Waste Management 52 (2016) 34–49

Contents lists available at ScienceDirect

Waste Management

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

Modeling municipal solid waste collection: A generalized vehicle routing model with multiple transfer stations, gather sites and inhomogeneous vehicles in time windows

Le Hoang Son [a], Amal Louati [b,*]

[a] VNU University of Science, Vietnam National University, Viet Nam
[b] Faculty of Economics Sciences and Management, University of Sfax, Tunisia

ARTICLE INFO

Article history:
Received 26 December 2015
Revised 23 February 2016
Accepted 22 March 2016
Available online 29 March 2016

Keywords:
Empirical modeling
Multi-objective optimization
Municipal solid waste collection
Vehicle routing models

ABSTRACT

Municipal Solid Waste (MSW) collection is a necessary process in any municipality resulting in the quality-of-life, economic aspects and urban structuralization. The intrinsic nature of MSW collection relates to the development of effective vehicle routing models that optimize the total traveling distances of vehicles, the environmental emission and the investment costs. In this article, we propose a generalized vehicle routing model including multiple transfer stations, gather sites and inhomogeneous vehicles in time windows for MSW collection. It takes into account traveling in one-way routes, the number of vehicles per m^2 and waiting time at traffic stops for reduction of operational time. The proposed model could be used for scenarios having similar node structures and vehicles' characteristics. A case study at Danang city, Vietnam is given to illustrate the applicability of this model. The experimental results have clearly shown that the new model reduces both total traveling distances and operational hours of vehicles in comparison with those of practical scenarios. Optimal routes of vehicles on streets and markets at Danang are given. Those results are significant to practitioners and local policy makers.

1. Introduction

The world has witnessed over 10,000 natural and industrial disasters, killing millions and affecting many more, because of climate change (Technology, 2013). Municipal solid waste (MSW) is one of the primary factors that contribute greatly to the rising of climate change and global warming (Consonni et al., 2005). In 2011, 1.3 billion metric tons of municipal solid waste (MSW) were generated, and this is expected to grow to 2.2 billion metric tons by 2025 (Levis et al., 2013). In the U.S., MSW systems processed approximately 250 million tons of waste and produced 118 Tg of CO2e emissions, which represents over 8% of non-energy related greenhouse gas (GHG) emissions, and 2% of total net GHG emissions (Levis et al., 2013). Technological advancements, environmental regulations, and emphasis on resource conservation and recovery have greatly reduced the environmental impacts of MSW management, including emissions of greenhouse gases (Weitz et al., 2002). More effective, technically viable, environmentally effective and economically sustainable collection schemes are the target of waste managers (Teixeira et al., 2014). They make feasible CO_2 reduction (Cioca et al., 2015) and affect maintenance strategies of MSW incinerators (Ragazzi et al., 2013). It was shown that developing countries are currently in the progress of urbanization and industrialization, resulting in the augmentation of various types of wastes that leaves a burden to both the municipality's infrastructure and the community (Dyson, 2011). Urbanization and demographic transition are key factors of economic development that lead to a significant concentration of human resources, economic activities, and resource consumption in cities (Madlener and Sunak, 2011). It is undoubted that optimizing MSW collection brings much meaning in terms of environmental, landscape developments and economic savings (Mora et al., 2014).

The intrinsic nature of MSW collection relates to the development of effective *vehicle routing* (VR) models that optimize the total traveling distances of vehicles, the environmental emission and the investment costs (Apaydin and Gonullu, 2011). VR is a scheduled process that allows vehicles to load waste at gather sites (a.k.a. sites) and dump it at a landfill with the target being oriented by a single or multiple objectives (Tung and Pinnoi, 2000). Waste generation and collection cannot be measured on a detailed basis, which would allow further evaluation of disposal habits, changes and trends so that modeling

* Corresponding author.
E-mail addresses: sonlh@vnu.edu.vn (L.H. Son), louatiamal@gmail.com (A. Louati).

http://dx.doi.org/10.1016/j.wasman.2016.03.041
0956-053X/

MSW collection is of particular importance (Beigl et al., 2008). Several VR models were presented in the literature with various objectives such as the minimum fuel consumption, minimum traveling distances and environmental emissions. Now, we herein summarize the relevant researches as follows.

- Tung and Pinnoi (2000) introduced a VR model for Hanoi city, Vietnam whose components are a depot, a landfill and multiple sites. Vehicles are homogeneous and are allowed to travel to sites under time window constraints. The works of handcarts are left manually. The objectives are to minimize the traveling times and distances of vehicles.
- Apaydin and Gonullu (2008) argued that route optimization in a VR model should be taken into account the exhaust emission of vehicles when they are running. Therefore, the environmental emission was attached to the objective function besides the traveling times and distances of vehicles. Based on a standard table about the exhaust emission of a specific type of vehicles per a distance unit, the quantities of some gases such as CO_2, HC, CO and PM could be determined and used in the objective function.
- Tavares et al. (2009) stated that short routes do not guarantee minimum fuel consumption of vehicles, but long routes having negative road gradients may require less fuel since the resistance of vehicles to traction decreases. They proposed the uses of three-dimensional geographic information systems (3D GIS) modeling for the waste collection and transportation. Some factors such as the driving situations, vehicle load and road gradient were integrated to the VR model. This model is capable of finding optimal routes for the minimum fuel consumption of vehicles.
- Fan et al. (2010) proposed a VR model containing a depot, a transfer station, multiple sites and landfills. Waste was classified by the heat value in the transfer station. Waste with high heat value was disposed by incineration while waste with low one was unloaded at the landfill. This research aims to minimize the traveling distance and maximize total heat value.
- Arribas et al. (2010) proposed a methodology for designing an urban solid waste collection system that minimises collection time, and operational and transport costs while enhancing the current solid waste collection system.
- Galante et al. (2010) considered the localization and dimensioning of transfer stations, which constitute a necessary intermediate level in the logistic chain of the solid waste stream, from municipalities to the incinerator. The model examined both initial investment and operative costs related to transportation and transfer stations. Two conflicting objectives are evaluated, the minimization of total cost and the minimization of environmental impact, measured by pollution.
- Larsen et al. (2010) presented five scenarios with alternative collection systems for recyclables were assessed by means of a life cycle assessment and an assessment of the municipality's costs. Enhancing recycling and avoiding incineration was recommendable because the environmental performance was improved in several impact categories.
- Tan et al. (2010a, 2010b) designed a superiority–inferiority-based inexact fuzzy two-stage mixed-integer linear programming model for municipal solid waste management under uncertainty. The developed approach is capable of tackling dual uncertainties presented as fuzzy boundary intervals in both constraints and objective functions.
- Apaydin and Gonullu (2011) suggested appending the parameters "population density per 100 m road distance" and "waiting time at stop signs" to the VR model for the estimation of traveling and collecting time. The objective function is similar to that in (Tung and Pinnoi, 2000).
- Faccio et al. (2011) used real time data to orient the route of a vehicle. They argued that if the real time data of each vehicle and that of replenishment level are known then what bin should be emptied and what should not are totally identified. The data of this research are either deterministic or stochastic. The objective function consists of the number of used vehicles and their traveling times and distances.
- Regarding review notes, Pires et al. (2011b) conducted a thorough literature review of models and tools illuminating possible overlapped boundaries in waste management practices in European countries and encompassing the pros and cons of waste management practices in each member state of the European Union. Tai et al. (2011) provided an overview of different methods of collection, transportation, and treatment of MSW in the eight cities; as well as making a comparative analysis of MSW source-separated collection in China. Beliën et al. (2012) reviewed the available literature on solid waste management problems, with a particular focus on vehicle routing problems.
- Chatzouridis and Komilis (2012) design a VR model whose objective function was a non-linear equation that minimized total collection cost. The cost comprised the capital and operating costs of: (i) the waste transfer stations, (ii) the waste collection vehicles, (iii) the semitrailers and tractors as well as the waste collection within a community, and the cost to haul the wastes to the transfer stations or to the landfills. The decision variables were binary variables that designated whether a path between two nodes is valid or not. Binary variables were also used to designate whether a transfer station should be constructed or not.
- Gunalay et al. (2012) showed how simulation-optimization modeling can be used to efficiently generate multiple policy alternatives that satisfy required system performance criteria in stochastically uncertain environments and yet are maximally different in the decision space. Islam et al. (2012) mentioned an integrated system combined of Radio Frequency Identification (RFID), Global Position System (GPS), General Packet Radio Service (GPRS), Geographic Information System (GIS) and Web camera for MSW collection.
- Hemmelmayr et al. (2013a) and Hemmelmayr et al. (2013b) designed a collection system consisting of the combination of a vehicle routing and a bin allocation problem in which the trade-off between the associated costs has to be considered. The solution approach combines an effective variable neighborhood search metaheuristic for the routing part with a mixed integer linear programming-based exact method for the solution of the bin allocation part.
- Levis et al. (2013) presented the first life cycle-based framework to optimize—over multiple time stages—the collection and treatment of all waste materials from curb to final disposal by minimizing cost or environmental impacts while considering user-defined emissions and waste diversion constraints.
- Mora et al. (2013) showed a planning model for an integrated waste management system based on kerbside collection. A heuristic procedure was also applied in order to obtain some admissible solutions of the real problem in reasonable computational time.

It is clear from the literature that the existing VR models partly examined the components such as the depot, the landfill, multiple transfer stations and multiple gather sites (Galante et al., 2010). Moreover, they worked with homogeneous vehicles only and did not take into account the traveling in one-way routes, the number of vehicles per m^2 and the waiting time at traffic stops for the reduction of operational time, which are essential factors to the real scenario of MSW collection (Apaydin and Gonullu, 2011). Regarding the objective functions in VR models, the most frequent

Table 1
Basic notations.

