Journal of Industrial and Systems Engineering
Vol. 11, No. 1, pp. 270-286
Winter (January) 2018

Solving a multi-objective location-routing problem for hazardous waste management industrial

Neda Manavizadeh[1*], Iman Moayed[1]

[1] *Department of Industrial Engineering, KHATAM University, Tehran, Iran*

n.manavi@khatam.ac.ir,iman.moayedi458@gmail.com

Abstract

Industrial hazardous materials (hazmat) are byproduct of industrial production and include hazardous goods, such as flammable, toxic and corrosive materials that pose a risk to the environment.Hazardous waste management includes collection, transportation, treatment, recycling and disposal of industrial hazardous material in an organized manner. With the increasing industrialization of countries, the issue of waste management is more important than before. Therefore, the main purpose of this research is to optimize locations of recycling centers and routing hazardous. The methods used to solve the mathematical model include the ε-constraint method and the NSGA II algorithm.First, we examine the validation of proposed model. Then, the optimal values of the parameters of multi-objective meta-heuristic algorithm are determined by Taguchi approach and the proposed algorithms are used to solve the given problem for 19 examples with different sizes. Finally, two algorithms are compared based on the fiveidentified criteria. In addition, the run time for both methods was calculated and large-scale results were presented based on the multi-objective genetic algorithm. The results show the efficiencyofmulti-objective genetic algorithm in solving given problem, and in particular for problems with larger sizes.

Keywords: Multi-objective location-routing, hazardous waste management, multi-objective model.

1-Introduction

Industrial hazardous materials (hazmat) are produced as a resultof the production and manufacturing industry and they are dangerous goods such as flammable, poisonous, toxic, and corrosivesubstances that pose risks to environment (Rabbani, et al. 2017). Examples of production processes that generate hazardous materials include wood preservation, production of inorganic dyes, production of organic chemicals/minerals, production of pesticides, explosives, oil, iron and steel, aluminum production, lead reprocessing, production of veterinary drugs, jewelry making, coke, plating and polishing operations on metals, dioxin bearing, and production of some chlorinated aliphatic hydrocarbons.

With increasing developments in technology and industry, industrial hazardous waste management has become a significant issue and in need of structured leadership and scientific management.
Such location-routing problems are rarely used for industrial hazardous waste management and require the implementation of solution methods with more effective predictive variables.

---

*Corresponding author
ISSN: 1735-8272,

Another requirement in waste management for managers and decision makers is to establish recycling, treatment and disposal facilities in places and environments that pose less risk for people with lower transport, construction, and start-up costs. In other words, in the last two decades, studies of environmental protection has become increasing important worldwide. Increased number of laws and regulations on this issue and increased general pressure has forced companies to care about the environment (Farrokhi-Asl, et al. 2017).

Hazardous waste management involves organized collection, transporting, treatment, recycling, and disposing of industrial hazardous materials. By increasing industrialization of countries, the issue of waste management is more important than before.

The main purpose of this research is considering the location routing problem for hazardous materials in a green and sustainable supply chain adopting an economic perspective and environmental concerns. In addition, due to the multi-objective nature of the given mathematical model, multi-objective solution approaches are used. The rest of the paper is organized as follows. In the next section, the literature review is presented; the problem definition and the proposed mathematical model are presented in section 3; the solution approach used to find an acceptable solution for the problem is developed in section 4; Numerical analysis is provided in section 5; and finally, Section 6 ended up with some concluding and recommendations for future research.

2-Literature Review

Many scholars have discussed issued similar to those addressed in this article. Related research can be divided in two areas of hazardous waste location management and routing in the supply chain. Some of these studies are discussed below.

In the literature, there are many attitudes on modeling of hazardous waste location-routing problems. Some models focus on minimizing the risk of transportation of hazardous waste. Erkuat and Veter (1995)presented an overview of the developed mathematical models and suggested that researchers need to be careful about risk modeling because an optimal approach for a specific model may not be useful for other models. In fact, risk has been modeled in many ways in the literature(Erkut and Verter, 1995). Another study on industrial waste management was conducted by Delhaye et al. (1991), which used the OSTRE method that considers various criteria. In fact, hazardous material management studies usually require simultaneous consideration of multiple objectives in the mathematical models .Gupta and Evans (2008) developed a multi-objective model of ideal planning for the selection of treatment and disposal facilities, and allocated the hazardous waste and the remainder of the waste from the production facilities to these facilities along the shipping route. Their model addresses the waste compatibility with waste treatment technologies and includes investment, maintenance and repair and operational costs related to treatment, transportation, and disposal. It also included the transportation risk and the risk of treatment and disposal sites. Risk is measured by several factors, such as the likelihood of an incident or emission, estimated consequences of the event and the volume of waste, potential hazard of the waste and the population exposed to an incident. Emek and Kara (2007) studied the burning sites and the total cost of transporting various types of waste from factories, recycling centers, and hospitals to the burners and minimized the cost of transportation of the waste from production plants to recycling centers. They also addressed government-issued air pollution standards, as well as the effect of wind and storms . Berman et al. (2008) studied the waste transportation routing problem, such as hazardous materials and nuclear wastes and they developed a model for minimizing the cost of compensation for the affected population and weighted costs of transportation. Shayou and Zhao (2011) develop a two-objective mathematical model for decision-making on the locations for treatment, disposal and recycling,theroutesof vehicles. Their proposed model included two minimization criteria: location and transportation costs and the overall risk of transportation and location, due to types of waste, technology for treatment, the compatibility of waste with technology, and the capacities of centers. They used the TOPSIS algorithm (which considers the same preferences as the ideal solution) and provided an efficient example from the literature (Shuai and Zhao, 2011). Zhang et al. (2000) developed a location-routing model for treatment centers of hazardous materials from production plants, considering the population living around the routes. Their model had three criteria: the total transportation costs, the fixed cost of facilities and vehicle security costs (Zhang, Hodgson, and Erkut, 2000.). Caballero et al. (2007) worked on a multi-objective location-routing problem that is used to locate areas for the burning and disposal of animal wastes and determine the routes to slaughterhouses. They considered three economic objectives that included the costs of setup, maintenance, repairs, and transportation costs, along with several social opposition-related objectives. Hang et al. (2004) worked on the location problem of hazardous materials and identified five criteria: exposed population, social and economic impact, including direct and indirect costs in a hazardous accident or a terrorist attack. Revelle et al. (1999) developed a multi-objective ideal planning model to select facilities for the treatment and disposal of hazardous waste and waste residues from the production facilities to these facilities throughout the transportation route. Their model addresses the compatibility of waste with waste management technologies and includes the capital, maintenance and repair costs, as well as the operating costs related to treatment, transportation, and disposal. Zhao and Zhao (2010) presented a bi-objective integer problem for locations of treatment and disposal centers and routing of various types of waste and the residues from the production centers to the disposal and treatment centers, taking into account different types of waste and technologies and the compatibility of the waste with the technology and capacity of these centers. They studied on two criteria: minimizing overall costs and overall risk. Alamur and Kara (2007) presented a multi-objective model for the location-routing problem of waste treatment and disposal sites and routing of various types of waste to treatment centers with appropriate technology and routing of the residue to the disposal centers. The study was implemented in central Anatolia, Turkey. Fehimnia et al. (2013) developed a new multi-objective mathematical model of location-routing problem that was implemented in Marmara, Turkey. The model aimed to help decision-makers to locate treatment centers that use different technologies, route different types of industrial wastes to proper centers, and locate recycling centers and route the waste and industrial residues to these centers and locate disposal facilities and route these sites.

