Adaptation of simulated annealing to an integrated municipal solid waste location-routing problem

Article *in* International Journal of Logistics Systems and Management · January 2017

DOI: 10.1504/IJLSM.2017.10007117

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Abstract: This paper aims to propose an integrated municipal solid waste management network covering multiple types of wastes concurrently and utilise a location-routing problem framework to minimise the establishment cost of interrelated facilities (i.e., transfer stations; treatment, recycling and disposal centres) in the network and the transportation cost of wastes in the entire network. The defined problem consists of the concurrent site selection of the locations of the system's all facilities among the candidate locations and the determination of routes and amount of shipments among the selected facilities to minimise the total cost of transportation and facility establishment. As the addressed problem exhibits the non-deterministic polynomial-time hardness (NP-hardness), an adaptation of the simulated annealing algorithm is proposed in this paper. The experiment results, when compared with the exact solutions obtained by mixed-integer programming in terms of solution fitness and computing time, imply that the employed algorithm works effectively and efficiently.

Keywords: municipal solid waste; MSW; location-routing problem; LRP; heuristic solution approach; simulated annealing.

Reference to this paper should be made as follows: Asefi, H., Lim, S. and Maghrebi, M. (2017) 'Adaptation of simulated annealing to an integrated municipal solid waste location-routing problem', *Int. J. Logistics Systems and Management*, Vol. 28, No. 2, pp.127–143.

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1 Introduction

Due to the recent population growth and technological progress, the amount of waste generation has increased and turned into a managerial challenge for responsible sectors including municipalities and private waste processing companies. Municipal solid waste management (MSWM) involves the processes associated with collection, transportation, treatment, recycling and disposal of wastes in a safe, hygienic and cost effective manner (Alumur and Kara, 2007; Asefi et al., 2015). In addition to the potential benefit in recycling recyclable wastes, efficient managerial approaches could be also utilised to economise the cost of MSWM systems. The transportation cost of waste shipment is one of major factors in MSWM which can be effectively economised by efficient planning approaches.

A municipal solid waste (MSW) location-routing problem (LRP) involves two NP-hard problems (facility location and routing) to be optimised concurrently (Alumur and Kara, 2007; Zhao and Zhao, 2010; Asefi et al., 2015). This problem includes optimising locations of the waste management system's facilities such as treatment and disposal centres, and routing the wastes to and from the facilities.

MSWs are generated in different kinds but can be classified into three types: recyclables, hazardous wastes and garbage. Recyclable wastes are those which can be fully or partly recycled at recycling centres (such as paper, glass and metal). Hazardous wastes are those having destructive impacts on human's well-being if they remain in the environment. Hazardous wastes such as the used batteries, pesticides and disposable syringes are defined as wastes which have one or more characteristics of ignitability, corrosiveness, reactivity and toxicity (Alumur and Kara, 2007). Hazardous wastes need to undergo treatment at treatment centres before recycling or disposing. The third group which is classified here as garbage is anything but neither recyclables nor hazardous ones and must go directly to disposal centres.

In this paper, three main real-world constraints are considered for modelling a MSWM system. First, it is assumed that hazardous wastes are generated in different types where each type needs a distinct technology for treatment. That is, a compatible treatment technology must be selected based on the waste characteristics (Nema and Gupta, 1999). Second, transfer stations are included in the problem network as the important interrelated facilities of the MSWM system. A transfer station is a processing site used for temporary deposition of wastes by collection vehicles. Sorting and balling wastes to load in large-class vehicles are performed in these facilities (EPA, 2002; Asefi et al., 2015). Lastly, distinct disposal centres are considered for hazardous and non-hazardous wastes, and residues. In real-world scenarios, disposal centres for hazardous wastes are under more strict regulations (EPA, 1996; Asefi et al., 2015).

In a LRP, joint decisions consist of opening a single or a set of depots and designing a number of routes for each opened depot, with the objectives of minimising the overall cost comprising the fixed costs of opening the depots and the costs of the routes (Lin et al., 2014). Some articles on a LRP can be found in Nagy and Salhi (2007) and Min et al. (1998), and comprehensive surveys about the state of the art in location-routing have been proposed in those studies with a classification scheme. Application of LRP in waste management has been studied for only hazardous wastes in almost all the existing models (Nema and Gupta, 1999; List and Mirchandani, 1991; Jacobs and Warmerdam, 1994; Giannikos, 1998; Alumur and Kara, 2007; Zhao and Zhao, 2010; Samanlioglu, 2013; Boyer et al., 2013; Ardjmand et al., 2015). While most studies on the hazardous waste LRP assumed a single type of hazardous wastes in their modelling, considering different types of hazardous wastes and waste technology compatibility as a real-world constraint are factored in mathematical models presented by List and Mirchandani (1991), Nema and Gupta (2003), Alumur and Kara (2007), Zhao and Zhao (2010), Samanlioglu (2013), Boyer et al. (2013) and Asefi et al. (2015). In the literature on MSWM, mostly locating the recycling centres and transfer stations are neglected and the majority of the presented models focused on locating treatment and disposal centres only (Asefi et al., 2015). Including recycling centres in the problem network has been addressed by few researchers (Samanlioglu, 2013; Asefi et al., 2015). Transfer stations also have been rarely included in waste management LRPs (Asefi et al., 2015). Moreover, the NP-hardness of the problem was not tackled by heuristic approaches (Caballero et al., 2007; Boffey et al., 2008; Xie et al., 2012; Ardjmand et al., 2015) where the mentioned real-world assumptions of waste technology compatibility and locating all the interrelated facilities (i.e., transfer stations; recycling, treatment and disposal centres) have not been considered before. To the best of the authors' knowledge, no heuristic approach has been applied yet for MSW LRPs, and the applied heuristics in the most similar problems in hazardous waste LRPs were not utilised for a problem consisting of all the constraints as those considered in this paper (i.e., factoring in all the interrelated facilities, multiple waste types and waste technology compatibility).

