	197
c_{k2}	Unit transferring costs with collected MSW (USD/(m*kg)) of semitrailer, $k_2 \in K_2$	198
d_{ij}	Distance (m) between node i and j , $i \in I \cup J$, $j \in I \cup J$	199
t_{ij}	Traveling time (min) between node i and j , $i \in I \cup J$, $j \in I \cup J$	200
D_{k_1}	Maximum operating time (min) of vehicles, $k_1 \in K_1$	201
W	An upper bound for number of vehicle trips, $k_1 \in K_1$	202
q_j	Daily demand (kg) of customer j	203
Q_{k_1}	Vehicle's capacity (kg), $k_1 \in K_1$	204
Q_{k_2}	Semitrailer's capacity (kg), $k_2 \in K_2$	205
FTL^m	Coefficient of increase in emission m when semitrailers travel Full-Truck-Load (FTL)	206

ψ^m	Amount (kg/m) of emission of type m from MSW transportation by vehicles	207
Ω^m	Amount (kg/(kg* m)) of emission of type m from MSW transferring by semitrailers semitrailer	208 209
ec_m	Unit environmental cost (USD/kg emissions) of emissions of type m , $m \in M$	210
$\mathcal{E}_{j,k,r,t}^{scr}$	Normalized weight of social criteria for routing which vehicle k during trip r of day t visits customer j	211 212
$\mathcal{E}_i^{scl}$	Normalized weight of social criteria for establishment of i	213
$\mathcal{E}_{ei}^{scl}$	Normalized weight of social criteria for relocating e to i	214
S^{scr}	Social score for routing	215
S^{scl}	Social score for redesign	216
Δ	The minimum acceptable rate for social score of the network	217
Variables		218 219
x_{ij}^{krt}	1 if vehicle k passes edge (i,j) in trip r and day t , 0 otherwise, $k_1 \in K_1$, $i,j \in I \cup J$, $r \in R$, $t \in T$	220
y_j^{krt}	1 if vehicle k collects demand of customer j in trip r and day t , 0 otherwise, $k_1 \in K_1$, $i,j \in I \cup J$, $r \in R$, $t \in T$	221 222
α_{pi}^{kt}	Amount of MSW (kg) transferred from ITrS i to treatment, recycling, disposal facilities p in day t , $i \in I$, $p \in P$, $t \in T$. $k \in k_2$	223 224

Tak_e^{krt}	Amount of MSW (kg) collected and disposed in ITrS e by vehicle k in trip r and day t	225
s_i	Number of vehicles assigned to the ITrS i , $i \in I$	226
s_i^t	Number of vehicles assigned to the ITrS i in day t , $i \in I$, $t \in T$	227
z_{ei}	1 if an existing ITrS e ($e \in Ex$) is relocated to the location i ($i \in I$, $i \neq e$) or an existing ITrS e ($e \in Ex$, $i = e$) be open, 0 otherwise	228 229
w_i	1 if a new ITrS is establish in candidate location for ITrS i , 0 otherwise, $i \in N$	230

Objective function

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$$\begin{aligned}
\text{Minimize } COST = & \sum_{j \in I \cup J} \sum_{i \in I \cup J} \sum_{k \in k_1} \sum_{r \in R} \sum_{t \in T} d_{ij} c_{k_1} q_{jt} x_{ij}^{krt} \\
& + \sum_{t \in T} \sum_{k \in k_2} \sum_{i \in I} \sum_{p \in P} d_{ip} c_{k_2} (\alpha_{ip}^{kt} + 1) \\
& + \sum_{e \in Ex} \sum_{i \in I} f r_{ei} z_{ei} \\
& + \sum_{i \in Ex} f m_i z_{ii} + \sum_{i \in N} f m_i w_i \\
& - \sum_{j \in Ex} [f s_j (1 - \sum_{i \in I} z_{ji}) \\
& + f m_j \sum_{\{i \in Ex, i \neq j\}} z_{ji}] \\
& + \sum_{i \in I} f c \times s_i \\
& + \sum_{m \in M} e c_m \times \\
& [\sum_{j \in I \cup J} \sum_{i \in I \cup J} \sum_{k \in k_1} \sum_{r \in R} \sum_{t \in T} d_{ij} \Psi^m x_{ij}^{krt} \\
& + \sum_{t \in T} \sum_{k \in k_2} \sum_{i \in I} \sum_{p \in P} \Omega^m d_{ip} \times FTL^m \times \alpha_{ip}^{kt} \\
& + \sum_{t \in T} \sum_{k \in k_2} \sum_{i \in I} \sum_{p \in P} \Omega^m d_{ip} \alpha_{ip}^{kt}]
\end{aligned} \tag{3}$$