Term	Meaning
Household solid wastes	A waste type consisting of daily items that are discarded by householders.
Street solid wastes	A waste type consisting of daily items that are discarded by the public.
Handcart	A small, two-wheeled cart pulled or pushed by hand
Site/Waste Container	A container for temporarily storing refuse and waste
Time Windows	A set of time intervals at each site to collect rubbish
Waste quantity	The collected quantity of rubbish, measured by tons
Tipper/Vehicle (tricycles, hook-lifts and forklifts)	A special type of trucks to collect rubbish. It could be tricycles, hook-lifts or forklifts depending on the purposes
Depot	Tipper park
Landfill	A site for the disposal of waste materials by burial
Morning/Afternoon/Night Shift	The period to collect rubbish
Route/Trip	A journey of tipper from the depot to the landfill through sites
Sequence	The visited sites of a tipper in a route
Tour	A number of predefined routes in a shift
Pick-up/Inter-arrival time	The waiting time of a tipper at a site
Node	Depot/Sites/Landfill
Penalty	The punishment of running cost for the waiting time of a tipper at a site
Loading (at a site)	Dump rubbish from handcart to tipper
Unloading (at the landfill)	Dump rubbish from tipper to landfill
Partial Load	The status of loading a part of rubbish at a site
Incineration plant	The rubbish-burning factory
Transfer station	The temporary waste storing site
Vehicle capacity	The maximal quantity of rubbish that a vehicle can tolerate
Parking area	The parking site of vehicles

used objectives are the collection time, the cost of environmental impacts measured by pollution. However, they rarely made a possible combination of various objectives, such as the traveling distances, the traveling time of vehicles and the exhaust emission. Some models are quite time-consuming such as the fuzzy two-stage mixed-integer linear programming model (Tan et al., 2010a, 2010b). This raises the motivation for this paper to handle those issues considering the available node structures, vehicles and parameters in a generalized context.

In this article, we propose a generalized vehicle routing model including multiple transfer stations, gather sites and inhomogeneous vehicles in time windows for MSW collection. It takes notice of traveling in one-way routes, the number of vehicles per m^2 and waiting time at traffic stops for reduction of operational time. The objectives are to maximize the collected waste quantities and to minimize the environmental emissions (the impact of climate change). The proposed model could be used for scenarios having similar node structures and vehicles' characteristics. A case study at Danang city, Vietnam is given to illustrate the applicability of this model. The experimental results have clearly shown that the new model reduces both total traveling distances and operational hours of vehicles in comparison with those of practical scenarios. Optimal routes of vehicles on streets and markets at Danang are given. Those results are significant to practitioners and local policy makers.

The next sections are organized as follows. Section 2 presents the generalized VR model. Section 3 introduces an application of this model in the waste collection scenario at Danang city, Vietnam. Finally, Section 4 gives the conclusions and outlines future works of this study.

2. The generalized vehicle routing model

In this section, we describe the formulation of the generalized VR model for MSW collection with multiple transfer stations, gather sites and inhomogeneous vehicles in time windows. Firstly, we introduce some basic notations (Table 1) and the scenario for the MSW collection.

The scenario for the MSW collection consists of two basic phases.

Phase 1: Household (street) solid wastes are collected by handcarts and assembled at sites (Fig. 1). Each site has its own time windows, and the waste quantities in various time windows are different.

Phase 2: In each shift, a vehicle starts from the depot and moves through nodes following by a scheduled route and finishes at the landfill. When moving to a site, the vehicle loads rubbish, and the waiting time for this process is called the pick-up time. Once the vehicle is full of rubbish, it moves to the landfill for unloading and completes a route. After reaching programmed routes in a tour, the vehicle comes back to the depot. Fig. 2 clearly illustrates this phase.

Take an example from (Tung and Pinnoi, 2000) to describe those phases. In Table 2, we have four vehicles whose capacities are 33, 33, 28 and 28, respectively. There is no difference between tricycles, hook-lifts and forklifts in this example, and they are generally called the vehicles. There are 149 handcarts assembled at 24 sites except two first nodes are the depot and the landfill. A tour consists of two routes. The scheduled routes for vehicles are shown in Table 2. For instance, the route 1 of vehicle 1 passes through the nodes as follow: $25 \to 3 \to 8 \to 7 \to 6 \to 5 \to 4 \to 2$ with the gross collected waste quantity being $2+3+4+6+7+5+2+3=32$ handcarts in time windows 9–10 am, and the total number of visited sites being 8. Finishing route 1, vehicle 1 unloads rubbish at the landfill and starts route 2 whose sequence is $11 \to 9 \to 8 \to 5 \to 6 \to 7 \to 4 \to 16 \to 15$. We recognize that sites of Route 2 are not similar to those of Route 1 so that maximal waste quantity could be collected by each vehicle. In Route 2, the total collected waste quantity being $3+2+3+5+4+4+2+2+2=27$ handcarts in time windows 10–11 am, and the gross number of visited sites being 9.

From this example, we clearly realize that if an effective VR model, especially for the Phase 2, is deployed then the total traveling distances of vehicles, the environmental emission with respect to vehicles and the investment costs could be reduced as a result.

Now, we present some assumptions of the proposed model.

- Distances between nodes are identified.
- The numbers of bins as well as their locations on the map are fixed.

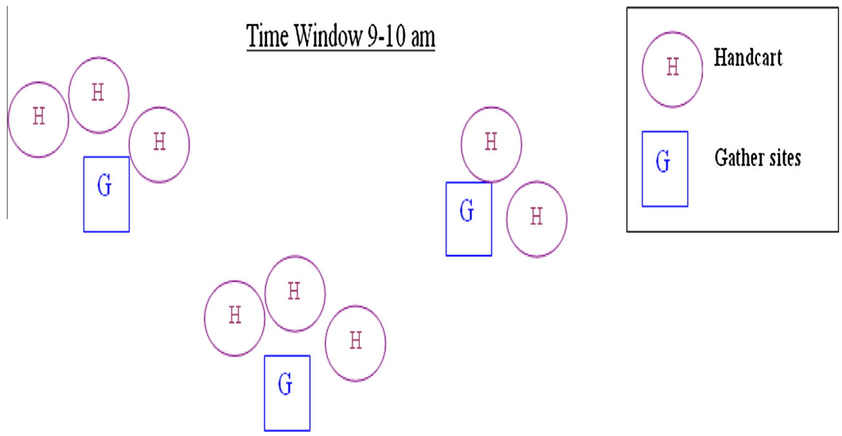

Fig. 1. Phase 1 of MSW collection.

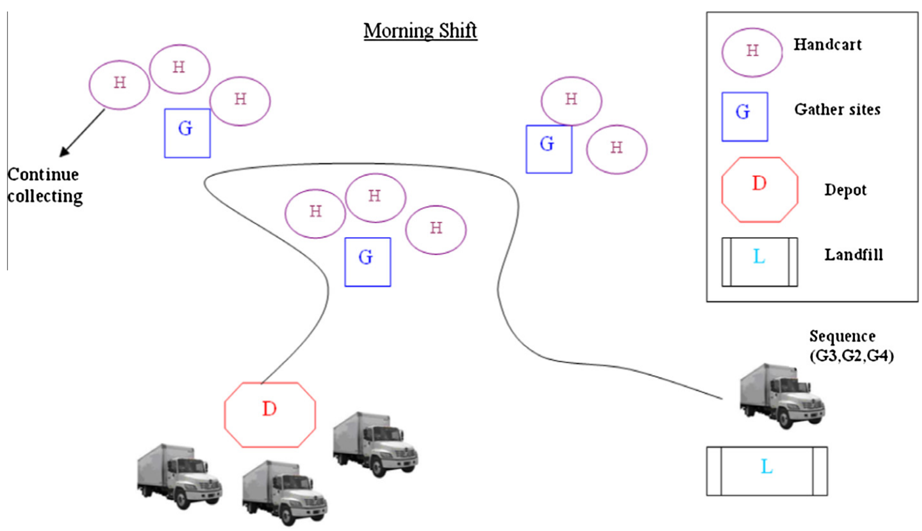

Fig. 2. Phase 2 of MSW collection.

Table 2
An example of vehicle routing (Tung and Pinnoi, 2000).

Best result of the morning subproblem obtained by the parallel construction										
	Total waste	Sequence of gather sites (pick-up no.) visited								
		1	2	3	4	5	6	7	8	9
Vehicle 1										
Route 1	32	25 (1)	3 (1)	8 (1)	7 (1)	6 (1)	5 (1)	4 (1)	2 (1)	
Route 2	27	11 (2)	9 (2)	8 (2)	5 (2)	6 (2)	7 (2)	4 (2)	16 (2)	15 (2)
Vehicle 2										
Route 1	33	22 (1)	19 (1)	12 (1)	17 (1)	13 (1)	14 (1)	16 (1)	15 (1)	
Route 2	16	23 (2)	13 (2)	14 (2)	2 (2)					
Vehicle 3										
Route 1	28	21 (1)	24 (1)	18(1)	10(1)	11 (1)	23 (1)			
Vehicle 4										
Route 1	13	20 (1)	9 (1)	26 (1)						

- Waste quantity at a site in a specific time window is determined.
- Since day and night shifts are equivalent, we perform with the day shift in the model only.
- The number of time windows in all sites is equal. Besides, all time windows are determined and are not overlapped.
- Departure times of all vehicles from the depot can be different.
- Loaded and unloaded times of a vehicle are equal. No partial load is allowed.
- The number of sites is larger than the number of vehicles. However, the number of transfer stations is smaller than or equal to the number of vehicles.
- Transfer stations are responsible for temporarily storing rubbish only and no incineration is permitted in transfer stations.

Table 3
Some terms of the proposed model.