The routing problem in supply chain has been investigated by various studies due to its high importance and the reduction of current costs. Revelle et al. (1991) used the aggregation model for general risk modeling and selected routes with lower opponents residing along the route. Cappanera et al. (2004) presented a discrete location-routing model that minimized transportation costs from places such as dump sites, chemical factories, electricity supply networks and industrial reactors, as well as the costs of disposal facility construction. Dadkar et al. (2008) focused on finding the collection routes with similar operating margins for alternative routes in order to deal fairly with the exposed population, as well as a potential security measure. Their model included two minimization aspects: location and transportation costs, and overall transport and location risk, taking into account the types of waste, treatment technology, compatibility of the waste and the technology and the capacity of the centers. They provided the TOPSIS algorithm (a technique for considering the same preferences as an ideal solution) and an efficient example derived from the literature.

Some researchers have focused on the supply chain. For example, Gutiérrez et al. (1996) studied on solid approach to supply chain design problems. Their approach was a configuration for the supply chain, which is suitable for a number of scenarios and find the solution close to optimal for the rest of the scenarios. Krikke et al. (1999) developed a mixed integer linear programming model for a two-level reverse supply chain network for a copy machine manufacturer. In this model, the cost of processing the returned goods and inventory costs are included in the objective function to minimize the total costs. In 2001, Tsiakis et al. (2001) developed a two-stage probabilistic model for designing a multi-level multi-product supply chain network under demand uncertainty. Jayaraman et al. (2003) presented a model to solve a single-product hierarchical two-level location problem, including reverse supply chain operations costs of high-risk products. They also developed an innovative way to solve relatively large-size problems.

The literature review showed that many researchers have overlooked the problems associated with waste residues. Such problems deal with determining the location of waste disposal and recycling sites and routing of waste residues. However, waste disposal costs should be included in the calculation of hazardous waste management costs. Thus, if the costs need to be minimized, the waste residues management costs should also be addressed. In addition to the common criteria in literature, environmental criteria are of utmost importance and should be taken into account. It can be concluded that hazardous waste location-routing literature lacks a mathematical model that includes the real and significant aspects of hazardous waste management problems.

3-Problem Definition

The problem discussed in this paper can be described as follows:
There are a number of waste generation nodes, each of which generates a certain amount of waste in a specific period. The quantity of generated waste is considered as the definite parameter of the problem.

A warehouse is considered in the network, where the vehicles are located. The vehicles move from the warehouse to collect waste from the waste generation nodes. If the waste can be recycled, they go to the recycling centers, where a percentage of the waste is recycled, and the amount that cannot be recycled is transferred to the disposal centers. Hazardous waste is transferred to treatment centers to reduce the hazard levels. In this place, the compatibility of the waste with the treatment center should be taken into account, meaning that each type of waste should be transferred to a center compatible with its own technology.

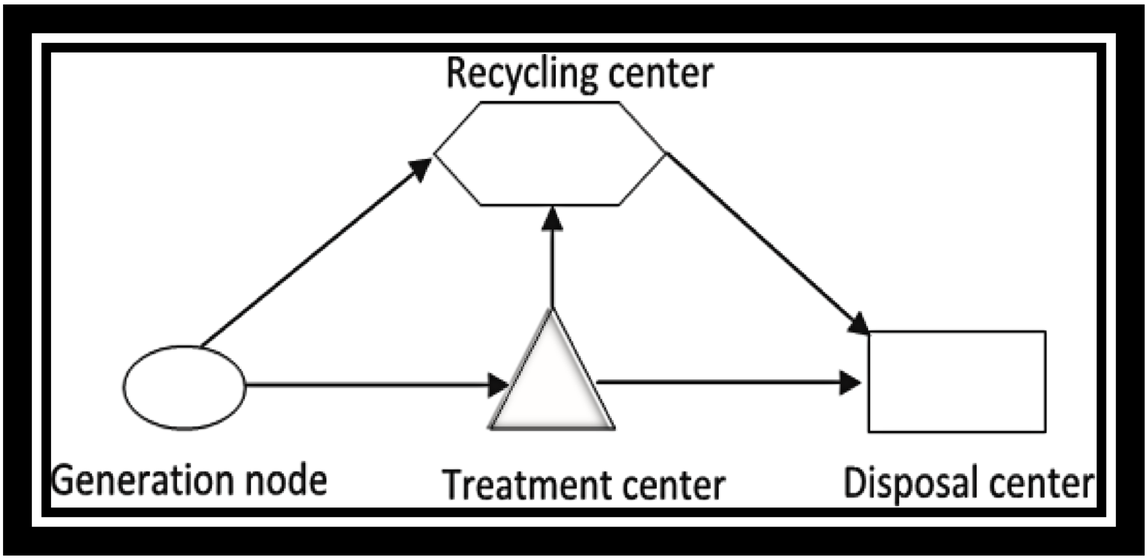

Fig 1. Frame of the hazmat management problem

This problem consists of three objective functions that are as follows:

1-Minimize the risk and hazard of industrial waste for people who living near industrial waste disposal routes. Risk and hazard are defined as a function of the waste entering amount into the site and the amount of waste residue that passes the routes and the number of people who live near these routes.

2-Minimize the risk and hazard for those who live near disposal and treatment centers. That is called the location risk. Location risk is expressed as a function of waste residues and the remainder available to these centers and the number of people who live in a certain radius of these centers.

3-Minimize the overall costs, including industrial waste and residuestransportationcosts, fixed costs associated with the establishment of treatment, disposal and recycling centers, and fixed and variable costs associated with the maintenance of treatment, disposal, and recycling centers.In addition, we consider holding cost of waste in the location of facilities, because wastes are undesirable materials and holding them needs to spending a time and energy and other sources which impose cost to the system.
In the following section, the notation, sets, parameters, decision variables of the model, and the proposed mathematical model are presented.