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.

$$\text{Minimize } COST = ECOCOST + ENVCOST \quad (4)$$

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

$$ECOCOST = TPCOST + TFCOST + RCOST + MCOST - SCOST + FVCOST \quad (5)$$

$TPCOST$ 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.

$$TPCOST = \sum_{j \in I \cup J} \sum_{i \in I \cup J} \sum_{k \in k_1} \sum_{r \in R} \sum_{t \in T} d_{ij} c_{k_1} q_{jt} x_{ij}^{krt} \quad (6)$$

$TFCOST$ 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.

$$TFCOST = \sum_{t \in T} \sum_{k \in k_2} \sum_{i \in I} \sum_{p \in P} d_{ip} c_{k_2} (\alpha_{ip}^{kt} + 1) \quad (7)$$

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

$$RCOST = \sum_{e \in Ex} \sum_{i \in I} f r_{ei} z_{ei} \quad (8)$$

$MCOST$ is fixed maintenance costs of a new or an existing ITrS including insurance, taxes, and renting costs, as described in Eq. (9).

$$MCOST = \sum_{i \in Ex} f m_i z_{ii} + \sum_{i \in N} f m_i w_i \quad (9)$$

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

$$SCOST = \sum_{j \in Ex} [f s_j (1 - \sum_{i \in I} z_{ji}) + f m_j \sum_{\{i \in Ex, i \neq j\}} z_{ji}] \quad (10)$$

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

$$FVCOST = \sum_{i \in I} f c \times s_i \quad (11)$$

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.

$$ENVCOST = \quad (12)$$

$$\begin{aligned} & \sum_{m \in M} e c_m \times [\sum_{j \in I \cup J} \sum_{i \in I \cup J} \sum_{k \in k_1} \sum_{r \in R} \sum_{t \in T} d_{ij} \Psi^m x_{ij}^{krt} \\ & + \sum_{t \in T} \sum_{k \in k_2} \sum_{i \in I} \sum_{p \in P} \Omega^m d_{ip} \times FTL^m \times \alpha_{ip}^{kt} \\ & + \sum_{t \in T} \sum_{k \in k_2} \sum_{i \in I} \sum_{p \in P} \Omega^m d_{ip} \alpha_{ip}^{kt}] \end{aligned}$$

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

$$\sum_{k \in k_1} \sum_{r \in R} \sum_{t \in T} y_j^{krt} \geq 1 \quad j \in J \quad (13)$$

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

$$\sum_{k \in k_1} \sum_{r \in R} y_j^{krt} \leq 1 \quad j \in J, t \in T \quad (14)$$

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

$$\sum_{i \in I \cup J} x_{ij}^{krt} = y_j^{krt} \quad j \in J, k \in k_1, r \in R, t \in T \quad (15)$$

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

$$\sum_{i \in I \cup J} x_{ie}^{krt} = \sum_{j \in I \cup J} x_{ej}^{krt} \quad e \in I \cup J, k \in k_1, r \in R, t \in T \quad (16)$$

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

$$\sum_{k \in k_1} \sum_{r \in R} y_j^{krt} \leq \sum_t \sum_{k \in k_1} \sum_{r \in R} y_j^{krt} \quad j \in J, t \in T - 1, t < T \quad (17)$$

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

Vehicle's constraints

$$\sum_{j \in I \cup J} q_{jt} y_j^{krt} \leq Q_{k_1} \quad k \in k_1, r \in R, t \in T \quad (18)$$

Constraints (18) ensure the total MSW collected during a trip should not exceed the vehicle's maximum capacity.

$$\sum_{i \in I \cup J} \sum_{j \in I \cup J} \sum_{r \in R} t_{ij} x_{ij}^{krt} \leq D_{k_1} \quad k \in k_1, t \in T \quad (19)$$

Constraints (19) are limitation on collection operation time.