Terms	Modeling
A. Places	
A_1. Node	– $N = \{1, 2, 3, \ldots, ts, ts+1, \ldots, gs\}$ where o 1: depot; o 2: landfill; o $3, .., ts$: transfer stations with $(ts-2)$ being the number of stations; o $ts+1, .., gs$: sites with $(gs-ts)$ being the number of sites.
A_2. Waste quantities at all nodes in time window $p \in P$	– $R = \{0, 0, R_3^p, \ldots, R_{ts}^p, R_{ts+1}^p, \ldots, R_{gs}^p\}$ where R_i^p $(\forall i = \overline{3, gs})$ is waste quantity at node i in time window $p \in P$. Waste quantities at the depot and the landfill are assigned value 0.
B. Time	
B_1. Time Windows	– $P = \{P_1, P_2, \ldots, P_{tw}\}$ with tw being the number of time windows of sites and $P_i = [P_i^L, P_i^U]$ $(\forall i = \overline{1, tw})$ containing lower and upper bounds of time window P_i – All time windows are in the ascending order that means $P_j > P_i \iff P_j^L \geqslant P_i^U$ $(\forall i,\ j \in [1, tw];\ j > i)$
B_2. Loaded/unloaded time of a vehicle at a node in a time window	– $LU^{ip} = \{LU_1^{ip}, \ldots, LU_{n1+n2+n3}^{ip}\}$ $(\forall i \in N;\ \forall p \in P)$
B_3. Departure time of a vehicle from the depot	– $DT = \{DT_1, \ldots, DT_{n1}, DT_{n1+1}, \ldots, DT_{n1+n2}, DT_{n1+n2+1}, \ldots, DT_{n1+n2+n3}\}$ with $n1,\ n2,\ n3$ being the number of tricycles, hook-lifts and forklifts, respectively
B_4. Arriving time of a vehicle at a site in a time window	– $T^{ip} = \{T_1^{ip}, \ldots, T_{n1}^{ip}, 0, \ldots, 0, T_{n1+n2+1}^{ip}, \ldots, T_{n1+n2+n3}^{ip}\}$ $(\forall i \in [ts+1, gs];\ \forall p \in P)$ where $T_1^{ip}, \ldots, T_{n1}^{ip}$ and $T_{n1+n2+1}^{ip}, \ldots, T_{n1+n2+n3}^{ip}$ are the arriving times of tricycles and forklifts, respectively. If vehicle k does not visit site i in time window p then $T_k^{ip} = 0$ – The formula to calculate these values is: $$T_k^{ip} = \begin{cases} DT_k + TV_{1i}(V^*) & \text{If}\quad Depot - Gather\_site \\ T_k^{jq} + LU_k^{jq} + TV_{ji}(V^*) & \text{If}\quad Gather\_site - Gather\_site \end{cases} \quad (\forall k \in [1, n1] \wedge [n1+n2+1, n1+n2+n3];\ \forall i,\ j \in [ts+1, gs];\ \forall p,\ q \in P;\ p \geqslant q)$$ Where, o $TV_{ij}(V^*)$: Standard travel time of a tricycle/forklift in arc (i, j);
B_5. Arriving time of a tricycle at a transfer station	– $Tri_k = \{Tri_k^{ip} \mid \forall k \in [1, n1];\ \forall i \in [3, ts];\ \forall p \in P\}$ where Tri_k^{ip} is the arriving time of tricycle k at transfer station i in time window p. These arriving times are in the ascending order. The formula to calculate these values is: $$Tri_k^{ip} = T_k^{jq} + LU_k^{jq} + TV_{ji}(V_1) \quad \text{If}\quad Gather\_site - Transfer\_Station \quad (\forall k \in [1, n1];\ \forall j \in [ts+1, gs];\ \forall i \in [3, ts];\ \forall p, \in P;\ p \geqslant q)$$
B_6. Maximal number of times that a tricycle can stay at transfer stations in a shift.	– mt
B_7. Arriving time of a hook-lift at a transfer station	– $HookTS_k = \{HookTS_k^{ip} \mid \forall k \in [n1+1, n1+n2];\ \forall i \in [3, ts];\ \forall p \in P\}$ where $HookTS_k^{ip}$ is the arriving time of hook-lift k at transfer station i in time window p. These arriving times are in the ascending order. The formula to calculate these values is: $$HookTS_k^{ip} = DT_k + TV_{1i}(V_2) \quad \text{If}\quad Depot - Transfer\_Station \quad (\forall k \in [n1+1, n1+n2];\ \forall i \in [3, ts];\ \forall p \in P)$$
B_8. Arriving time of a hook-lift at a landfill	– $HookLF_k = \{HookLF_k^{2p} \mid \forall k \in [n1+1, n1+n2]; \forall p \in P\}$ where $HookLF_k^{2p}$ is the arriving time of hook-lift k at the landfill in time window p. These arriving times are in the ascending order and are calculated from those at a previous transfer station.
B_9. Maximal number of times that a hook-lift can stay at the landfill in a shift.	– mh
B_{10}. Arriving time of a forklift at a landfill	– $Fork_k = \{Fork_k^{2p} \mid \forall k \in [n1+n2+1, n1+n2+n3];\ \forall p \in P\}$ where $Fork_k^{2p}$ is the arriving time of forklift k at the landfill in time window p. These arriving times are in the ascending order. The formula to calculate these values is: $$Fork_k^{2p} = T_k^{jq} + LU_k^{jq} + TV_{j2}(V_3) \quad \text{If}\quad Gather\_site - Landfill \quad (\forall k \in [n1+n2+1, n1+n2+n3]; \forall j \in [ts+1, gs];\ \forall p,\ q \in P;\ p \geqslant q)$$
B_{11}. Maximal number of times that a forklift can stay at the landfill in a shift.	– mf
B_{12}. Pick-up time	– $PickT$
B_{13}. Waiting time at a traffic light	– WTL
B_{14}. Standard travel time of a vehicle in arc (i, j)	– $TV_{ij}(V^*) = \frac{D_{ij} \times VD_{ij}}{V^*} + TL_{ij} \times WTL$ where o V^*: average velocity of a vehicle; o D_{ij}: Distances between nodes (i, j); o VD_{ij}: Number of vehicles per m^2 in arc (i, j); o TL_{ij}: Number of traffic lights in arc (i, j);

Table 3 (*continued*)

Terms	Modeling
	o *WTL*: Waiting time at a traffic light – If (i,j) is not connected or the vehicle are not allowed to travel this arc then $$TV_{ij}(V^*) = TV_{ik}(V^*) + TV_{kl}(V^*) + .. + TV_{mj}(V^*)$$ where o $(i,k),\ (k,l),\ \ldots,\ (m,j)$ are all arcs on the way from node i to node j
C. Inhomogeneous vehicles	
C_1. Vehicle	– $K = \{1,\ldots,n1,n1+1,\ldots,n1+n2,n1+n2+1,\ldots,n1+n2+n3\}$ where o $1,\ldots,n1$: tricycles; o $n1+1,\ldots,n1+n2$: hook-lifts; o $n1+n2+1,\ldots,n1+n2+n3$: forklifts; o $n1,n3 < gs - ts$; $n2 \geqslant ts - 2$; o $n1 > n2$; $n1 > n3$.
C_2. Average Velocities	– $V = \{V_1,V_2,V_3\}$ where o V_1: the average velocity of a tricycle; o V_2: the average velocity of a hook-lift; o V_3: the average velocity of a forklift.

C_3. Capacities of vehicles	– $C = \{C_1,\ldots,C_{n1},C_{n1+1},\ldots,C_{n1+n2},C_{n1+n2+1},\ldots,C_{n1+n2+n3}\}$ where
	o $C_1 = C_2 = \cdots = C_{n1} = C_T$: Capacities of tricycles;
	o $C_{n1+1} = C_{n1+2} = \cdots = C_{n1+n2} = C_H$: Capacities of hook-lifts;
	o $C_{n1+n2+1} = C_{n1+n2+2} = \cdots = C_{n1+n2+n3} = C_F$: Capacities of forklifts.

C_4. Current waste quantities of vehicles after leaving a node in a time window	– $WQ^{ip} = \{WQ_1^{ip},\ldots,WQ_{n1+n2+n3}^{ip}\}$ where WQ_k^{ip} $(\forall k \in [1,n1+n2+n3];\ \forall i \in [1,gs];\ \forall p \in P)$ is the waste quantity of vehicle k after leaving site/transfer station i in time window p.
D. Map's Information	
D_1. Arc's weight	– The value of $X_{jq}^{ip}(k)$ $(i,j \in N;\ k \in K;\ p,q \in P)$ is: o 3: if a forklift $(k \in [n1+n2+1, n1+n2+n3])$ travel arc (i,j) in the duration of time windows (p,q); o 2: if a hook-lift $(k \in [n1+1, n1+n2])$ travel arc (i,j) in the duration of time windows (p,q); o 1: if a tricycle $(k \in [1,n1])$ travel arc (i,j) in the duration of time windows (p,q); o 0: Otherwise.
D_2. Distances between nodes (i,j) based on their geographic locations in the map	– D_{ij} $(\forall i,j \in N)$ – $D_{ii} = 0$
D_3. Permission to travel arc (i,j) of a vehicle in a time window	– $Travel_{ij}^{pk}$ with $i,\ j \in N,\ k \in K,\ p \in P$: o 1: if vehicle k is allowed to travel arc (i,j) in time window p; o 0: Otherwise.
D_4. Number of traffic lights in arc (i,j)	– TL_{ij}
D_5. Number of vehicles per m^2 (vehicle density) in arc (i,j)	– VD_{ij}
D_6. Node's weight	– The value of $Y_{ip}(k)$ $(i \in N;\ k \in K;\ p \in P)$ is: o 3: if a forklift $(k \in [n1+n2+1, n1+n2+n3])$ travel node i in time window p; o 2: if a hook-lift $(k \in [n1+1, n1+n2])$ travel node i in time window p; o 1: if a tricycle $(k \in [1,n1])$ travel node i in time window p; o 0: Otherwise.

Table 4
The generalized VR model.