The principles of our addressed problem are similar to those of Asefi et al. (2015) where all the MSWM system's facilities are factored in. Our formulated model can cover different types of wastes (i.e., recyclables, hazardous wastes and garbage) in an integrated framework. Moreover, different types of hazardous wastes and the waste technology compatibility for treatment of different hazardous waste types are considered as real-world constraints. To tackle the NP-hardness of the problem, an adaptation of the simulated annealing (SA) method is proposed in this paper. The obtained results from the

SA method are compared against the exact solutions by mixed-integer programming in terms of solution fitness and computing time.

2 Problem formulation

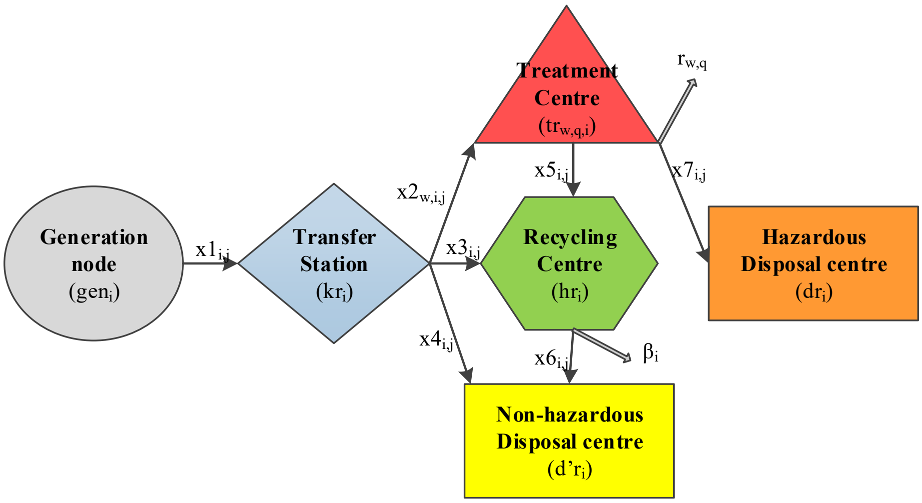
2.1 Problem framework

The main aim of this study is to develop a heuristic solution approach for an integrated MSW LRP which can cover multiple types of MSWs concurrently. The problem involves concurrent locating of the system's all interrelated facilities (i.e., transfer stations; recycling, treatment, non-hazardous disposal and hazardous disposal centres) and routing wastes to and from the facilities with respect to the objective of minimising the total cost of transportation and facility establishment. The schematic view of the addressed problem is displayed in Figure 1. The framework of the problem is based on the following assumptions.

- It is assumed that wastes are transported from generation nodes to transfer stations in unsorted packs ($x1_{i,j}$); and, at transfer stations they are sorted and balled into the multiple waste types: hazardous wastes in different types ($x2_{w,i,j}$) are transferred to treatment centres, recyclable wastes ($x3_{i,j}$) are shipped to recycling centres and garbage ($x4_{i,j}$) is sent to non-hazardous disposal centres to get disposed there.
- It is assumed that hazardous wastes after the treatment process go through one of three flows: the first one is that the treated wastes are reduced as mass reduction and are released out of network ($r_{w,q}$); the second flow consists of a part which does not have any characteristics of hazardous wastes anymore and is suitable for recycling ($x5_{i,j}$); and the last flow is the part which still has hazardous characteristics and must be disposed at hazardous disposal centres ($x7_{i,j}$).
- The major proportion of recyclable wastes after the recycling process (β_i) is assumed to be converted to recycled materials and is released out of network to be reused in the market and manufacturing sectors. Also, the recycling process of recyclable wastes produces residues which must be disposed at non-hazardous disposal centres ($x6_{i,j}$).
- Processing facilities (i.e., transfer stations; treatment, recycling, non-hazardous disposal and hazardous disposal centres) work under pre-determined limited capacities. Also, there should be at least a pre-determined minimum amount of input waste to establish a processing facility.
- Transportation cost is proportional to the distance between origin and destination nodes. For hazardous wastes and hazardous residues the constant factor of $\delta = 1.43$ is multiplied by the distance to consider special care and equipment associated with transportation of these types of wastes (Alumur and Kara, 2007; Samanlioglu, 2013; Asefi et al., 2015).
- There is no capacity constraint for the roads and transporting vehicles.
- Amounts of waste generation at generation nodes are known and deterministic.