3-1-Sets

$N=(V,A)$	Transportation network of node (V) and arcs (A)
$G=\{1,...,g\}$	Hazmat generation nodes, $G \in V$
$T=\{1,...,t\}$	Location of the potential treatment nodes, $T \in V$

T'	The locations of existing treatment nodes, $T' \subset T$
$D = \{1,\ldots,d\}$	The locations of potential disposal nodes, $D \in V$
D'	Existing disposal nodes, $D' \subset D$
$H = \{1,\ldots,\mathrm{h}\}$	The locations of potential recycling nodes, $H \in V$
H'	Existing recycling nodes, $H' \subset H$
$W = \{1,\ldots,\mathrm{w}\}$	Types of the hazardous waste
$Q = \{1,\ldots,\mathrm{q}\}$	Treatment technologies
Q'	Existing treatment technologies, $Q' \subset Q$
$U = \{1,\ldots,u\}$	Time periods

3-2-Parameters

c_{ij}	The cost for transferring a unit of a hazardous waste between nodes i and j, $(\mathrm{i},\mathrm{j}) \in \mathrm{A},\ \mathrm{i} \in \mathrm{G},\ \mathrm{j} \in \mathrm{T}$
cz_{ij}	The cost for transferring a unit of waste residue between nodes i and j, $(\mathrm{i},\mathrm{j}) \in \mathrm{A},\ \mathrm{i} \in \mathrm{T},\ \mathrm{j} \in D$
cv_{ij}	cost of transporting one unit of waste residue between nodes i and j, $(\mathrm{i},\mathrm{j}) \in \mathrm{A},\ \mathrm{i} \in H,\ \mathrm{j} \in D$
cr_{ij}	The cost for transferring a unit of a recyclable waste between nodes i and j, $(\mathrm{i},\mathrm{j}) \in \mathrm{A},\ \mathrm{i} \in G,\ \mathrm{j} \in H$
crr_{ij}	The cost for transferring a unit of a recyclable waste residue between nodes i and j, $(\mathrm{i},\mathrm{j}) \in \mathrm{A},\ \mathrm{i} \in T,\ \mathrm{j} \in H$
fc_{qi}	fix cost of opening a treatment technology $q \in Q,$ at node $\mathrm{i} \in T$
fd_i	fix cost of opening a disposal center at node $\mathrm{i} \in D$
fh_i	fix cost of opening a recycling technology at node $\mathrm{i} \in H$
HCG_{wi}^{u}	The maintenance cost of an inventory unit in the waste warehouse type $w \in W$, in the production place $i \in G$, and at the end of the period $u \in U$
HCT_{wi}^{u}	The maintenance cost of an inventory unit in the waste warehouse type $w \in W$,in the treatment $i \in T$,and at the end of the period $u \in U$
HCR^{u}	The maintenance cost of an inventory unit in theinput warehouse of the recycling center at the end of the period $u \in U$
HCD^{u}	The maintenance cost of an inventory unit in theinput warehouse of the disposal center in the period $u \in U$
$CAPG_{wi}^{u}$	The capacity of the waste warehouse $w \in W$, in the generation node $i \in G$, at the end of the period $u \in U$
$CAPT_{wi}^{u}$	The capacity of the waste warehouse $w \in W$, in the treatment $i \in T$ and at the end of the period $u \in U$
$CAPR^{u}$	The capacity of the inputwaste warehouse of the recycling center at the end of the period $u \in U$
$CAPD^{u}$	The capacity of the input wastewarehouse of the disposal center in the period $u \in U$
pop_{gt}	The number of people who living in the distance between waste generation centers and treatment centers
pop_{td}	The number of people living in the distance between treatment centers and disposal centers
pop_{A}	The number of people living around the technological treatment centers

pop_B	The number of people living in the vicinity of disposal center *i*
gen_w	The amount of hazardous waste type *w*generated atgeneration node
α_{wi}	The proportion of recycling of hazardous waste generated at generation node *i*
β_{wq}	proportion of recycling of hazardous waste type *w*, treated with technology *q*
r_{wq}	proportion of mass reduction of hazardous waste type*w*, treated with technology *q*
γ_i	proportion of total hazardous waste recycled at node i
tc_{qi}	The capacity of the treatment center type i, consistent with the treatment technology type *q*
tc_{qi}^m	The minimum amount of the hazardous wastes needed for establishing the treatment center i, consistent with the treatment technology type *q*
dc_i	The disposal capacity in the disposal center *i*
dc_i^m	minimum amount of waste residue required to establisha disposal center at node *i*
rc_i	The recycling capacity of the recycling centers in the node *i*
rc_i^m	minimum amount of waste required to establish a recycling center at node *i*
com_{wq}	The hazardous wastes type *w*, compatible with technology *q*, 1, otherwise, 0

3-3-Decision variables

x_{wij}^u	The amount of the hazardous wastes type *w* transferred between two nodes of *i* and *j*, $(\mathrm{i},\mathrm{j})\in \mathrm{A},\ \mathrm{i}\in \mathrm{G}, \mathrm{j}\in \mathrm{T}$
z_{ij}^u	The amount of the waste residue transferred between two nodes of *i* and *j*, $(\mathrm{i},\mathrm{j})\in \mathrm{A},\ \mathrm{i}\in \mathrm{T}, \mathrm{j}\in D$
l_{ij}^u	The amount of the recyclable waste transferred between two nodes of *i* and *j*, $(\mathrm{i},\mathrm{j})\in \mathrm{A},\ \mathrm{i}\in G, \mathrm{j}\in H$
k_{ij}^u	The amount of the recyclable waste residue transferred between two nodes of *i* and j, $(\mathrm{i},\mathrm{j})\in \mathrm{A},\ \mathrm{i}\in T, \mathrm{j}\in H$
v_{ij}^u	The amount of the waste residue transferred between two nodes of *i* and *j*, $(\mathrm{i},\mathrm{j})\in \mathrm{A},\ \mathrm{i}\in H, \mathrm{j}\in D$
$y_{w,q,i}^u$	The amount of the waste type $w\in W$, treated with the technology $q\in Q$ at node $i\in T$.
dis_i^u	The amount ofwaste residue disposed of in the period $u\in U$ and node $i\in D$.
hr_i^u	The amount of the waste recycled at the node $i\in H$ and period $u\in U$
f_{qi}	If a treatment is established with the technology $q\in Q$ and at node $i\in T$, 1, otherwise, 0.
dz_i	If the disposal site is established at the node $i\in D$, 1, otherwise, 0
b_i	If a recycling center is established at the node $i\in H$, 1, otherwise, 0
IG_{wi}^u	waste warehouse inventory type $w\in W$, in the production place $i\in G$, and at the end of the period $u\in U$
IT_{wi}^u	waste warehouse inventory type $w\in W$,in the refinery $i\in T$, and at the end of the period $u\in U$
IR^u	Input waste warehouse inventory of the recycling site at the end of the period $u\in U$
ID^u	Input waste warehouse inventory of the disposal site at the period $u\in U$