The objective function

Minimize

$$J = \frac{c_1}{\sum_{k\in[1,n1]\wedge[n1+n2+1,n1+n2+n3]}\sum_{i\in[ts+1,gs]}\sum_{p\in P} WQ_k^{ip}} + c_2 \times (n1+n2+n3) + c_3 \times \left(\sum_{k\in[1,n1]}\sum_{i\in[ts+1,gs]}\sum_{j\in[3,ts]} X_{jq}^{ip}(k) + \sum_{k\in[n1+1,n1+n2]}\sum_{j\in[3,ts]} X_{2q}^{jp}(k) + \sum_{k\in[n1+n2+1,n1+n2+n3]}\sum_{i\in[ts+1,gs]} X_{2q}^{ip}(k)\right) \quad (p \leqslant q)$$

Subject to:

No.	Constraints	Explanation
A_0	All variables are positive integers	
Waste quantity constraints		
A_1	$R_i^{P1} = 0 \qquad (\forall i \in N \setminus \{2, ts+1, \ldots, gs\})$	Waste quantities at all transfer stations and at the landfill in the first time window are equal to zeros
A_2	$WQ_k^{1P1} = WQ_k^{2q} = WQ_h^{jq} = 0 \qquad (\forall k \in [1, n1+n2+n3];\ \forall h \in [1, n1]; \forall j \in [3, ts];\ \forall P1,\ q \in P)$	Waste quantities of vehicles (tricycles) leaving depot & landfill (transfer stations) are set to zeros
A_3	$\sum_{i\in[ts+1,gs]} Y_{iP1(k)} \leqslant 1 \quad (\forall k \in [1, n1])$	Maximal number of sites to be visited by tricycles in the first time window is $n1$
A_4	$\sum_{k\in[n1+1,n1+n2]} Y_{iP1}(k) \leqslant 2 \times round(n2/(ts-2)) \qquad (\forall i \in [3, ts])$	Maximal number of hook-lifts staying at a transfer station in the first time window is $n2/(ts-2)$
A_5	$\sum_{i\in[ts+1,gs]} Y_{iP1}(k) \leqslant 3 \qquad (\forall k \in [n1+n2+1, n1+n2+n3])$	Maximal number of sites to be visited by forklifts in the first time window is $n3$
A_6	$R_l^q \geqslant \sum_{i\in[ts+1,gs]:X_{lq}^{ip}=1} WQ_k^{ip} \qquad (\forall k \in [1, n1];\ \forall i \in [ts+1, gs];\ \forall l \in [3, ts];\ \forall p, q \in P;\ q \geqslant p)$	Current waste quantity at a transfer station in a time window is greater than or equal to the total waste quantities of tricycles visiting that station in the same time window
A_7	$\sum_{k\in[n1+1,n1+n2]} WQ_k^{ip} > R_i^p qquad \qquad (\forall i \in [3, ts];\ \forall p \in P)$	Total waste quantity carried by hook-lifts from a transfer station to the landfill must be greater than the remain at the station
A_8	$WQ_k^{ip} \leqslant C_k \qquad (\forall k \in [1, n1+n2+n3];\ \forall i \in [3, gs];\ \forall p \in P)$	Current waste quantity of a vehicle in a time window must be smaller than its capacity
A_9	$R_i^p \geqslant \sum_{k\in[1,n1]\wedge[n1+n2+1,n1+n2+n3]} WQ_k^{ip} - \sum_{k\in[1,n1]\wedge[n1+n2+1,n1+n2+n3]} WQ_k^{jq} \qquad (\forall i, J = \overline{ts+1, gs};\ \forall p, q \in P; p \geqslant q;\ X_{ip}^{jq}(k) > 0)$	Waste quantity at a site in a time window is larger than or equal to the total waste quantities that vehicles will bring out from that site
Time constraints		
A_{10}	$DT_k \leqslant P_1^L \qquad (\forall k \in K)$	The departure time of a vehicle from the depot is smaller than the lower bound of the first time window
A_{11}	$(T_k^{iq} > 0) \wedge (P_q^L \leqslant T_k^{iq} \leqslant P_q^U) = 1 \qquad (\forall i \in [ts+1, gs];\ \forall q \in P;\ \forall k \in [1, n1] \wedge [n1+n2+1, n1+n2+n3])$	The arriving time of a vehicle at a site in a time window must belong to the lower and upper bound of that time window
A_{12}	$(T_k^{jq} - T_k^{ip})(X_{jq}^{ip}(k) - X_{ip}^{jq}(k)) \geqslant 0 \qquad (\forall p, q \in P;\ q > p;\ \forall i, j \in [ts+1, gs];\ \forall k \in [1, n1] \wedge [n1+n2+1, n1+n2+n3])$	The arriving time of a vehicle at a site in a time window is larger than that in a previous time window
A_{13}	$\Vert Tri_k \Vert \leqslant mt \qquad (\forall k \in [1, n1])$	The number of times that a tricycle can stay at transfer stations in a shift cannot exceed a threshold
A_{14}	$(Tri_k^{jq} - T_k^{ip}) X_{jq}^{ip}(k) \geqslant 0 \qquad (\forall k \in [1, n1];\ i \in [ts+1, gs];\ \forall j \in [3, ts];\ \forall p, q \in P;\ q \geqslant p)$	The arriving time of a tricycle at a transfer station is greater than those at previous sites
A_{15}	$HookTS_k^{ip} > DT_k \qquad (\forall k \in [n1+1, n1+n2];\ \forall i \in [3, ts]; \forall p \in P)$	The arriving time of a hook-lift at a transfer station is greater than its departure time at the deport
A_{16}	$HookTS_k^{ip} < HookLF_k^{2q} \qquad (\forall k \in [n1+1, n1+n2]; \forall i \in [3, ts];\ \forall p, q \in P; p \leqslant q)$	The arriving time of a hook-lift at a transfer station is smaller than that at the landfill
A_{17}	$\Vert HookLF_k \Vert \leqslant mh \qquad (\forall k \in [n1+1, n1+n2])$	The number of times that a hook-lift can stay at the landfill in a shift cannot exceed a threshold
A_{18}	$(HookLF_k^{2p} - HookTS_k^{iq}) X_{2p}^{iq}(k) \geqslant 0 \qquad (\forall k \in [n1+1, n1+n2];\ \forall i \in [3, ts];\ \forall p, q \in P)$	The arriving time of a hook-lift at the landfill is greater than that at the previous transfer station
A_{19}	$\Vert Fork_k \Vert \leqslant mf \qquad (\forall k \in [n1+n2+1, n1+n2+n3])$	The number of times that a forklift can stay at the landfill in a shift cannot exceed a threshold
A_{20}	$(Fork_k^{2p} - T_k^{jq}) X_{2p}^{jq}(k) \geqslant 0 \qquad (\forall k \in [n1+n2+1, n1+n2+n3];\ \forall j \in [ts+1, gs];\ \forall p, q \in P)$	The arriving time of a forklift at the landfill is greater than those at previous sites
A_{21}	$T_k^{ip} - T_k^{i(p-1)} \geqslant PickT \qquad (\forall k \in [1, n1] \wedge [n1+n2+1, n1+n2+n3];\ \forall i \in [ts+1, gs];\ \forall p \in P)$	The waiting time of a vehicle at a site in two consecutive time windows must be greater than the pick-up time
Map constraints		
A_{22}	$\sum_{k\in K}\sum_{i\in N}\sum_{p\in P} X_{jq}^{ip}(k) = \sum_{k\in K} Y_{jq}(k)$	A node can serve many incoming vehicles

A_{23}	$\sum_{k\in K}\sum_{j\in N}\sum_{q\in P} X_{jq}^{ip}(k)=\sum_{k\in K} Y_{ip}(k)$	A node can serve many outgoing vehicles
A_{24}	$\sum_{k\in[1,n1]} Y_{ip}(k)\leqslant 1 \quad (i\in[ts+1,gs];\ \forall p\in P)$	Maximal number of tricycles and forklifts at a site in a time window is 2
A_{25}	$\sum_{k\in[n1+n2+1,n1+n2+n3]} Y_{ip}(k)\leqslant 3 \quad (i\in[ts+1,gs];\ \forall p\in P)$	
A_{26}	$\lvert Y_{ip}(k)-Y_{jq}(k)\rvert \leqslant \begin{cases} 1-X_{jq}^{ip}(k) & k\in[1,n1] \\ 2-X_{jq}^{ip}(k) & k\in[n1+1,n1+n2] \\ 3-X_{jq}^{ip}(k) & k\in[n1+n2+1,n1+n2+n3] \end{cases}$	Two connected nodes will be visited by the same vehicle
A_{27}	$R_i^p\times\sum_{k\in[1,n1]\wedge k\in[n1+n2+1,n1+n2+n3]} Y_{ip}(k)\geqslant R_i^p \quad (\forall i=\overline{ts+1,gs};\ p\in P)$	Any site will be visited by at least a vehicle
A_{28}	$\sum_{k\in[1,n1]\wedge k\in[n1+n2+1,n1+n2+n3]} Y_{ip}(k)\leqslant R_i^p \quad (\forall i=\overline{ts+1,gs};\ p\in P)$	Sites that do not have waste are not visited

Some terms and definitions of the proposed model are shown in Table 3. The novel VR model is also described in Table 4.

In Table 3, we clearly see that the standard travel time of a vehicle in an arc (term B_{14}) depends on many factors consisting of the static and dynamic ones. The static factors are adherent to the map's information such as the distances between nodes and the number of traffic lights in an arc. The dynamic ones relate to the information at a certain time point such as the number of vehicles per m^2 in an arc and the waiting time at a traffic light. Each type of vehicles will have its own travel time in an arc since the average velocities of all types of vehicles are different. Those factors orient the selection of best route of vehicles in order to achieve the objectives and are the generalization of some parameters in (Apaydin and Gonullu, 2011). In some relevant articles such as (Tung and Pinnoi, 2000), an arc is assumed to be two-way that means a vehicle can travel from a starting point to an ending point of the arc and vice versa. Such an assumption does not exist in reality since very often it turns out that there are some one-way routes on a map. In order to remedy this limitation, we introduce the term D_3 (Table 3) which expresses the permission to travel an arc of a vehicle in a time window. Because $Travel_{ij}^{pk}$ can be different with $Travel_{ji}^{pk}$ $(i,j\in N, k\in K, p\in P)$, the modeling of one-way route is possible. Furthermore, two different vehicles may not have the same access to an arc in a time window. This is quite suitable since some routes on a map permit special types of vehicles to travel. The objective function in Table 4 aims to maximize the collected waste quantities and to minimize the environmental emission with respect to vehicles. While the first component is popular in MSW collection, the second one is designed to dynamically change the number of vehicles so that the total collected waste quantity and the number of vehicles could be optimal. The last component in the objective function implies the minimization of the total traveling distances of vehicles. Due to the emission of exhaust fumes such as CO_2, NO, HC from working vehicles whether a process is loading or unloading, it is better that the number of used vehicles can be reduced whilst the total waste quantity are maximum. Therefore, we have a multi-objectives optimization problem in this case and a Pareto ranking system can be applied to obtain the best results. The VR model in Table 4 can process inhomogeneous vehicles and the structure of components that are not existed in previous models. Several constraints about waste quantity, time windows and the map are presented to ensure the scenario above.