- Cost of establishment for each type of the facilities is pre-determined and deterministic at every candidate node.
- Every node can be a candidate location for different types of the facilities at the same time.

Figure 1 The problem network (see online version for colours)



Source: Asefi et al. (2015)

2.2 Mathematical model

The mathematical model of the addressed problem is presented as a mixed-integer programming as below. The notations in programming are presented as follows.

Sets:

$N = (V, A)$	is a transportation network of nodes V and arcs A
$G = \{1, \ldots, g\}$	is a set of waste generation nodes, $G \in V$
$K = \{1, \ldots, k\}$	is a set of potential transfer station nodes, $K \in V$
$T = \{1, \ldots, t\}$	is a set of potential treatment nodes, $T \in V$
$D = \{1, \ldots, d\}$	is a set of potential hazardous disposal nodes, $D \in V$
$D' = \{1, \ldots, d'\}$	is a set of potential non-hazardous disposal nodes, $D' \in V$
$H = \{1, \ldots, h\}$	is a set of potential recycling nodes, $H \in V$
$W = \{1, \ldots, w\}$	is a set of hazardous waste types
$Q = \{1, \ldots, q\}$	is a set of treatment technologies.

Parameters:

d_{ij}	is the distance on link $(i, j) \in A$, $i, j \in V$
fk_i	is a fixed cost of opening a transfer station at node $i \in K$
$fc_{q,i}$	is a fixed cost of opening a treatment technology $q \in Q$ at node $i \in T$
fd_i	is a fixed cost of opening a hazardous disposal centre at node $i \in D$
fd_i'	is a fixed cost of opening a non-hazardous disposal centre at node $i \in D'$
fh_i	is a fixed cost of opening a recycling centre at node $i \in H$
gn_i	is an amount of waste generated at generation node $i \in G$
$ph_{w,i}$	is a proportion of hazardous waste type $w \in W$ sorted at transfer station node $i \in K$
pr_i	is a proportion of recyclable waste sorted at transfer station node $i \in K$
pg_i	is a proportion of garbage waste sorted at transfer station node $i \in K$
$r_{w,q}$	is a proportion of mass reduction of hazardous waste type $w \in W$ treated with technology $q \in Q$
$\alpha_{w,q}$	is a proportion of recycling of hazardous waste type $w \in W$ treated with technology $q \in Q$
β_i	is a proportion of total waste recycled at node $i \in H$
δ	is the constant factor in transporting hazardous wastes and hazardous residues
$tc_{q,i}$	is a capacity of treatment technology $q \in Q$ at node $i \in T$
rc_i	is a capacity of recycling centre at node $i \in H$
dc_i	is a capacity of hazardous disposal centre at node $i \in D$
$d'c_i$	is a capacity of non-hazardous disposal centre at node $i \in D'$
sc_i	is a capacity of transfer station at node $i \in K$
$tc_{q,i}^m$	is the minimum amount of hazardous waste required to establish treatment technology $q \in Q$ at node $i \in T$
rc_i^m	is the minimum amount of recyclable waste required to establish a recycling centre at node $i \in H$
dc_i^m	is the minimum amount of hazardous waste residue required to establish a hazardous disposal centre at node $i \in D$
$d'c_i^m$	is the minimum amount of garbage and non-hazardous waste residue required to establish a non-hazardous disposal centre at node $i \in D'$

sc_i^m is the minimum amount of waste required to establish a transfer station at node $i \in K$

$yn_{w,q}$ is 1 if hazardous waste type $w \in W$ is compatible with technology $q \in Q$; or 0 otherwise.

Decision variables:

$\boldsymbol{x1}_{i,j}$ is an amount of waste transported through link $(i, j) \in A$, $i \in G, j \in K$

$\boldsymbol{x2}_{w,i,j}$ is an amount of hazardous waste type $w \in W$ transported through link $(i, j) \in A$, $i \in K, j \in T$

$\boldsymbol{x3}_{i,j}$ is an amount of recyclable waste transported through link $(i, j) \in A$, $i \in K, j \in H$

$\boldsymbol{x4}_{i,j}$ is an amount of garbage waste transported through link $(i, j) \in A$, $i \in K$, $j \in D'$

$\boldsymbol{x5}_{i,j}$ is an amount of treated recyclable waste residue transported through link $(i, j) \in A$, $i \in T, j \in H$

$\boldsymbol{x6}_{i,j}$ is an amount of waste residue transported through link $(i, j) \in A$, $i \in H$, $j \in D'$

$\boldsymbol{x7}_{i,j}$ is an amount of hazardous waste residue transported through link $(i, j) \in A$, $i \in T, j \in D$

$\boldsymbol{kr}_i$ is an amount of waste transferred at node $i \in K$

$\boldsymbol{tr}_{w,q,i}$ is an amount of hazardous waste type $w \in W$ treated at node $i \in T$ with technology $q \in Q$

$\boldsymbol{dr}_i$ is an amount of hazardous waste residue disposed at node $i \in D$

$\boldsymbol{d'r}_i$ is an amount of non-hazardous waste residue disposed at node $i \in D'$

$\boldsymbol{hr}_i$ is an amount of waste recycled at node $i \in H$

$\boldsymbol{f}_{q,i}$ is 1 if treatment technology $q \in Q$ is established at node $i \in T$; or 0 otherwise

$\boldsymbol{dz}_i$ is 1 if hazardous disposal centre is established at node $i \in D$; or 0 otherwise

$\boldsymbol{d'z}_i$ is 1 if non-hazardous disposal centre is established at node $i \in D'$; or 0 otherwise

$\boldsymbol{b}_i$ is 1 if recycling centre is established at node $i \in H$; or 0 otherwise

$\boldsymbol{a}_i$ is 1 if transfer station is established at node $i \in K$; or 0 otherwise.