ITrS's constraints

$$\sum_{j \in J} q_{jt} x_{ej}^{krt} + \sum_{j \in J} \sum_{i \in J} q_{jt} x_{ij}^{krt} = Tak_e^{krt} \quad e \in I, t \in T, r \in R, k \in K_1 \quad (20)$$

$$\sum_{k \in K_1} \sum_{r \in R} Tak_i^{krt} = \sum_{k \in K_2} \sum_{p \in P} \alpha_{ip}^{kt} \quad i \in I, t \in T \quad (21)$$

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.

$$\sum_{e \in EX} z_{ei} \leq |Ex| z_{ii} \quad i \in Ex \quad (22)$$

$$\sum_{e \in EX} z_{ei} \leq |Ex| w_i \quad i \in N \quad (23)$$

$$\sum_{i \in EX \cup N} z_{ei} \leq 1 \quad e \in Ex \quad (24)$$

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 can not 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.

$$z_{ei} \leq z_{ee} \quad e \in Ex, i \in N \quad (25)$$

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.

$$s_i^t \leq w_i \quad i \in N, t \in T \quad (26)$$

$$s_i^t \leq z_{ii} \quad i \in Ex, t \in T \quad (27)$$

Constraints (26) and (27) denote that prior to allocating the vehicles to any ITrSs, it must be pre-established. 280

$$s_i^t \leq s_i \quad i \in I, t \in T \quad (28)$$

$$\sum_{i \in I} s_i = NV \quad (29)$$

Constraints (28) and (29) indicate the relation between the number of vehicles that should be allocated to 281

ITrSs and the number of total existing vehicles. 282

Tours constraints 283

$$\sum_{i, v_i \in S} \sum_{j, v_j \in S} x_{ij}^{krt} \leq |S| - 1 \quad k \in k_1, r \in R, t \in T, \forall S \subseteq I \cup J; |S| \geq 2 \quad (30)$$

Constraints (30) are subtour elimination constraints. 284

Connection among vehicles and generation nodes constraints 285

$$\sum_{j \in J} x_{ij}^{krt} \leq 1 \quad i \in I, k \in k_1, r \in R, t \in T \quad (31)$$

$$\sum_{i \in J} x_{ij}^{krt} \leq 1 \quad j \in I, k \in k_1, r \in R, t \in T \quad (32)$$

After leaving the ITrS, each vehicle could only visit a generation node on its trip and the return trip to the 286

ITrS should be from a generation node addressed in Constraints (31) and (32). 287

Connection among vehicles, generation nodes and ITrSs constraints 288

$$x_{ij}^{krt} \leq \sum_{i \in I} z_{ei} \quad e \in Ex, j \in J, k \in K_1, r \in R, t \in T \quad (33)$$

$$x_{ij}^{krt} \leq w_i \quad i \in N, j \in J, k \in K_1, r \in R, t \in T \quad (34)$$

Similarly, Constraints (33) and (34) emphasize that before the collection operation commences, the origin 289

of these flows must establish. 290

$$x_{ij}^{krt} \leq \sum_{j \in I \cup J} \sum_{i \in I} x_{ij}^{krt} \quad i \in J, j \in J, k \in K_1, r \in R, t \in T \quad (35)$$

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.

$$\begin{aligned} & \sum_{scr \in SCR} \sum_{t \in T} \sum_{k \in K_1} \sum_{r \in R} \sum_{j \in J} S^{scr} \\ & \times E_{j,k,r,t}^{scr} \times y_j^{krt} \\ & + \sum_{scl \in SCL} \sum_{e \in Ex} \sum_{i \in I} S^{scl} \times E_{ei}^{scl} \times z_{ei} \\ & + \sum_{scl \in SCL} \sum_{i \in N} S^{scl} \times E_i^{scl} \times w_i \geq \Delta \end{aligned} \quad (36)$$