3. An application at Danang city

In what follows, we apply the proposed model in Tables 3 and 4 to model the waste collection scenario at Danang city, Vietnam, which is one of largest industrial centers of Vietnam (Fig. 3). According to Harmeling (2009), Vietnam is one of 11 countries in the world that suffered greatest damage from climate change and sea-level rise. As a consequence, Danang has to cope with some impacts of climate change such as severe weather conditions and natural disasters. Optimizing MSW collection at Danang will both minimize the vulnerability caused by climate change and ensure the sustainable ecological environments. MONRE (2010) stated that Danang is one of four largest municipalities in Vietnam, having high quantity of the average waste load per person which is from 0.84 to 0.96 kg/person/day that is higher than that of South-east Asia, whose number is 0.85 kg/person/day. A summary from Danang Bureau of Statistics (2011) showed that the solid waste quantity increases much larger than the population in the duration of years from 1995 to 2010. 91 percents of the solid waste quantity at Danang in that period came from the households whilst 7 and 2 percents were reserved for markets and hotels & restaurants, respectively. The total waste quantity per day of Danang city is

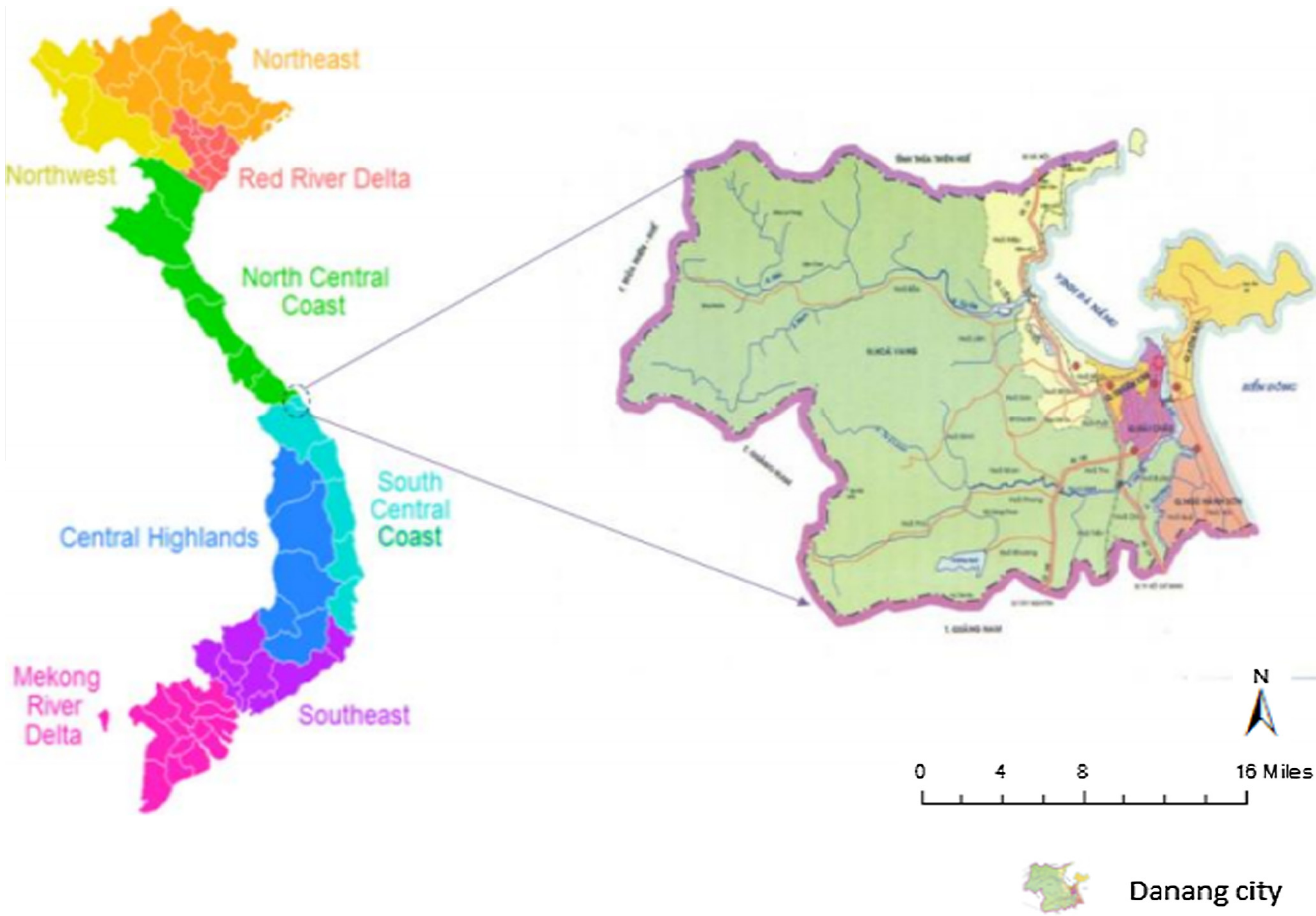

Fig. 3. Danang city, Vietnam.

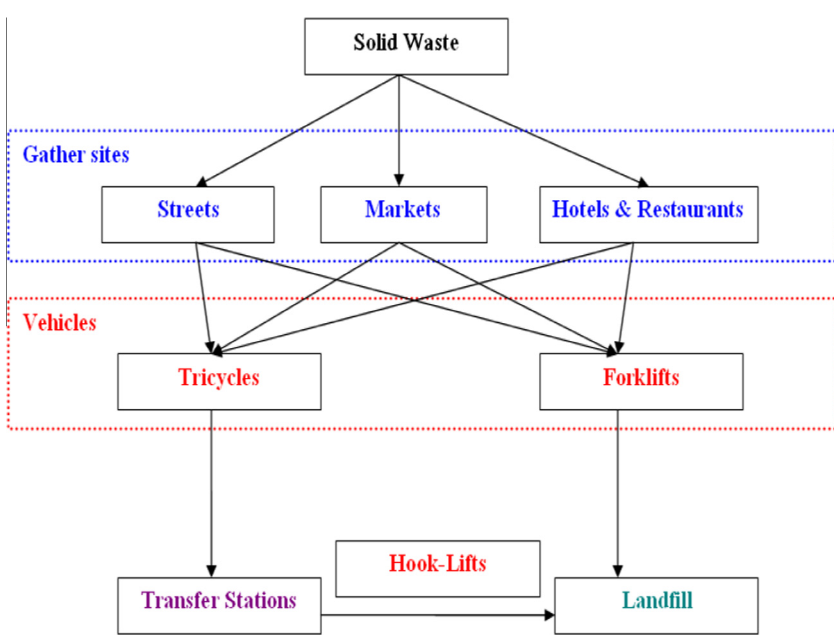

Fig. 4. Current scenario of MSW collection at Danang.

around 661.6 tons. This number is likely to increase dramatically by years and can attain 550 thousands tons in 2020. If an effective optimization method for MSW collection at Danang had been deployed, many benefits would have been achieved such as the economic aspect, urban planning and waste recycling.

Let us investigate the scenario of MSW collection at Danang (Fig. 4). Current model of Danang includes a depot, a landfill, many sites and many transfer stations. Solid waste at Danang is contained at three primary sources: streets, markets and hotels & restaurants. These sources are called the sites. There are three

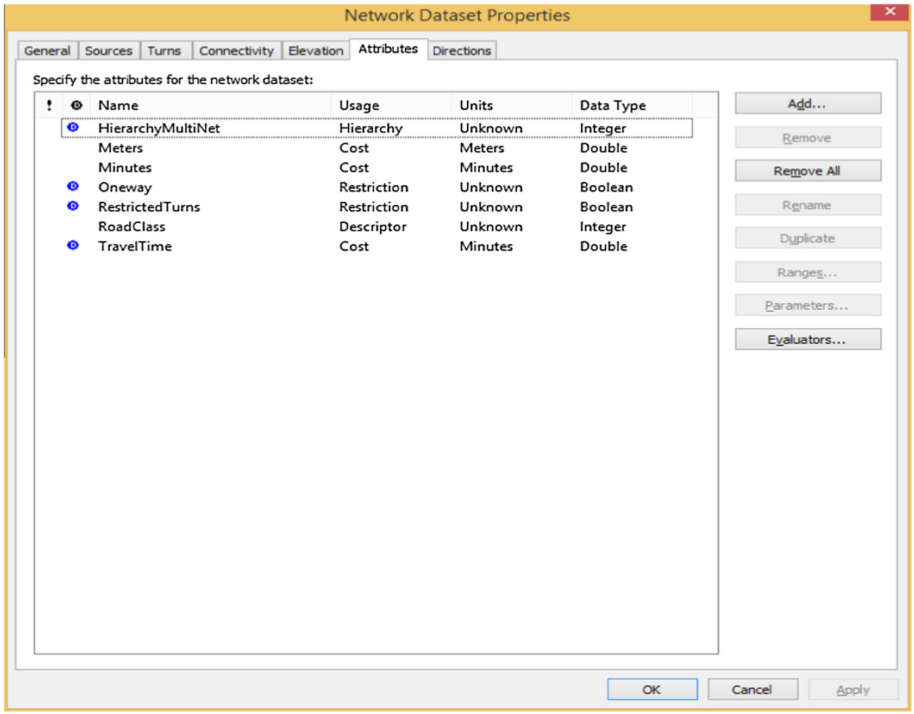

Fig. 5. Parameter setup.