The main objective of the problem is to minimise the total cost under the given constraints as follows:

$$\begin{aligned}\text{Minimise } f(x) = & \sum_{i\in G}\sum_{j\in K} d_{i,j}\boldsymbol{x1}_{i,j} + \sum_{i\in K}\sum_{j\in T}\sum_{w\in W}\delta d_{i,j}\boldsymbol{x2}_{w,i,j} + \sum_{i\in K}\sum_{j\in H} d_{i,j}\boldsymbol{x3}_{i,j} \\ & + \sum_{i\in K}\sum_{j\in D'} d_{i,j}\boldsymbol{x4}_{i,j} + \sum_{i\in T}\sum_{j\in H} d_{i,j}\boldsymbol{x5}_{i,j} + \sum_{i\in H}\sum_{j\in D'} d_{i,j}\boldsymbol{x6}_{i,j} \\ & + \sum_{i\in T}\sum_{j\in D}\delta d_{i,j}\boldsymbol{x7}_{i,j} + \sum_{i\in K} fk_i\boldsymbol{a}_i + \sum_{i\in T}\sum_{q\in Q} fc_{q,i}\boldsymbol{f}_{q,i} + \sum_{i\in H} fh_i\boldsymbol{b}_i \\ & + \sum_{i\in D} fd_i\boldsymbol{dz}_i + \sum_{i\in D} fd'_i\boldsymbol{d'z}_i \end{aligned} \tag{1}$$

subject to

$$gn_i = \sum_{j\in K}\boldsymbol{x1}_{i,j} \quad \forall i\in G \tag{2}$$

$$\sum_{i\in G}\boldsymbol{x1}_{i,j} = \boldsymbol{kr}_j \quad \forall j\in K \tag{3}$$

$$\sum_{w\in W} ph_{w,i}\boldsymbol{kr}_i = \sum_{j\in T}\sum_{w\in W}\boldsymbol{x2}_{w,i,j} \quad \forall i\in K \tag{4}$$

$$pr_i\boldsymbol{kr}_i = \sum_{j\in H}\boldsymbol{x3}_{i,j} \quad \forall i\in K \tag{5}$$

$$\left(1-\sum_{w\in W} ph_{w,i} - pr_i\right)\boldsymbol{kr}_i = \sum_{j\in D'}\boldsymbol{x4}_{i,j} \quad \forall i\in K \tag{6}$$

$$\sum_{i\in K}\boldsymbol{x2}_{w,i,j} = \sum_{q\in Q}\boldsymbol{tr}_{w,q,j} \quad \forall w\in W, \forall j\in T \tag{7}$$

$$\sum_{w\in W}\sum_{q\in Q}\boldsymbol{tr}_{w,q,i}\left(1-r_{w,q}\right)\left(1-\alpha_{w,q}\right) = \sum_{j\in D}\boldsymbol{x7}_{i,j} \quad \forall i\in T \tag{8}$$

$$\sum_{w\in W}\sum_{q\in Q}\boldsymbol{tr}_{w,q,i}\left(1-r_{w,q}\right)\alpha_{w,q} = \sum_{j\in H}\boldsymbol{x5}_{i,j} \quad \forall i\in T \tag{9}$$

$$\sum_{i\in T}\boldsymbol{x5}_{i,j} + \sum_{i\in K}\boldsymbol{x3}_{i,j} = \boldsymbol{hr}_j \quad \forall j\in H \tag{10}$$

$$\boldsymbol{hr}_i\left(1-\beta_i\right) = \sum_{j\in D'}\boldsymbol{x6}_{i,j} \quad \forall i\in H \tag{11}$$

$$\sum_{i\in T}\boldsymbol{x}7_{i,j} = \boldsymbol{dr}_j \quad \forall j\in D \tag{12}$$

$$\sum_{i\in H}\boldsymbol{x6}_{i,j} + \sum_{i\in K}\boldsymbol{x4}_{i,j} = \boldsymbol{d'r}_j \quad \forall j\in D' \tag{13}$$

$$\boldsymbol{kr}_i \le sc_i\boldsymbol{a}_i \quad \forall i\in K \tag{14}$$

$$\sum_{w\in W}\boldsymbol{tr}_{w,q,i} \le tc_{q,i}\boldsymbol{f}_{q,i} \quad \forall q\in Q, \forall i\in T \tag{15}$$