According to the notation, the mathematical model is formulated as follows:

$$\min\ f_1(x)=\sum_{i\in G}\sum_{j\in T}\sum_{w\in W}\sum_{u\in U}c_{ij}x_{wij}^u+\sum_{i\in T}\sum_{j\in D}\sum_{u\in U}cz_{ij}z_{ij}^u \tag{1}$$

$$+\sum_{i\in H}\sum_{j\in D}\sum_{u\in U}cv_{ij}v_{ij}^u+\sum_{i\in G}\sum_{j\in H}\sum_{u\in U}cr_{ij}l_{ij}^u$$

$$+\sum_{i\in T}\sum_{j\in H}\sum_{u\in U}crr_{ij}k_{ij}^u+\sum_{i\in T}\sum_{q\in Q}fc_{q,i}f_{q,i}$$

$$+\sum_{i\in D}fd_i dz_i+\sum_{i\in H}fh_i b_i$$

$$+\sum_{i\in G}\sum_{w\in W}\sum_{u\in U}HCG_{wi}^u IG_{wi}^u+\sum_{i\in T}\sum_{w\in W}\sum_{u\in U}HCT_{wi}^u IT_{wi}^u+\sum_{u\in U}HCT^u IT^u+\sum_{u\in U}HCD^u ID^u$$

$$\min\ f_2(x)=\sum_{i\in G}\sum_{j\in T}\sum_{w\in W}\sum_{u\in U}POPgt_{ij}x_{wij}^u+\sum_{i\in T}\sum_{j\in D}\sum_{u\in U}POPtd_{ij}z_{ij}^u \tag{2}$$

$$\min\ f_3(x)=\sum_{w\in W}\sum_{q\in Q}\sum_{i\in T}\sum_{u\in U}POPA_{q,i}y_{w,q,i}^u+\sum_{i\in D}\sum_{u\in U}POPB_i dis_i^u \tag{3}$$

s.t.

$$IG_{wi}^{u-1}+gen_{wi}^u=\sum_{j\in T}x_{wij}^u+IG_{wi}^u+\sum_{j\in H}l_{ij}^u \qquad \forall i\in G, w\in W, u\in U, u\geq 2 \tag{4}$$

$$\sum_{j\in T}x_{wij}^u\leq(1-\alpha_{wi})(IG_{wi}^{u-1}+gen_{wi}^u) \qquad \forall i\in G, w\in W, u\in U, u\geq 2 \tag{5}$$

$$\sum_{j\in H}l_{ij}^u\leq\alpha_{wi}(IG_{wi}^{u-1}+gen_{wi}^u) \qquad \forall i\in G, \mathrm{w}\in \mathrm{W}, u\in U, u\geq 2 \tag{6}$$

$$\sum_{i\in G}x_{wij}^u+IT_{wj}^{u-1}=\sum_{q\in Q}y_{wqj}^u+IT_{wj}^u \qquad \forall j\in T, w\in W, u\in U, u\geq 2 \tag{7}$$

$$\sum_{j\in D}z_{ij}^u=\sum_{w\in W}\sum_{q\in Q}y_{wqi}^u(1-r_{wq})(1-\beta_{wq}) \qquad \forall i\in T, u\in U \tag{8}$$

$$\sum_{j\in H}k_{ij}^u=\sum_{w\in W}\sum_{q\in Q}y_{wqi}^u(1-r_{wq})\beta_{wq} \qquad \forall i\in T, u\in U \tag{9}$$

$$f_{q,i}=1 \quad \forall q\in Q', i\in T' \tag{10}$$

$$hr_j^u+IR^u=\sum_{i\in T}k_{ij}^u+\sum_{i\in G}l_{ij}^u+IR^{u-1} \qquad \forall j\in H, u\in U, u\geq 2 \tag{11}$$

$$hr_i^u(1-\gamma_i)=\sum_{j\in D}v_{ij}^u \qquad \forall i\in H, u\in U \tag{12}$$

$$b_i=1 \qquad \forall i\in H' \tag{13}$$

$$dis_j^u+ID^u=\sum_{i\in H}v_{ij}^u+\sum_{i\in T}z_{ij}^u+ID^{u-1} \qquad \forall \mathrm{j}\in \mathrm{D},\ \mathrm{u}\in \mathrm{U},\ \mathrm{u}\geq 2 \tag{14}$$

$$dz_i=1 \qquad \forall i\in D' \tag{15}$$

$$\sum_{w\in W}y_{wqi}^u\leq tc_{qi}f_{qi} \qquad \forall q\in Q, \forall i\in T, u\in U \tag{16}$$

$$\sum_{w\in W}y_{wqi}^u\geq tc_{qi}^m f_{qi} \qquad \forall q\in Q, \forall i\in T, u\in U \tag{17}$$

$$y_{wqi}^u\leq tc_{qi}com_{wq} \qquad \forall w\in W, \forall q\in Q, \forall i\in T, u\in U \tag{18}$$

$$dis_i^u\leq dc_i dz_i \qquad \forall i\in D, \forall u\in U \tag{19}$$

$$dis_i^u\geq dc_i^m dz_i \qquad \forall i\in D, \forall u\in U \tag{20}$$

$$hr_i^u\leq rc_i b_i \qquad \forall i\in H, \forall u\in U \tag{21}$$

$$hr_i^u \geq rc_i^m b_i \qquad \forall i \in H, \forall u \in U \tag{22}$$

$$IG_{wi}^u \leq CAPG_{wi}^u \qquad \forall i \in G, \forall u \in U, \forall w \in W \tag{23}$$

$$IT_{wi}^u \leq CAPT_{wi}^u \qquad \forall i \in T, \forall u \in U, \forall w \in W \tag{24}$$

$$IR^u \leq CAPR^u \qquad \forall u \in U \tag{25}$$

$$ID^u \leq CAPD^u \qquad \forall u \in U \tag{26}$$

$$IG_{wi}^1 = 0 \qquad \forall i \in G, \forall w \in W \tag{27}$$

$$IT_{wi}^1 = 0 \qquad \forall i \in T, \forall w \in W \tag{28}$$

$$IR^1 = 0 \tag{29}$$

$$ID^1 = 0 \tag{30}$$

The first objective function (1) minimizes the overall costs, includingindustrial waste and residues transportationcosts, fixed costs associated with the establishment of treatment, disposal and recycling centers, and fixed and variable costs associated with the maintenance of treatment, disposal, and recycling centers.

The second objective function (2) minimizes the risk and hazard of industrial waste transportation for people living near industrial waste disposal routes. Risk and hazard are defined as a function of wasteand residuesamount transported via routes and the number of people living near the same routes.

The third objective function (3) minimizes the risk and hazard for people who live near disposal and treatment centers, i.e., the location risk. Location risk is defined as a function of the waste and residues exiting at these centers and the number of people who live within a certain radius of these centers.