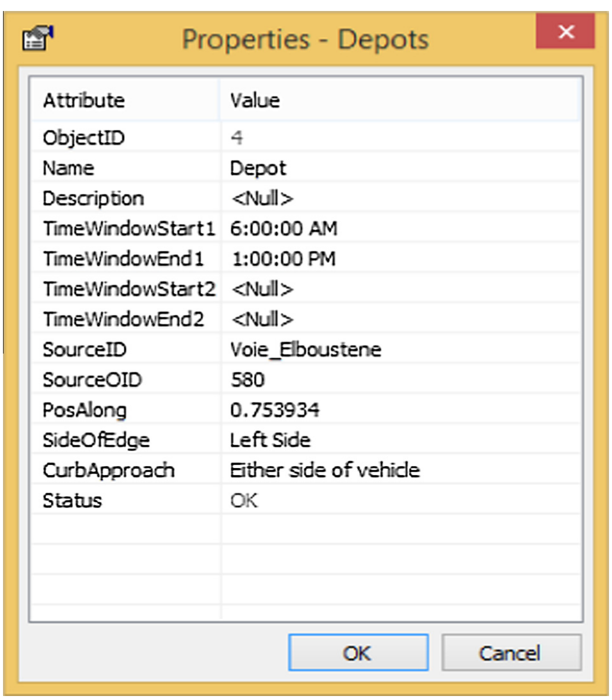

Fig. 6. Depot information.

types of vehicles serving for MSW collection namely tricycles, forklifts and hook-lifts. The two first vehicles are responsible for collecting waste at sites. The last one has to transport waste in containers from transfer stations to the landfill. The tricycle can carry up to a 6601 bin of waste (~170 kg) or two 2401 bins (~140 kg/bin). The forklift and the hook-lift have the maximal capacity around 9 tons of waste. After loading waste at some sites, a tricycle will unload it at a transfer station and then start a new route. Waste at a transfer station is sprayed by chemicals and compressed into containers. When the hook-lift is full of containers, it starts traveling to the landfill to unload them. The works of forklifts are similar to those of tricycles except that destination of forklifts is the landfill. In the current scenario of Danang, tricycles are allowed to work from 8 am to 6 pm (the day shift) whilst forklifts are from 8 pm to 12 pm (the night shift). All vehicles are designated to work under restriction from 6.30 to 8 am and from 5 to 6 pm.

From the scenario of Danang and the proposed model in Tables 3 and 4, we create the optimal vehicle routing model for MSW collection at this city as follow. The objective function is to maximize the collected waste quantities,

$$\tilde{J} = \sum_{k\in[1,n1]\wedge[n1+n2+1,n1+n2+n3]} \sum_{i\in[ts+1,gs]} WQ_k^i \to \max . \tag{1}$$

Since the scenario of Danang does not include time window, the constraints (A_1–A_5) and (A_9–A_{21}, A_{24}–A_{25}) are neglected. The constraints are:

$$R_l \geqslant \sum_{i\in[ts+1,gs]:X_l^i=1} WQ_k^i, \quad (\forall k \in [1,n1], \forall i \in [ts+1, gs], \forall l \in [3, ts]) \tag{2}$$

$$\sum_{k\in[n1+1,n1+n2]} WQ_k^i > R_i, \quad (\forall i \in [3, ts]) \tag{3}$$

$$WQ_k^i \leqslant C_k, \quad (\forall k \in [1, n1 + n2 + n3], \forall i \in [3, gs]) \tag{4}$$

$$\sum_{k\in K} \sum_{i\in N} X_j^i(k) = \sum_{k\in K} Y_j(k), \tag{5}$$

$$|Y_i(k) - Y_j(k)| \leqslant \begin{cases} 1 - X_j^i(k) & k \in [1, n1] \\ 2 - X_j^i(k) & k \in [n1 + 1, n1 + n2] \\ 3 - X_j^i(k) & k \in [n1 + n2 + 1, n1 + n2 + n3] \end{cases}, \tag{6}$$

$$R_i \times \sum_{k\in[1,n1]\wedge k\in[n1+n2+1,n1+n2+n3]} Y_i(k) \geqslant R_i, \quad (\forall i = \overline{ts+1, gs}) \tag{7}$$

$$\sum_{k\in[1,n1]\wedge k\in[n1+n2+1,n1+n2+n3]} Y_i(k) \leqslant R_i. \quad (\forall i = \overline{ts+1, gs}) \tag{8}$$

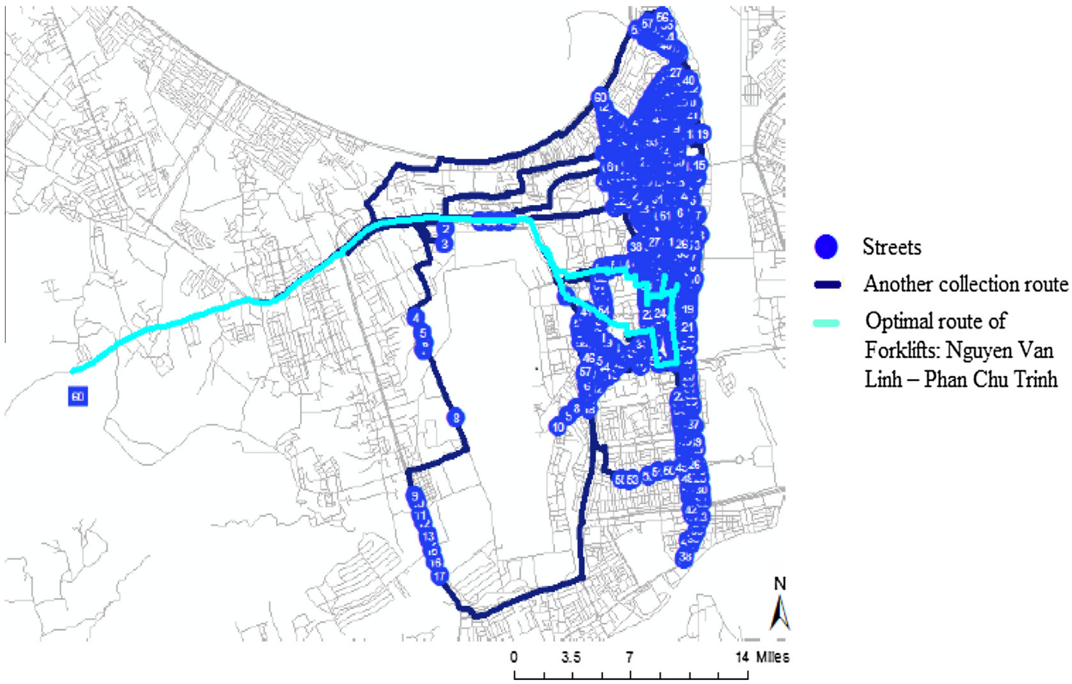

Fig. 7. An optimal route in streets.

Fig. 8. An optimal route in markets.

Obviously, the model (1)–(8) demonstrates a subset of the generalized model described in Tables 3 and 4, and matches the MSW collection scenario at Danang above. A recent result in (Son, 2014) about constructing a VR model for Danang city has shown that the VR model in (Son, 2014) and that in (1)–(8) are nearly identical in terms of meaning and description.

In what follows, we use the ArcGIS Network Analyst toolbox (ArcGIS, 2015) to find the optimal routes for the model of Danang in equations (1)–(8). The model has been implemented with Python scripts for preprocessing tasks. Some parameters are then selected as in Figs. 5 and 6. The results are illustrated by mean of Geographical Information Systems as in Figs. 7 and 8.

Table 5
The comparative results.

Criteria	Practical routes (Danang Bureau of Statistics, 2011)	ArcGIS with the model (1)–(8)
Travelling distances (km)	2958	2471
Operational time (h)	6.3	5.4

In Table 5, comparison between the results of practical routes and those of ArcGIS with the model (1)–(8) in terms of total traveling distances and operational hours is made. The results clearly

Table 6
Criteria and sub-criteria used in the model.

Criteria	Sub-criteria	Description
Economic	Operation and maintenance cost	Capability of routes to minimize operation and maintenance cost
	Fuel cost	Capability of routes to minimize fuel cost
Environmental	Quantity of waste	Capability of routes to load maximum quantity of waste
	Fuel emission	Capability of routes to alleviate fuel emissions
	Noise	Noise from garbage truck
Technological	Reliability	Policy may have been only tested in laboratory or only performed in pilot plants, or it could be still improved
	Efficiency	Alternative with higher efficiency is considered
Socio-political	Labour acceptance	Capability of routes to minimize additional working hours
	Compatibility with the national energy policy objectives	The criterion also takes into account the government's support, the tendency of institutional actors, and the policy of public information

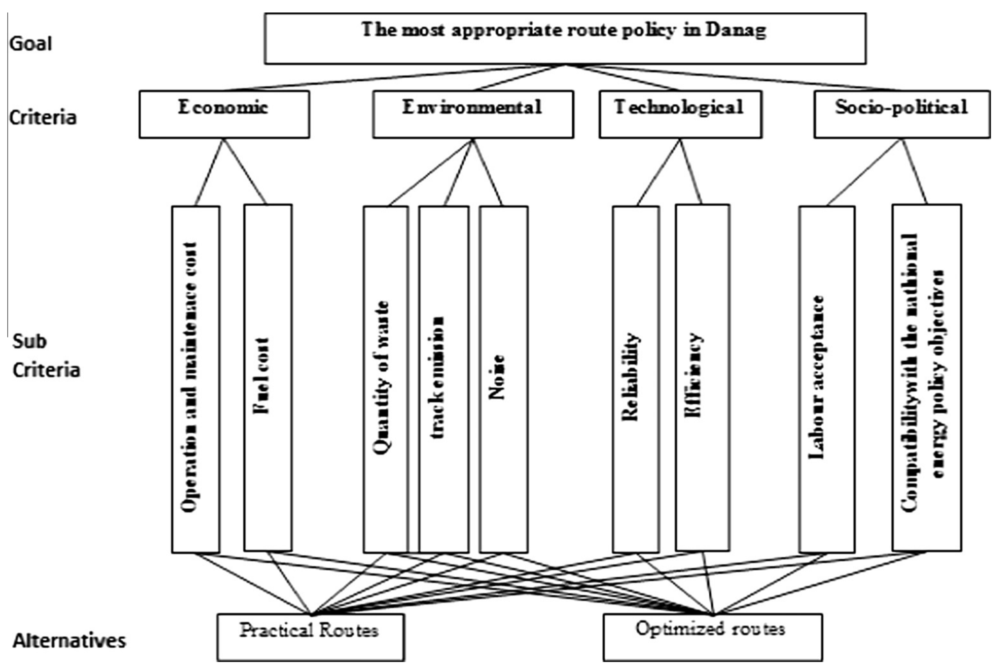

Fig. 9. The hierarchy for selection of the most appropriate route policy in Danang.

affirm that using the new model (1)–(8) would reduce both total traveling distances and operational hours of vehicles. This indicates applicability of the generalized model for practical applications.