$$\boldsymbol{hr}_i \le rc_i \boldsymbol{b}_i \quad \forall i \in H \tag{16}$$

$$\boldsymbol{dr}_i \le dc_i \boldsymbol{dz}_i \quad \forall i \in D \tag{17}$$

$$\boldsymbol{d'r}_i \le d'c_i \boldsymbol{d'z}_i \quad \forall i \in D' \tag{18}$$

$$\boldsymbol{kr}_i \le sc_i^m \boldsymbol{a}_i \quad \forall i \in K \tag{19}$$

$$\sum_{w \in W} \boldsymbol{tr}_{w,q,i} \ge tc_{q,i}^m \boldsymbol{f}_{q,i} \quad \forall q \in Q, \forall i \in T \tag{20}$$

$$\boldsymbol{hr}_i \le rc_i^m \boldsymbol{b}_i \quad \forall i \in H \tag{21}$$

$$\boldsymbol{dr}_i \le dc_i^m \boldsymbol{dz}_i \quad \forall i \in D \tag{22}$$

$$\boldsymbol{d'r}_i \le d'c_i^m \boldsymbol{d'z}_i \quad \forall i \in D' \tag{23}$$

$$\boldsymbol{tr}_{w,q,i} \le tc_{q,i} \boldsymbol{yn}_{w,q} \quad \forall w \in W, \forall q \in Q, \forall i \in T \tag{24}$$

$$\left(\boldsymbol{x1}_{i,j}, \boldsymbol{kr}_i, \boldsymbol{x2}_{w,i,j}, \boldsymbol{x3}_{i,j}, \boldsymbol{x4}_{i,j}, \boldsymbol{tr}_{w,q,i}, \boldsymbol{k}_{i,j}, \boldsymbol{hr}_i, \boldsymbol{x6}_{i,j}, \boldsymbol{d'r}_i, \boldsymbol{x7}_{i,j}, \boldsymbol{dr}_i\right) \in \{\mathbb{R}^{12}\}^+ \tag{25}$$

$$\left(\boldsymbol{f}_{q,i}, \boldsymbol{dz}_i, \boldsymbol{d'z}_i, \boldsymbol{b}_i, \boldsymbol{a}_i\right) \in \{0,1\}^5 \tag{26}$$

The objective function given in equation (1) is formulated to minimise the total cost consisting of the transportation cost of different waste types and waste residues and the fixed cost of opening transfer stations, treatment, recycling and disposal centres.

Equation (2) shows the flow balance constraint of the flows from generation nodes to transfer stations. This constraint ensures that all the generated wastes are transported to transfer stations. Equation (3) indicates the total amount of the transported wastes to transfer stations that have to be sorted and balled at these centres. Equations (4) to (6) are formulated to indicate the flows of hazardous wastes, recyclables and garbage regarding their proportions from transfer stations to treatment, recycling and non-hazardous disposal centres, respectively. Equation (7) ensures that all hazardous wastes transported to treatment centres have to be treated. Equations (8) and (9) provide the flows from treatment centres to hazardous disposal centres and recycling centres regarding the ratios of recycling and mass reduction associated with different treatment technologies at treatment centres, respectively. Equation (10) indicates the flow from transfer stations and treatment centres to recycling centres. Equation (11) provides the flow of generated residues from recycling centres to non-hazardous disposal centres. Equation (12) shows the flow of hazardous waste residues from treatment centres to hazardous disposal centres ensuring that all the transported hazardous residues to these centres have to be disposed at these centres. Equation (13) shows the flow of garbage and generated non-hazardous residues from screening and recycling centres to non-hazardous disposal centres and ensures that the total amount of transported residues to these centres has to be disposed at these centres. Equations (14) to (18) indicate the capacity limitation for transfer stations, treatment, recycling and disposal centres, respectively. Equations (19) to (23) ensure that minimum amounts of different waste types and waste residues have to exist in order to open the related facilities, i.e., transfer stations, treatment, recycling, disposal centres, respectively. Equation (24) provides the compatibility limitation for treatment of different types of hazardous wastes with different treatment technologies. Equations (25) and (26) are formulated for stating non-negative and binary variables, respectively.

3 Solution methodology

SA as an efficient heuristic approach for solving combinatorial optimisation problems is employed to tackle the problem. The addressed problem can be proven to be NP-hard which implies the inefficiency of exact methods for solving the problem in large scales. Therefore, SA is utilised in an adaptive framework to solve the addressed MSW LRP. The proposed SA, like other meta-heuristics, needs an efficient initial solution to begin with. In the proposed heuristic method, an initial solution is first generated. Then, the initial solution (S_0) is utilised as the current solution for the proposed algorithm and the algorithm proceeds by searching neighbourhood solutions.