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.

$$x_{ij}^{krt} \in \{0,1\} \quad i \in I \cup J, j \in I \cup J, k \in K_1, r \in R, t \in T \quad (37)$$

$$y_j^{krt} \in \{0,1\} \quad j \in J, k \in K_1, r \in R, t \in T \quad (38)$$

$$s_i \in N \quad i \in I \quad (39)$$

$$s_i^t \in N \quad i \in I, t \in T \quad (40)$$

$$\alpha_{ip}^{kt} \geq 0 \quad i \in I, p \in P, t \in T \quad (41)$$

$$z_{ei} \in \{0,1\} \quad e \in Ex, i \in I \quad (42)$$

$$w_i \in \{0,1\} \quad i \in I \quad (43)$$

$$Tak_e^{krt} \geq 0 \quad e \in I, t \in T, r \in R, k \in K_1 \quad (44)$$

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

Case study description	299
To represent the applicability of the <i>SMTP-reLRP</i> 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.	300 301 302 303 304 305 306 307 308 309 310
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 <i>SMTP-reLRP</i> 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.	311 312 313 314
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 4.6×10^{-7} UC per meter and per kg respectively (TWMO 2020). The maximum daily working time for them is 300 minutes.	315 316 317 318 319 320

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.

(a)

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 5.6×10^{-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: 342
(Dropboxlink). 343

For solving the problem presented of a real case study, some main parameters of the *SMTP-reLRP* model 344
should be set. For the case study, the environmental and social parameters setting process are provided in 345
next sections respectively. 346

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Environmental parameters 348

About environmental costs, four main types of emissions are considered, i.e., CO₂, SO₂, NO_x, and VOC 349
emissions. The unit environmental cost and the amount of emissions caused by transportation and 350
transferring operations is considered based on recent researches (Mirdar Harijani et al. 2017). As the MSW 351
is transported and transferred by diesel-fueled trucks named vehicles and semitrailers it is supposed that 352
GHG emissions (kg emissions/kg of MSW) for them are equal. 353

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Social parameters 355

About social constraints, at first, the inventory indicators for the social score of routing and redesign 356
operation were scored by 43 people, including employees of TWMO and contractors in charge of waste 357
collection. Secondly, for routing and redesign operation, the summation of normalized weight is 0.6 and 358
0.4 respectively. Thirdly, the minimum acceptable rate for the total social score of the network is chosen 359
via sensitivity analysis. Considering that all participants choose the worst and the best score for each 360
indicator, the social score of the routing section will be equal to 0.25 and 1 respectively. It is the same for 361

the social score of the redesigning. Considering economic and environmental function 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 Δ parameter is considered 0.004.

Finally, about the social score for routing and relocation, Fig.4(a) indicates that the diagram related to S^{scr} . $S^{scl} = 1$ 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 $S^{scl} = 0.62$ with considering the scores of employees of TWMO and contractors in charge of waste collection.

Results and discussion

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 Δ 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

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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 CO ₂ Emission reduction from transportation (kg)				447	
Optimal total transferring distance (km)				94	
Current total transferring distance (km)				685	
Weekly CO ₂ 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 ITrS will not be unexpected. Moreover, in current Tehran ITrSs' structure there is no cooperative perspective between ITrSs as value chain actors. Cooperating municipal solid waste collection scheme demonstrated in Fig.1(c) could result in changing in ITrSs' structure. In other words, if the ITrSs 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 ITrSs and the average annual amount of Tehran MSW generation rate indicates that the redesign of ITrSs will be more probable. The average daily amount of Tehran MSW generation rate is about 9000 tons which equals 328×10^4 tons in a year. According to the annual capacity of an ITrS which is 175×10^4 tons, it seems that the existence of 11 ITrSs 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	414
considered in model (II) it's calculated cost is more than the cost of model (I).	415
Similarly, comparison of the <i>SMTP-reLRP</i> model and model (III) shows that the solutions of both are same.	416
For the case, involving the sustainability concept results in a sustainable solution with a higher social score	417
and higher system costs in comparison with the solution of the model without considering the sustainability	418
factors.	419