The constraints (4), (5), and (6) are flow balance constraints of the flow from generation nodes to recyclingcenters, and treatment centers.The restrictions (7), (8), and (9) show the flow of materials transported from treatment centers to disposal and recycling centers by considering the fact that the transported waste loses some volume and becomes concentrated due to the wide range of technologies used at treatment centers. The constraint (10) shows the existing treatment centers equipped with treatment technologies. The constraint (11) is indicative of the flow of the waste from generation nodes to treatment and recycling centers. The constraint (12) demonstrates the flow of material from treatment centers to disposal centers. The constraint (13) shows the available recycling centers. The constraint (14) presents the flow of waste from recycling and treatment centers to disposal centers. The constraint (15) points out to the existing disposal centers. The constraints (16) to (22) are indicative of the capacity limitations associated with generation nodes and treatment, disposal, and recycling centers, respectively. The constraints (23) to (26) show the minimum waste required for the establishment of generation nodes and treatment, disposal, and recycling centers. The constraints (27) to (30) express that in the first period, all generation nodes, treatment, recycling, and disposal centers have no inventory.

4-Multi-objective optimization using the ε-constraint method

A common way to obtain the optimum solution is to use the ε-constraint method. In this method, one of the objective functions is considered as the main objective function, while the others are limitedby the εconstraint, which can change to generate the Pareto solution set. This change is made by the decision-maker in order to generate Pareto solutions. The following equationsare used to find the optimal points in the ε-constraint method.

$$MinZ = f_1(x) + \varepsilon_2 S_2 + \varepsilon_3 S_3 \tag{31}$$

$$AX \leq B \quad (32)$$

$$f_2(x)+S_2=e_2 \quad (33)$$

$$f_2(x)+S_3=e_3 \quad (34)$$

e_2 and e_3 in equation 33 and 34 areoptimal values of the second and third objective functions. This process is repeated for various objective functions, and the set of solutions found as the Pareto range from the ε-constraint method are known.

4-1-NSGA II Multi-Objective Genetic Algorithm

The classical location-routing problem is NP-HARD problem.Such problems refer to cases where any increase in the size of the problem leads to the solution time being exponentially increased (Farrokhi-Asl, et al. 2017).Sincethis problem is an extended location-routing problem, the research's mathematical model will also be NP_HARD problem. In this situation, it is expected that an increase in the problem size lead to a considerable increase in the exact solution time. Thus, the use of approximate solution methods with rational solution times is justified.

After analysis in the beginning stage of designing the proposed NSGA II algorithm, it was known that, given the variety of decision variables, it is possible to design a single set of solutions that include all decision variables. Therefore, the designed set of variables is basically a vector with the length of the total number of decision variables. In each cell of the set, the solution takes a value between 0 and 1. For binary variables, the values of less than 0.5 indicate that the corresponding variable is 0, while the values greater than 0.5 mean that the corresponding variable is 1. For the continuous variables, it is determined using the amount of waste generated and demographic information, as well as the material balance equations in the mathematical model. The reason for choosing this coding system is that crossover and mutation is easy to do, which speeds up the algorithm.

The roulette wheel method was used to run the selection operator. In the roulette wheel, a certain probability is assigned to each specific solution, depending on their fit. Then, based on this probability, the probability of parents is selected for the crossover operation in the roulette wheel. Better solutions have higher probability; therefore, they are more likely to becomeparents. The crossover in the genetic algorithm aims at sharing the good features of solutions and generating new solutions. The single-point method is used to generate solutions. In this method, the solution string of two parents iscute from a random point and combined.

The mutation operator is performed in the genetic algorithm with the goal of escaping from local optimality. For crossover in this research, a cell of the solution string is selected and its value randomlychanges.

4-2-Numerical examples and model validation

In order to determine the model validity and performance, a sample problem (example 1) was generated and solved using GAMS with the linear programming solver CPLEX on a personal computer Intel Core i5-3230M 2.6GHz processor and 6 GB of RAM and Windows 8 Version 1 operating system.
Example data are shown in table (1).

Table 1. Data for the model validation example

Parameter	Value
Total number of nodes	8
Number of hazardous substances generation sites	2
Number of treatment centers	2
Number of disposal centers	2
Number of recycling centers	2
Number of hazardous substances	2
Number of time periods	3
Number of treatment technologies	3

Other parameters of problem are randomly set. Since the mathematical model is multi-objective, and GAMS solves mathematical model in a single-objective way, the objective presented to this software is the sum of the three objective functions provided in the mathematical model. The problem was solved with GAMS and the CPLEX solver. The optimal value of each objective function is as follows.

Table 2. Objective functions results obtained from GAMS

Objective function	Value
First objective (cost minimization)	405
Second objective function (transportation risk minimization)	124
Third objective function (Disposal and treatment risk minimization)	0

Since the main part of this problem is location of recycling centers, disposal centers, and treatment centers, the following outputs are provided by solving the mathematical location problem.

Location of treatment centers are specifies in below. The value 0 means no selection, and 1 means the selection of the treatment center. The first row show the number of the center, the second row shows the establishment or lack thereof, and the third row shows the technology in each center.

Table 3. Established treatment centers in the optimal mode

Treatment center	1	2
Selection/ lack of selection	1	1
Selected technology	1	2

The location of disposal centers is also similar to that of treatment centers. In the following table, the first row is the center number, or the number of potential centers, and the second row is selection or lack of selection.

Table 4. Selected disposal centers in the optimal mode

Center	1	2
Selection/lack of selection	1	1

The last item is location of treatment centers, as shown in the table below. The first row is the number for the potential treatment center, and the second row indicates whether it is selected or not.

Table 5. Selected treatment centers in the optimal mode

Center	1	2
Selection/lack of selection	1	1

Given that the solutions obtained for decision variables are reasonable and consistent with the manual analysis of this example, the proposed mathematical model is valid and efficient. In the following, we analyze and evaluate the efficiency of the proposed metaheuristic algorithm for solving the proposed model. First, it is necessary to optimize the parameters of each algorithm. For this purpose, the design of experiments technique in the Taguchi method was used.

4-3- Design of experiments for the NSGA II parameters

In this study, the Taguchi method was used for the design of the experiments. Based on the structure of the Taguchi method, 3 values are first proposed for each of the parameters of the NSGA II algorithm. The proposed values are as follows.

Table 6. Parameters and their values for the NSGAII algorithm

Studied algorithm	Parameter	Value of each level		
		Level 1	Level 2	Level 3
NSGA-II	Percentage of Crossover (Pc)	0.7	0.8	0.9
	Percentage of Mutation (Pm)	0.03	0.1	0.15
	Number of Solutions in the Population (N-pop)	50	100	150
	Maximum iteration(Max-iteration)	100	200	300

Then, for the L9 Taguchi scheme, the NSGA II algorithm was executed for the following scenarios, and the outputs are presented in the following table.