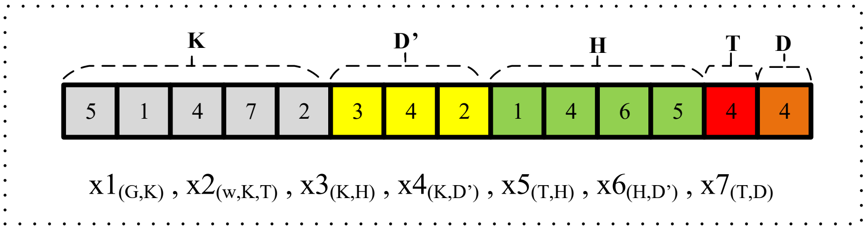
3.1 Initial solution, fitness evaluation and neighbouring structures

In this paper, a candidate solution for the addressed problem is constructed by eight distinct components. The first component is an array consisting of the selected nodes for the all facility types (i.e., K, D', H, T and D respectively). The length of the array for each facility type is considered as the minimum possible number of the facility type which can satisfy the demand (amounts of input waste to the facilities) based on the capacities of the selected nodes. The next seven components are then generated as transportation matrices (i.e., $x1$, $x2$, $x3$, $x4$, $x5$, $x6$ and $x7$) which show the amount of waste transportation on each link of the network.

To generate the initial solution, the first component (a locating array) is generated using the Roulette Wheel method in which the probability of selecting each node is proportional to the inverse of its establishment cost. Then, the seven transportation matrices are developed by the policy of allocating the maximum possible amount of waste from each of the origin nodes to their nearest (the least distance) destination node among the selected nodes of the target facility type. The structure of a candidate solution is schematically displayed in Figure 2. It is noticeable that the internal array for treatment centres (T) repeats in the solution array as the number of available treatment technologies. Also, $x2_{w,i,j}$ is developed as a multi-dimension matrix in the same dimension as the number of considered hazardous waste types in the problem.

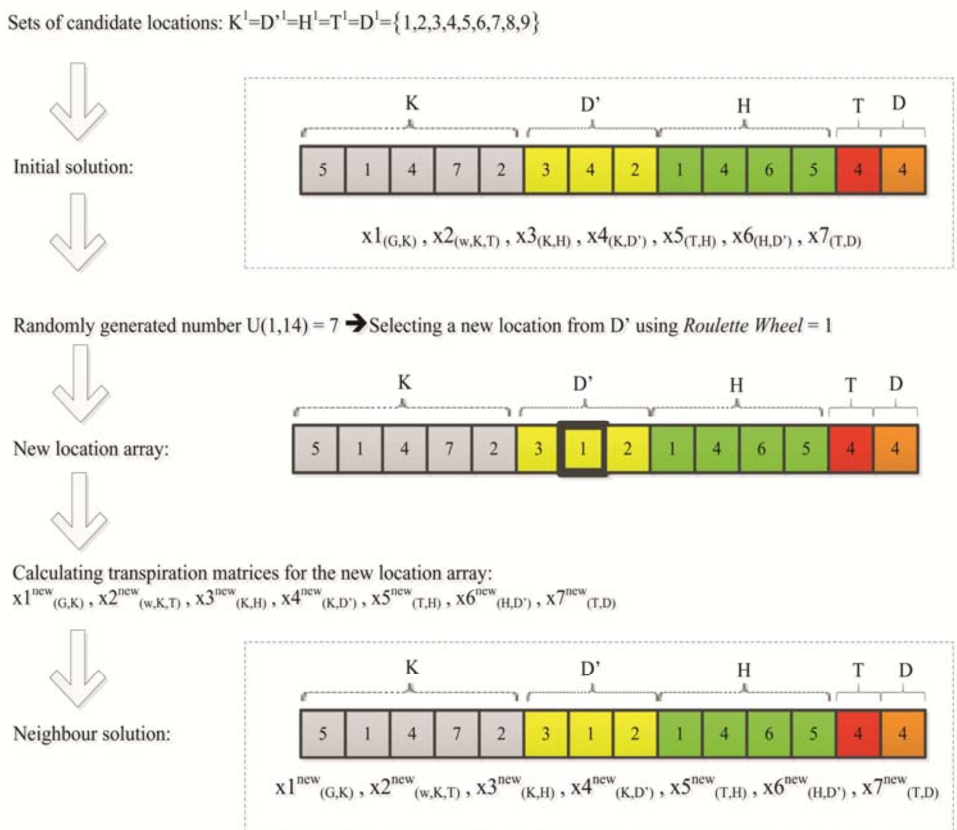
In cases where the problem constraints (i.e., minimum amounts of wastes for establishment and the facilities' capacities) are not met a repair strategy is conducted. In the developed repair strategy, the overly allocated amount of wastes to a facility which its processing capacity is overloaded is deducted and transferred to its nearest available facility of the same type. For the facilities those allocated wastes are less than their minimum requirements for establishment, transported wastes between the farthest pair of nodes (the nodes with the highest cost of transportation) is selected, deducted and re-allocated to the required nodes until their minimum requirements are satisfied.

Figure 2 Construction of a candidate solution and its eight components (see online version for colours)



The applied approaches for generating an initial solution (i.e., the opening minimum possible number of nodes for each facility type, employing roulette wheel based on the establishment cost for the locating array, and the policy of allocating the maximum waste to the nearest destination for transportation matrices) are designed to improve fitness of the generated solutions. The fitness of a candidate solution is measured by the inverse of the total cost which is calculated by summation of costs in transportation matrices (i.e., the amount of shipment multiplied by the distance and the constant factor of hazardous wastes shipment plus summation of establishment costs for the selected nodes).