In what follows, we perform the environmental analysis based on the experimental results. Municipal solid waste management (MSWM) is known as a complicated process that involves multiple environmental, economic, political and social criteria. Multi-criteria Decision Analysis (MCDA) is employed in many studies on MSWM through various methods such as ELECTRE III (Hokkanen and Salminen, 1997), fuzzy TOPSIS (Pires et al., 2011a), (Korucu, 2011), (Soltani et al., 2015) and (Khan and Samadder, 2014). Various studies have been done to check the suitability of landfill locations and garbage transfer stations, and to compare the existing facilities and scientifically optimized locations of garbage bins and landfill sites. In this paper, we use MCDA method to compare the practical routes in Danang and the optimization route (ArcGIS with the model) with Analytic Hierarchy Process (AHP) (Saaty, 1990) which allows decision makers to issue judgments based on their experience and informational data available for complex problems. The approach starts by identifying the goal and develops potential scenarios which can meet the objec-

Table 7
AHP importance scale.

Scale	Description
1	A is equally important as B
3	A is moderately more important than B
5	A is strongly more important than B
7	A is very strongly more important than B
9	A is extremely more important than B

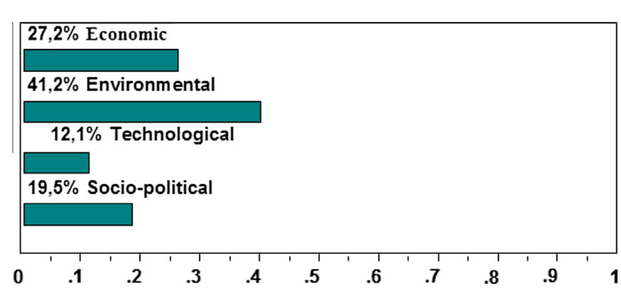

Fig. 10. Relative weights of criteria with respect to goal.

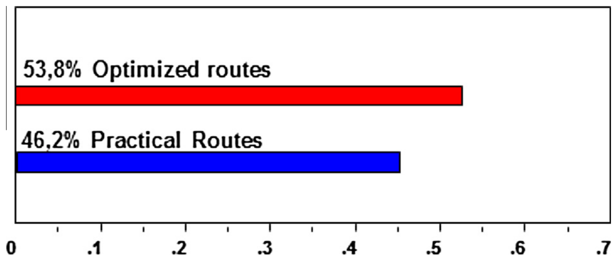

Fig. 11. Ranking of Routes.

tive. Finally, identify the criteria and sub-criteria that influence the decision. These three categories are all levels in the hierarchical representation and each problem consists of at least three levels. AHP procedure can be divided into five steps:

1. Decompose the problem of a hierarchy.
2. Determine relative importance of the criteria and sub criteria.
3. Determine weight (relative importance) of each option versus each of the criteria, and sub criteria.
4. Synthesize priorities for each level.
5. Assess consistency of judgments made.

In this study, the main objective is to evaluate different types of waste collection routes based on four criteria namely economic, environmental, technological and socio-political. To further enrich the model, nine sub-criteria have been identified to get direct influence on the best route and the goal of decision problem. The criteria and sub-criteria are also supported by the literature. The details of assessment criteria are provided in Table 6.

The AHP model formulated in this study consists of four levels. At the top level is the goal of the model followed by the criteria at level two. Sub-criteria are at level three while two route policies are at the fourth level, named, alternatives. The hierarchy for selection of the most appropriate route policy in Danang is presented below (see Fig. 9).

At each level of the model, a pair-wise comparison matrix is developed. The matrix entries signify numerical importance of each element with other elements in comparison. The scale is explained in Table 7. For each comparison matrix, a normalized priority vector of the matrix is computed. A priority vector indicates the importance of each element with respect to its parent level, and a consistency of the comparison is done.

An expert evaluates different criteria and assessment model results indicate that the most important criteria – environmental aspect's weight is 0.412 and economic and socio-political aspects have relative weight of 0.272 and 0.195, respectively. Technological criterion is the least important one among all. The relative weights of the criteria are shown in Fig. 10. The inconsistency in the pair-wise comparison for criteria is measured to be around 0.0017 which is within the limits.

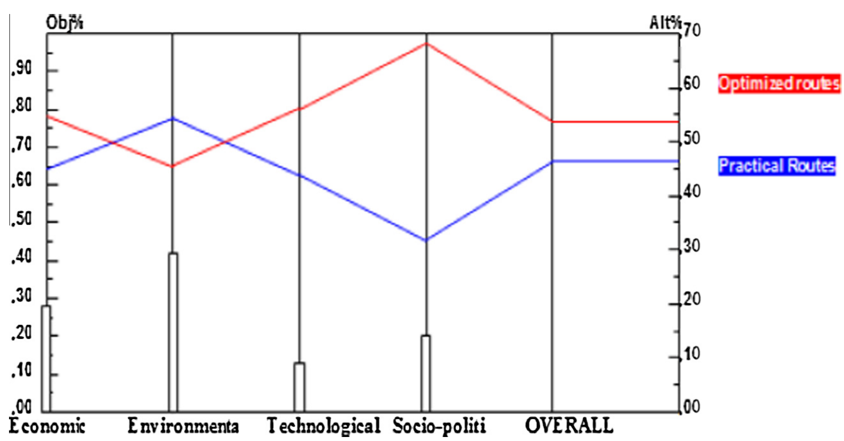

Fig. 12. Sensitivity for the most appropriate route in Danang.

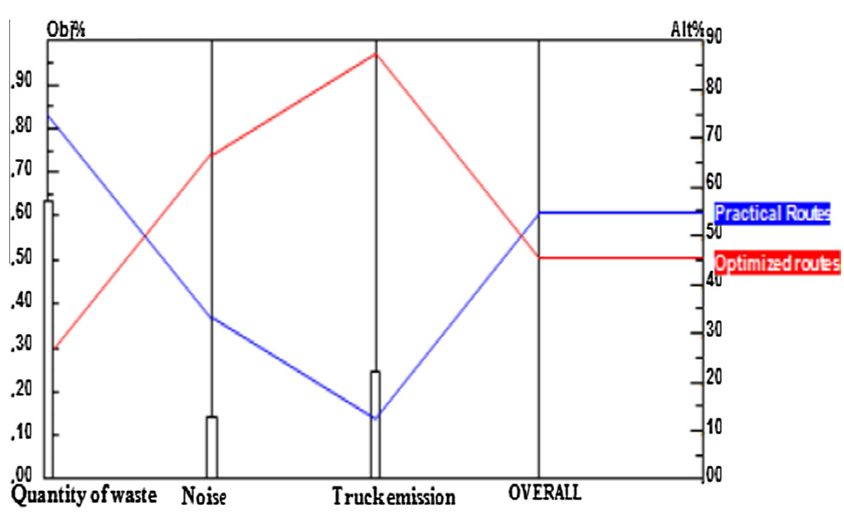

Fig. 13. Sensitivity for environmental criteria.

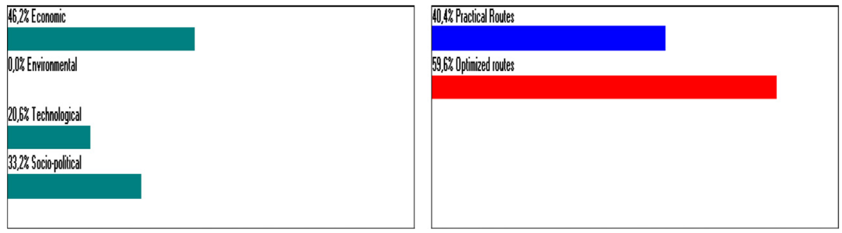

Fig. 14. First comparison.

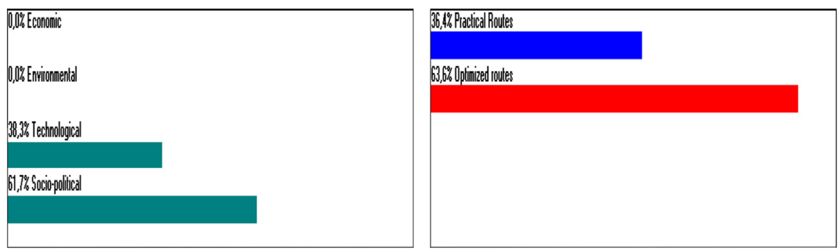

Fig. 15. Second comparison.

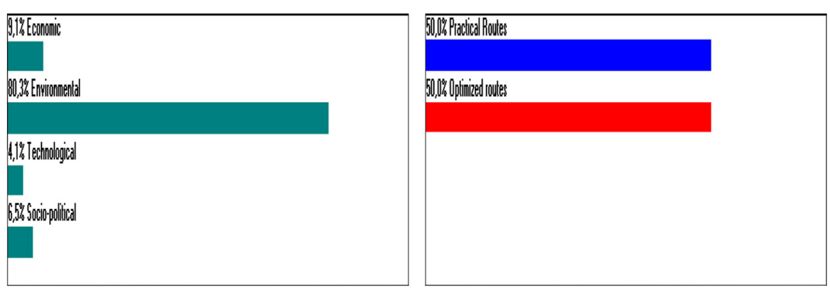

Fig. 16. Third comparison.