Table 7. Value of the response variable in the Taguchi method for NSGAII

Run order	Algorithm parameters				Response
	P_{cr}	P_{mut}	N- Pop	Max-iteration	NSGA-II
1	1	1	1	1	21.98
2	1	2	2	2	33.79
3	1	3	3	3	28.91
4	2	1	2	3	27.83
5	2	2	3	1	26.47
6	2	3	1	2	15.55
7	3	1	3	2	48.05
8	3	2	1	3	19.34
9	3	3	2	1	20.02

After entering this data into MINITAB and implementing the Taguchi method, the S/N chart is presented as follows.

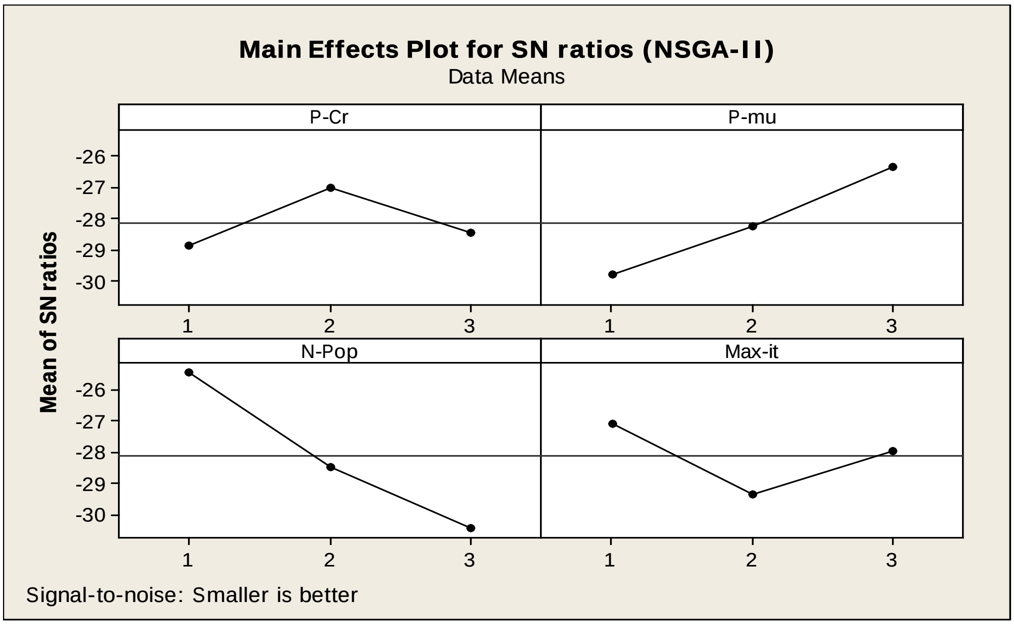

Fig 2. MINITAB output for the Taguchi Method in the NSGA II Algorithm

Based on the above diagram, the suitable value for each parameter is the lowest S/N value. Therefore, for the NSGA II algorithm, the following values are optimal values, and other examples were implemented with these values.

Table (8). Optimal value of NSGAII parameters

Studied algorithm	Parameter	Optimal Value
NSGA-II	Percentage of Crossover (Pc)	0.7
	Percentage of Mutation (Pm)	0.05
	Number of Solutions in the Population (N-pop)	150
	Maximum iteration(Max-iteration)	200

4-4-Comparison Criteria of the NSGA II and EP Algorithms

Six criteria are used to evaluate the performance of metaheuristic multi-objective algorithms. These criteria include spread measure (SM), mean ideal distance (MID), spacing (S) maximum spread or diversity (MD), number of partial solution (NPS), and rate of achievement to objectives simultaneously (RAS).

5-Numerical results

To compare the algorithms based on the mentioned criteria, 25 examples were generated in different dimensions. These examples are randomly generated and include all dimensions of the problem, namely small, medium and large dimensions. Small and medium dimensions are those that GAMS can optimize at areasonable time. This time in this study is 3600 seconds equivalent to 1 hour.
The characteristics of these examples are as follows:

Table9. Initial dimensions of the generated examples

Dimensions	Example number	i	gs	t	d	h	q	w	u
Small sized problems	1	8	2	2	2	2	2	2	3
	2	15	5	3	3	4	3	3	3
	3	20	8	4	3	4	4	4	4
	4	25	8	5	6	6	5	5	5
	5	30	10	6	7	7	6	6	5
	6	40	10	10	10	10	7	8	7
	7	50	15	10	15	10	8	9	8
	8	60	20	15	15	10	9	9	9
	9	70	20	20	15	15	10	9	10
Medium sized problems	10	80	25	15	20	20	12	10	15
	11	90	30	20	20	20	13	11	17
	12	100	30	30	25	15	14	12	17
	13	110	35	30	30	15	15	13	20
	14	120	35	35	30	20	16	14	20
	15	130	40	35	35	20	17	15	22
	16	140	40	35	40	25	18	15	23
	17	150	45	35	40	30	19	17	24
	18	160	50	40	45	30	20	18	25
	19	170	50	40	50	35	21	19	25
Large sized problems	20	180	55	45	50	35	22	20	26
	21	190	55	50	50	40	23	21	27
	22	200	60	55	55	40	24	22	28
	23	250	80	70	50	50	25	23	29
	24	300	100	80	60	60	26	24	30
	25	400	150	100	80	70	27	25	30

The NSGA II algorithm was coded in MATLAB, and the EP method was implemented in the GAMS environment. Then, both methods were performed with their optimal values for their parameters and each of the 19 examples, and the values of criteria were calculated.

5-1-Numerical results in small and medium scales

It should be noted that the time limit of 3600 seconds is considered in GAMS. Therefore, only 19 problems (small to medium dimensions examples) were solved. Thus, in comparison of these two algorithms, only 19 initial examples are compared and examined.

5-2-Comparison of two algorithms based on different criteria

In this section, the algorithms are compared based on different criteria, the results are presented in the following graphs.

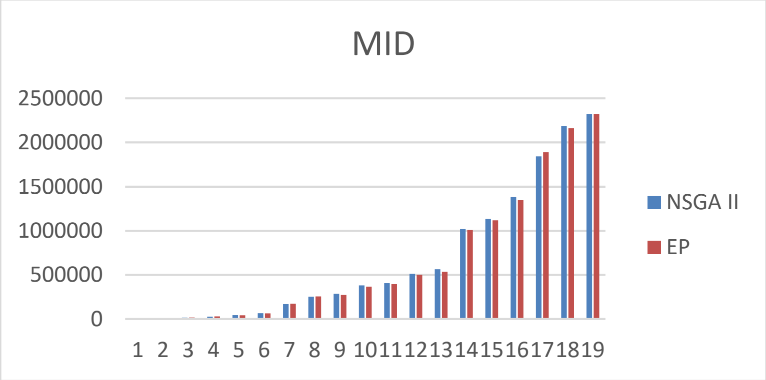

Fig3. Comparison of algorithms based on the MID criteria

The average of MID criteriain the NSGA II algorithm was 664694, while it was 566283 in the EP method. The following figure presents the value of this index for each example solved by the two methods. Given the nature of the index, and based on the above diagram, it can be concluded that the EP method has a better performance than NSGA II in this index.