Figure 3 Generating a neighbour solution (see online version for colours)



A neighbour solution for a candidate solution is also generated by a single relocation of one of the selected nodes of a facility type. That is, a random number between one and the length of the locating array is generated and used to identify which facility requires the relocation operation. Then, a new node from the set of candidate location nodes for the selected facility type is chosen using the roulette wheel method and is inserted in the removed position. The procedure of generating a neighbour solution is exemplified in Figure 3, assuming that there is one treatment technology and the minimum possible numbers of the facility types are 5, 3, 4, 1 and 1, for transfer station, non-hazardous disposal centre, recycling centre, treatment centre and hazardous disposal centre, respectively.

3.2 Adaptation of SA to an integrated MSW LRP

SA is one of the well-known meta-heuristic algorithms. SA has been widely applied for many non-polynomial optimisation problems. Efficiency of SA for LRPs is validated by many researchers (Wu et al., 2002; Lin and Kwok, 2006; Vincent et al., 2010; Lin et al., 2009; Mousavi and Tavakkoli-Moghaddam, 2013). SA was introduced by Metropolis et al. (1953) and popularised by Kirkpatrick (1984). SA is basically a simulation of the re-crystallisation of atoms in metal during its annealing. It starts with a starting temperature (T_0) which decreases gradually to reach the final temperature (T_f) using an annealing trend. Here, we assume the geometric cooling trend which updates the temperature at each time by the formula of $T_i = \alpha \times T_{i-1}$ where α represents a positive constant number less than one namely cooling factor.

Figure 4 The pseudo code of the proposed SA

```
Initialise parameters;
S = Initial solution ();
T = T0
While (T < Tf)
{
    Until (n ≤ nmax)
    {
        Generate solution S' in the neighbourhood of S
        if f(S') > f(S)
            S ← S'
        else
            Δ = f(S') – f(S);
            r = random ();
            if (r < exp(–Δ/K × T))
                S ← S'
        n = n + 1;
    }
    T = ∝ × T;
}
Report: The obtained solution with the highest f(S)
```

The applied optimisation procedure in SA is a search for finding an optimum (or near-optimum) solution. The algorithm starts with a generated initial solution (S_0) and sets the system's temperature as T_0. Then, a neighbour solution (S') is generated for the current solution (S) at each iteration and the fitness of the generated neighbour solution ($f(S')$) is compared against the current solution ($f(S)$). If the neighbour solution showed better fitness, the current solution would be replaced by the neighbour solution. However, a worse solution may still have a chance to be selected as the current solution with a probability of $\exp\left(\frac{-\Delta}{KT}\right)$ where K represents the Boltzman constant and Δ is the difference in fitness between the current and neighbour solutions. This approach of allocating a probability to accept even worse solutions enables SA to avoid trapping in local optima. The procedure of searching neighbour solutions continues until it reaches a predefined number of iterations ($n_{\max}$) at each temperature. The explained method continues for each temperature until it meets the stopping criterion (T_f). The pseudo code of the applied SA algorithm is shown in Figure 4.

4 Experimental results

To evaluate the efficiency of the proposed SA, a number of test problems are generated in different sizes. Test problems are implemented in MATLAB 8.3 on a PC with Core i7 2.40 GHz processor and 8 GB RAM memory. The mathematical model is solved for each test problem using GAMS optimisation software with CPLEX solver version 12.4.0.1 on a RedHat ® CentOS ® 5.9 Linux server with 83.60 GHz Intel ® Xeon ® CPUs with a 198 GB physical memory. The required input data and parameters of the problem (i.e., the minimum required wastes for opening the facilities, processing capacities of the facilities, facility establishment costs, recycling ratios at the facilities, amounts of waste generation at resources nodes and distances in the network) for generating test problems is extracted from a real case study in New South Wales, Australia addressed by Asefi et al. (2015). The results of applying the proposed SA to these test problems are compared against the exact solutions obtained by mixed-integer programming. Table 1 shows the generated test problems in small and large sizes. For as much as the importance of proper tuning of the algorithm's parameters on the algorithm performance, some primary experiments were conducted. To do this, first some primary suggestive values were allocated per parameter, then in an order from the smallest suggestive value to the largest value the value of each parameter was set by assuming fixed values for the other parameters on their lowest levels. A test problem was run per suggestive value in the mentioned order and the final value of each parameter was selected regarding to the obtained objective function and computing time on each problem run. The explained procedure was conducted on one of the defined test problems to obtain the final values of the algorithm parameters.

Table 2 shows the results of the SA and exact solutions and their comparison by calculating the relative difference between them where T_0 = 1,000, α = 0.97, K = 0.4 and T_f = 0.001. The formula of $\frac{Y' - Y}{Y} \times 100$ is used for calculating the relative difference where Y' represents the results by the proposed SA and Y denotes the obtained solution by mixed-integer programming.