Fig. 17. Analysis of results by many factors.

According to the expert choice software, the optimized route with ArcGIS seems to be the best appropriate route policy in Danang. The priority weight of optimized route is 0.538 vs. 0.462 for the practical route (Fig. 11).

The practical route capable to load 10,166,382 kg quantity of waste more than optimized routes but this one minimizes the traveling distance while minimizing fuel and cost fuel and fuel emission (Figs. 12 and 13).

Summary of sensibility analysis:

(a) Eliminate to environmental analysis, optimized route is the first rank (Fig. 14).
(b) Eliminate to economic and environmental criteria, optimized route is still first rank (Fig. 15).
(c) Increase the weight of environmental criteria to 80.3 gives same tank for practical routes and optimized routes (Fig. 16).

The most appropriate route policy at Danang is given in Fig. 17.

4. Conclusions

In this paper, we concentrated on the problem of modeling the municipal solid waste collection with respect to various objectives. A generalized optimal vehicle routing model including inhomogeneous vehicles, multiple transfer stations and sites for this problem was proposed. This model possibly handled the limitations of existing VR models and can be applied for various municipal solid waste collection scenarios. An application of the proposed model for Danang city, Vietnam was given to illustrate the usefulness and utility of the model. The experimental results showed that total traveling distances and operational hours of vehicles of the new model are less than those of the practical routes. Environmental analysis using the AHP method was done for better investigation of the results which emphasized the applicability of the proposed measures to waste management.

The significance and practical implication of the proposed work are three-folds. Firstly, the proposed model in this paper could be applied to a variety of problems having the same nodes' structures and vehicles' characteristics. Secondly, the proposed model enriches knowledge about modeling municipal waste collection in generalized contexts. Thirdly, this paper could evolve a research orientation regarding development of optimization methods for handling the generalized and sub- models.

From those points of views, our further studies continue to investigate theoretical base and applications of waste collection optimization such as (i) using heuristic methods find the (sub-) optimal solutions of the model; (ii) analyzing the most dominant factors of the model's results to environmental emission and climate change; and (iii) integrating other types of waste collection scenarios to the model and implementation in ArcGIS. Those works would contribute significant roles to environmental science as a matter of fact.

References

Apaydin, O., Gonullu, M.T., 2008. Emission control with route optimization in solid waste collection process: a case study. Sadhana 33 (2), 71–82.
Apaydin, O., Gonullu, M.T., 2011. Route time estimation of solid waste collection vehicles based on population density. Glob. Nest J. 13 (2), 162–169.
ArcGIS, 2015. ArcGIS Network Analyst Overview <http://www.esri.com/software/arcgis/extensions/networkanalyst> (accessed 10.05.15).
Arribas, C.A., Blazquez, C.A., Lamas, A., 2010. Urban solid waste collection system using mathematical modelling and tools of geographic information systems. Waste Manage. Res. 28 (4), 355–363.
Beigl, P., Lebersorger, S., Salhofer, S., 2008. Modelling municipal solid waste generation: a review. Waste Manage. 28 (1), 200–214.
Beliën, J., De Boeck, L., Van Ackere, J., 2012. Municipal solid waste collection and management problems: a literature review. Transp. Sci. 48 (1), 78–102.
Chatzouridis, C., Komilis, D., 2012. A methodology to optimally site and design municipal solid waste transfer stations using binary programming. Resour. Conserv. Recycl. 60, 89–98.
Cioca, L.I., Ivascu, L., Rada, E.C., Torretta, V., Ionescu, G., 2015. Sustainable development and technological impact on CO2 reducing conditions in Romania. Sustainability 7 (2), 1637–1650.
Consonni, S., Giugliano, M., Grosso, M., 2005. Alternative strategies for energy recovery from municipal solid waste: Part B: Emission and cost estimates. Waste Manage. 25 (2), 137–148.
Da Nang Bureau of Statistics, 2011. Municipal Solid Waste Management at Danang City (in Vietnamese). Danang Foreign Affairs Department <http://www.cucthongke.danang.gov.vn> (accessed 20.04.15).
Dyson, T., 2011. The role of the demographic transition in the process of urbanization. Popul. Dev. Rev. 37 (s1), 34–54.
Faccio, M., Persona, A., Zanin, G., 2011. Waste collection multi objective model with real time traceability data. Waste Manage. 31 (12), 2391–2405.
Fan, X., Zhu, M., Zhang, X., He, Q., Rovetta, A., 2010. Solid waste collection optimization considering energy utilization for large city area. 2010 IEEE International Conference on Logistics Systems and Intelligent Management, vol. 3, pp. 1905–1909.
Galante, G., Aiello, G., Enea, M., Panascia, E., 2010. A multi-objective approach to solid waste management. Waste Manage. 30 (8), 1720–1728.
Gunalay, Y., Yeomans, J.S., Huang, G.H., 2012. Modelling to generate alternative policies in highly uncertain environments: an application to municipal solid waste management planning. J. Environ. Inform. 19 (2), 58–69.
Harmeling, S., 2009. Global Climate Risk Index 2010: Who is most vulnerable? Weather-related loss events since 1990 and how Copenhagen needs to respond, Briefing Paper, Germanwatch, Bonn.
Hemmelmayr, V.C., Doerner, K.F., Hartl, R.F., Vigo, D., 2013a. Models and algorithms for the integrated planning of bin allocation and vehicle routing in solid waste management. Transp. Sci. 48 (1), 103–120.
Hemmelmayr, V., Doerner, K.F., Hartl, R.F., Rath, S., 2013b. A heuristic solution method for node routing based solid waste collection problems. J. Heurist. 19 (2), 129–156.
Hokkanen, J., Salminen, P., 1997. Choosing a solid waste management system using multicriteria decision analysis. Eur. J. Oper. Res. 98, 19–36.
Islam, M.S., Hannan, M.A., Arebey, M., Basri, H., 2012. An overview for solid waste bin monitoring system. J. Appl. Sci. Res. 8 (2), 879–886.
Khan, D., Samadder, S.R., 2014. Municipal solid waste management using geographical information system aided methods: a mini review. Waste Manage. Res. 32, 1049–1062.
Korucu, M.K., 2011. Discussion of "Combining AHP with GIS for landfill site selection: A case study in the Lake Beysehir catchment area (Konya, Turkey), Waste Management, 30, 11, 2010, 2037–2046". Waste Manage. 31, 1250–1251.
Larsen, A.W., Merrild, H., Møller, J., Christensen, T.H., 2010. Waste collection systems for recyclables: an environmental and economic assessment for the municipality of Aarhus (Denmark). Waste Manage. 30 (5), 744–754.
Levis, J.W., Barlaz, M.A., DeCarolis, J.F., Ranjithan, S.R., 2013. A generalized multistage optimization modeling framework for life cycle assessment-based integrated solid waste management. Environ. Modell. Softw. 50, 51–65.
Madlener, R., Sunak, Y., 2011. Impacts of urbanization on urban structures and energy demand: what can we learn for urban energy planning and urbanization management? Sustain. Cit. Soc. 1 (1), 45–53.
MONRE, 2010. Current Statuses of Municipal Solid Waste Management at Vietnam (in Vietnamese). Vietnam Environment Administration <http://vea.gov.vn> (accessed 20.04.15).
Mora, C., Manzini, R., Gamberi, M., Cascini, A., 2014. Environmental and economic assessment for the optimal configuration of a sustainable solid waste collection system: a 'kerbside'case study. Prod. Plann. Control 25 (9), 737–761.
Pires, A., Chang, N.B., Martinho, G., 2011a. An AHP-based fuzzy interval TOPSIS assessment for sustainable expansion of the solid waste management system in Setúbal Peninsula, Portugal. Resour. Conserv. Recycl. 56, 7–21.
Pires, A., Martinho, G., Chang, N.B., 2011b. Solid waste management in European countries: a review of systems analysis techniques. J. Environ. Manage. 92 (4), 1033–1050.
Ragazzi, M., Torretta, V., Ionescu, G., Istrate, I.A., 2013. Maintenance strategies and local impact of MSW incinerators. WIT Trans. Ecol. Environ. 176, 235–244.
Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res. 48, 9–26.
Soltani, A., Hewage, K., Reza, B., Sadiq, R., 2015. Multiple stakeholders in multi-criteria decision-making in the context of municipal solid waste management: a review. Waste Manage. 35, 318–328.
Son, L.H., 2014. Optimizing municipal solid waste collection using chaotic particle swarm optimization in GIS based environments: a case study at Danang city, Vietnam. Expert Syst. Appl. 41 (18), 8062–8074.
Tai, J., Zhang, W., Che, Y., Feng, D., 2011. Municipal solid waste source-separated collection in China: a comparative analysis. Waste Manage. 31 (8), 1673–1682.
Tan, Q., Huang, G.H., Cai, Y.P., 2010a. Identification of optimal plans for municipal solid waste management in an environment of fuzziness and two-layer randomness. Stoch. Env. Res. Risk Assess. 24 (1), 147–164.
Tan, Q., Huang, G.H., Cai, Y.P., 2010b. Waste management with recourse: an inexact dynamic programming model containing fuzzy boundary intervals in objectives and constraints. J. Environ. Manage. 91 (9), 1898–1913.
Tavares, G., Zsigraiova, Z., Semiao, V., Carvalho, M.D.G., 2009. Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling. Waste Manage. 29 (3), 1176–1185.

Technology, D., 2013. United Nations Environment Programme <www.unep.org> (accessed 20.04.15).

Teixeira, C.A., Avelino, C., Ferreira, F., Bentes, I., 2014. Statistical analysis in MSW collection performance assessment. Waste Manage. 34 (9), 1584–1594.

Tung, D.V., Pinnoi, A., 2000. Vehicle routing–scheduling for waste collection in Hanoi. Eur. J. Oper. Res. 125 (3), 449–468.

Weitz, K.A., Thorneloe, S.A., Nishtala, S.R., Yarkosky, S., Zannes, M., 2002. The impact of municipal solid waste management on greenhouse gas emissions in the United States. J. Air Waste Manage. Assoc. 52 (9), 1000–1011.