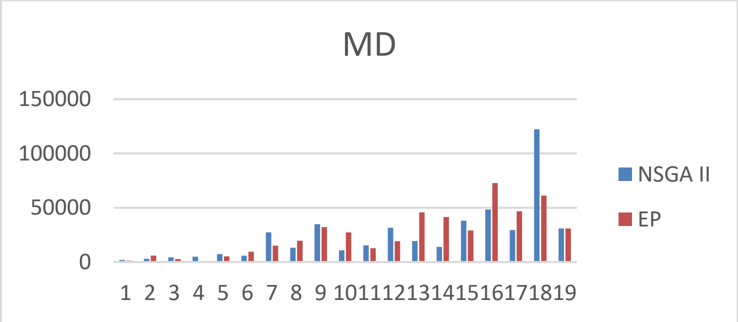

Fig4. Comparison of algorithms based on the MD index

As can be seen, in some examples, the NSGA II algorithm has a better performance, and in other examples, the EP method. Among these 20 examples, the EP outperformed in examples 2, 6, 8, 13, 14 and 16. Giventhe nature of this index, and based on the above diagram, it can be concluded that the EP method in this index has a better performance than NSGA II.

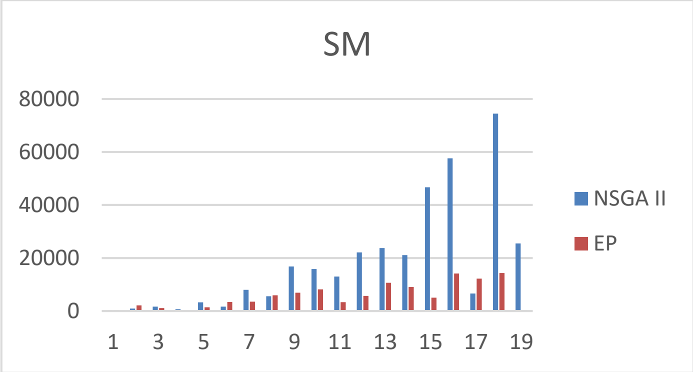

Fig 5. Comparison of algorithms based on SM index

SM index show that how much obtained non dominated solutions are uniformly distributed in the objective functions space. Less values for this criterion is better and the relative superiority of the EP method over NSGA II is clearly seen based on this index. Considering the nature of this index, also based on the above diagram, it can be concluded that the EP method in this index has a better performance than NSGA II.

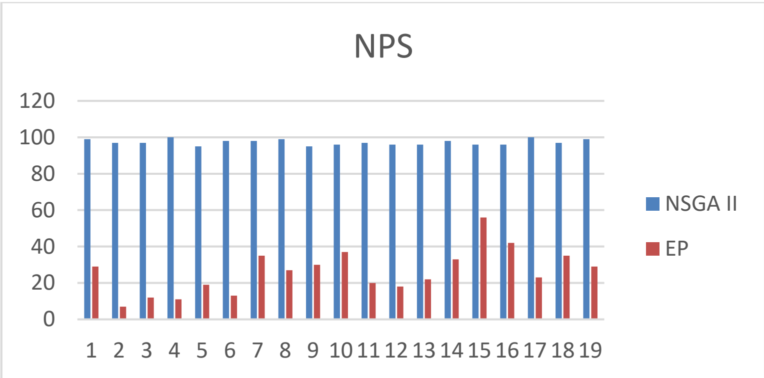

Fig 6. Comparison of algorithms based on the NPS index

The relative superiority of the NSGA II algorithm over the EP method is clearly seen based on this index. Considering the nature of this index, also based on the above diagram, it can be concluded that the NSGA II algorithm in this index has a better performance than the EP method.

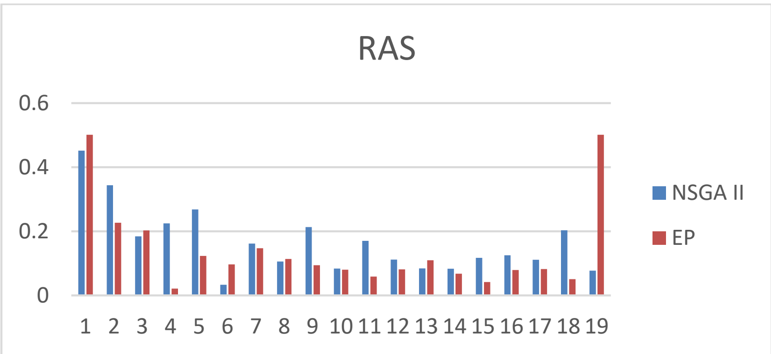

Fig 7. Comparison of algorithms based on the RAS index

As can be seen, in most examples, the EP method yields a lower value for this index. Given the nature of this index, and based on the above diagram, it can be concluded that the EP method in this index has a better performance than NSGA II.

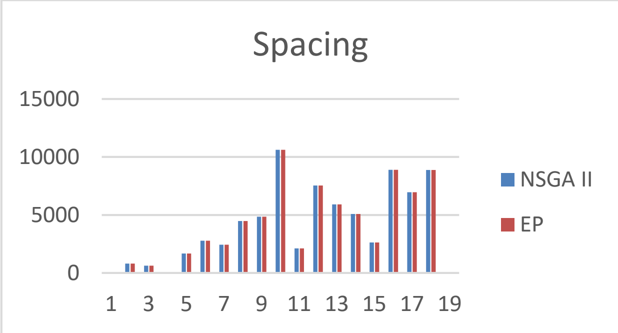

Fig 8. Comparison of algorithms based on the Spacing Index

As can be seen, in most examples, the EP method yields a lower value for this index. Given the nature of this index, and based on the above diagram, it can be concluded that the EP method in this index has a better performance than NSGA II.

A comparison between the two algorithms based on the solution time is given, which shows that the solution time for the EP method is exponentially increasing, and, considering the 3600-second limit, many problems exceeded the time limit. Meanwhile, the NSGA II algorithm spent an average of 71 seconds for solutions, which shows the efficiency of the NSGA II method in reaching acceptable solutions in a short duration.