Table 1 The generated test problems

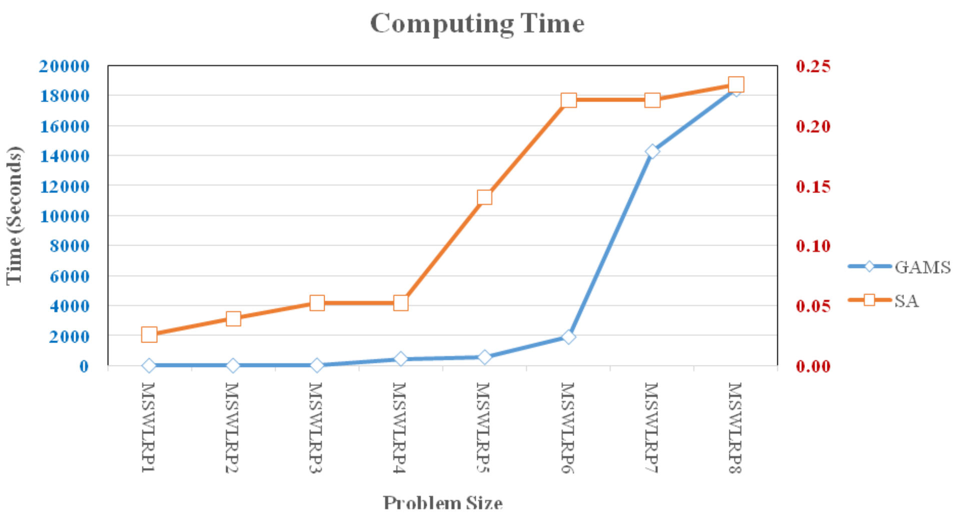
Size	*Problem ID*	*Number of generation nodes*	*Number of candidate nodes for:* Transfer stations	*Recycling centres*	*Treatment centre (q=1)*	*Treatment centre (q=2)*	*Non-hazardous disposal centres*	*Hazardous disposal centres*
Small	MSWLRP1	14	7	7	6	6	6	6
	MSWLRP2	16	8	8	7	7	6	6
	MSWLRP3	18	10	9	8	8	7	7
	MSWLRP4	20	12	9	8	8	8	8
Large	MSWLRP5	21	16	15	13	13	12	12
	MSWLRP6	22	19	19	16	16	15	15
	MSWLRP7	23	21	21	19	19	18	18
	MSWLRP8	24	23	23	22	22	22	22

Table 2 The numerical results

Test problem	*Exact*		*SA*		*Rel. diff. (%)*
	Solution	*Time (S)*	*Best found*	*Time (S)*	
MSWLRP1	8.16E+02	0.85	8.43E+02	0.03	3.3
MSWLRP2	7.81E+02	1.019	8.08E+02	0.04	3.5
MSWLRP3	8.52E+02	17.324	8.82E+02	0.05	3.5
MSWLRP4	9.20E+02	453.66	9.54E+02	0.05	3.7
MSWLRP5	9.58E+02	561.12	9.94E+02	0.14	3.8
MSWLRP6	9.53E+02	1909.25	9.97E+02	0.22	4.6
MSWLRP7	9.18E+02	14290.02	9.63E+02	0.22	4.9
MSWLRP8	1.07E+03	18427	1.12E+03	0.23	5.3

As the results show, the proposed SA produced solutions with small differences from exact solutions in the range of 3.3%–5.3% which gradually increases by the size of the problem. However, the results can support efficiency of the proposed SA for different problem sizes even in large scales. Figure 5 illustrates the computing time spent by the proposed SA and CPLEX solver. It can be seen that the CPLEX running time increases sharply in a nonlinear trend when the size of problem increases. This behaviour is rooted in the nature of NP-hard problems implying the inefficiency of exact solution approaches to solve these problems in large scales. As can be seen in Table 2 and Figure 5, the proposed SA achieved near-optimal solutions within practical time much shorter than the applied exact method. Overall, the proposed SA produced a good solution in a short time for all the test problems. According to the experiment results, the proposed SA copes with the complexity very well and can produce a good solution in a very short time even for the test problem MSWLRP8 with 158 nodes in the network.

Figure 5 Computing times of the applied solution approaches (see online version for colours)



5 Concluding remarks

An integrated MSW LRP where multiple waste types are factored in concurrently is addressed in this paper. The considered problem is formulated by a mixed-integer programming. Applying real-world constraints such as the waste technology compatibility for treatment and considering recycling centres and transfer stations in the problem network led to study a practical problem which can be applied to realistic scenarios. The problem involves concurrent optimisation of the locations of the system's all facilities (i.e., transfer stations; recycling, treatment, non-hazardous disposal and hazardous disposal centres), and optimisation of routing wastes to and from the facilities. To tackle the NP-hardness of the problem, a SA algorithm as an efficient meta-heuristic method is applied to solve the problem. The numerical results imply that the proposed SA can efficiently solve the problem within a practical computing time even for large size cases.

Taking even more real-world constraints such as different technologies for recycling centres into account could enrich the practicality of the proposed SA. Moreover, developing multi-objective optimisation approaches to include other objectives such as the risk of transporting hazardous wastes could be an extension of this study. Also, stochastic optimisation methods could be utilised for cases with uncertainty in the data such as amounts of waste generation at resources nodes.

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