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Table 4 The key results of the *SMTP-reLRP* model and the models (I), (II) and (III)

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Model	Sustainability dimensions							
	Sustainability	Objective function	Subject to the constraints set given by:	COST(UC)	ECOCOST(UC)	ENVCOST(UC)	Relocation social	Routing social
							score	score
Current	Excluded	-	-	3534941.42	794570.78	2740370.635	0.624	0.715
<i>SMTP-reLRP</i> model	Included	Minimize ECOCOST and ENVCOST	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 ENVCOST	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

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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 <i>SMTP-reLRP</i> model applicability a real case study was	444
investigated. For obtaining the exact solution of the problem CPLEX optimizer is used. It has been	445
described that for the real case, the proposed model can result in total cost reduction by 66% that occurred	446
by 86% reduction in weekly traveled distance and a 12% decrease in routing social score. The results	447
indicate that there are many inefficiencies in current collection operation.	448
Furthermore, involving the sustainability concept results in a sustainable solution for the case with a higher	449
social score and higher system costs in comparison with the solution of the model without considering the	450
sustainability factors.	451
For future research, involving the environmental factors about different collection frequency options, for	452
example, the effect of collection frequency on attracting pests and leakage of leachate is suggested.	453
Because of the limited real data for testing of the model, observation of some potential features of the	454
model, such as, the closing or relocation of facilities was hard. Solving the model for investigating the	455
reduction possibility of ITrSs numbers located in Tehran city is direction for future research. Moreover,	456
cooperative perspective between ITrSs as value chain actors will be another direction for future researches.	457
In addition, extension of the model in stochastic form to accommodate the demand uncertainty is suggested.	458
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Appendix A

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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):

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$$\begin{aligned} q_{jt} &= q_j[t - \max_{l=1, \dots, t-1} (\sum_{r \in R} \sum_{k \in k_1} y_j^{krl} l)] \\ &= q_j[t - \phi_{jt}] \end{aligned} \quad (45)$$

Then the model will be nonlinear and must be linearized:

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$$\phi_{jt} = \max_{l=1, \dots, t-1} (\sum_{r \in R} \sum_{k \in k_1} y_j^{krl} l) \quad (46)$$

$$\phi_{jt} \geq \sum_{r \in R} \sum_{k \in k_1} y_j^{krl} l \quad (47)$$

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.

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$$q_j[t - \phi_{jt}] \leq \mu_{jt} \leq Q_{k_1} \quad j \in J, t \in T \quad (48)$$

$$\begin{aligned} \mu_{it} - \mu_{jt} + Q_{k_1} \sum_{k \in k_1} \sum_{r=1}^w x_{ij}^{krt} \\ + (Q_{k_1} - q_i[t - \phi_{it}] - q_j[t - \phi_{jt}]) \\ \times \sum_{k \in k_1} \sum_{r=1}^w x_{ij}^{krt} \end{aligned} \quad i \neq j \in I \cup J, t \in T \quad (49)$$

$$\leq Q_{k_1} - q_j[t - \phi_{jt}]$$

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.

$$\phi_{jt}x_{ij}^{krt} = w_{ij}^{krt} \quad (50)$$

$$w_{ij}^{krt} \leq \phi_{jt} \quad (51)$$

$$w_{ij}^{krt} \leq Mx_{ij}^{krt} \quad (52)$$

$$w_{ij}^{krt} \geq \phi_{jt} - (1 - x_{ij}^{krt}) \times M \quad (53)$$

$$w_{ij}^{krt} \geq 0 \quad (54)$$

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

Figures

Figure 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

Figure 2

Steps of the proposed SLCA methodology for calculating the social score of routing and redesign system

(a)

(b)

(c)

(d)

Figure 3

a) Current approximate MSW container location, b, c) daily route pattern by vehicles, d) 26 key MSW container nodes

(a)

(b)

Figure 4

a) Acceptable range of Δ parameter via economic and environmental function consideration, b) Optimal routing and redesign for the case study