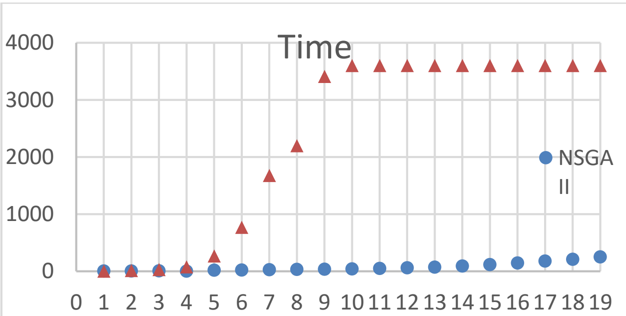

Fig 9. Comparison of algorithms based on the solution time

5-3-Numerical results in large dimensions

As shown in the previous sections, six examples were designed in large dimensions. Examples with large dimensions are those that were not solved by GAMS in a 3600-second time period, while NSGA II was able to solve all six examples in a reasonable time. Therefore, the following table presents the solution results only for the NSGA II method.

Table 10. Output of the NSGA II algorithm for the examples solved in large dimensions

NSGA II							
Problem number	MID	MD	SM	NPS	RAS	Spacing	Solution time
20	2471234	124615	81421	115	0.01254	9425.1	274.9
21	2491547	116314	74001	109	0.03648	9477.6	304.8
22	2510641	108745	94384	121	0.03480	10348.1	336.4
23	2561265	138741	101452	115	0.34801	11324.5	391.2
24	2874150	199742	11245	119	0.3731	12340.2	410.5
25	3142165	264158	139420	120	0.47139	12970.9	444.6
Mean	2675167	158719.17	83653.8	116.50	0.21	10981.07	360.40

The solution time for the problem shows that the NSGA II algorithm has a very good solution time in large-dimension problems. This is evident in Figure 9. In Figure 9, the time required to solve various problems by the NSGA II algorithm is much less than that by the EP algorithm.

6-Conclusion

In this study, after a thorough review of previous studies in supply chain and the importance of hazardous waste, the research gap and its innovation were identified. Then, the validity of the proposed model was explored and the efficiency and validity of the proposed model was shown by comparing the GAMS result with expected outputs. After demonstrating the model efficiency, since the location-routing problems are NP-Hard, and due to the weakness of the exact solution methods for solving large-scale problems, large-scale examples were solved using metaheuristic methods. In the other words, the results of two meta-heuristic algorithms, NSGAII and ε-constraint (EP) compared. In addition, relevant common methods were used to set those meta-heuristicparameters, which had a significant impact on its performance. It should be noted that the solutions obtained from the metaheuristic algorithm were compared in MINITAB, and theequality assumption of solutions is significant and the run times were tested. Finally, the parameters defined in this algorithm were set using the Taguchi approach. The results of this study are as follows:

1. The meta-heuristic EP algorithm is better than the NSGAllin all criteria, except for the NES index.

2. The NSGAII algorithm has a lower solution speed compared to the EP algorithm, thus it is more efficient.

3. Increased percentage of generated waste generallyincreases all objective functions, but thisincrease was higher and more sensible in the first objective function, while the lowest increase occurred in the third objective function. Generally, it can be concluded that variation in generated waste has the greatest effect on the system costs. Therefore, additional costs must be controlled by considering the special conditions and being prepared for changes.

References

Alamur, S., Kara, B.Y., 2007. A new model for the hazardous waste location-routing problem. Computers & Operations Research 34, 1406–1423.

Berman, O., Drezner, Z., Wang, Q., Wesolowsky, G.O., 2008. The route expropriation problem. IIE Transactions 40, 468–477.

Caballero, R., Gonzalez, M., Guerrero, F.M., Molina, J., Paralera, C., 2007. Solving a multiobjective location routing problem with a metaheuristic based on tabu search. Application to a real case in Andalusia. European Journal of Operational Research 177, 1751–1763

Cappanera, P., Gallo, G., Maffioli, F., 2004. Discrete facility location and routing of obnoxious activities. Discrete Applied Mathematics 133, 3–28 .

Dadkar, Y., Jones, D., Nozick, L., 2008. Identifying geographically diverse routes for the transportation of hazardous materials. Transportation Research Part E 44,333–349.

Delhaye, C., Teghem, J., Kunsch, P., 1991. Application of the ORESTE method to a nuclear waste management problem. International Journal of Production Economics 24 (1-2), 29–39.

Emek, E., Kara, B.Y., 2007. Hazardous waste management problem: the case for incineration. Computers & Operations Research 34, 1424–1441.

Erkut, E., Verter, V., 1995. A framework for hazardous materials transport risk assessment. Risk Analysis 15, 589–601.

Fahimnia, B., Sarkis, J., Dehghanian, F., Banihashemi, N., & Rahman, S. (2013). The impact of carbon pricing on a closed-loop supply chain: an Australian case study. Journal of Cleaner Production, 59, 210-225 .

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

Gupta, A. and Evans, G.W., 2008, January. Optimization modeling for the operation of closed-loop supply chains. In *IIE Annual Conference. Proceedings* (p. 1125). Institute of Industrial and Systems Engineers (IISE).

Gutiérrez, G. J., Kouvelis, P., &Kurawarwala, A. A. (1996). A robustness approach to uncapacitated network design problems. European Journal of Operational Research, 94(2), 362-376 .

Huang, B., Cheu, R.L., Liew, Y.S., 2004. GIS and genetic algorithms for HAZMAT routeplanning with security considerations. International Journal of GeographicalInformation Science 18 (8), 769–787.

Huang, B., Fery, P., Xue, L., Wang, Y., 2008. Seeking the Pareto front formultiobjective spatial optimization problems. International Journal ofGeographical Information Science 22 (5), 507–526.

Jayaraman, V., Patterson, R. A., & Rolland, E. (2003). The design of reverse distribution networks: Models and solution procedures. European journal of operational research, 150(1), 128-149 .

Krikke, H. R., van Harten, A., &Schuur, P. C. (1999). Business case Oce: reverse logistic network re-design for copiers. OR-Spektrum, 21(3), 381-409.

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

Revelle, C., Cohon, J., Shobrys, D., 1991. Simultaneous siting and routing in the disposal of hazardous wastes. Transportation Science 25 (2), 138–145.

Shuai, B., Zhao, J., 2011. Multi-objective 0–1 linear programming model for combined location – routing problem in hazardous waste logistics system. Journal of Southwest Jiaotong University 46 (2), 326–332.

Tsiakis, P., Shah, N., &Pantelides, C. C. (2001). Design of multi-echelon supply chain networks under demand uncertainty. Industrial & Engineering Chemistry Research, 40(16), 3585-3604 .

Zhang, J., Hodgson, J., Erkut, E., 2000. Using GIS to assess the risks of hazardous materials transport in networks. European Journal of Operational Research 121, 316–329.

Zhao, J., Zhao, J., 2010. Model and algorithm for hazardous waste location-routingproblem. In: Proceedings of the ICLEM 2010: Logistics for Sustained EconomicDevelopment, 2010 ASCE, pp. 2846–2852.