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A sustainable multi-objective model for the hazardous waste location-routing problem: A real case study

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ABSTRACT

A substantial extent of harmful rubbish produced from manufacturing processes and health segments has posed a significant warning to the health of humans by affecting environmental concerns and the pollution of soil, air, and water resources. In this research, a multi-objective mixed-integer nonlinear programming (MINLP) model is presented for a sustainable hazardous waste location-routing problem. The position of the facilities and decisions on the routes for transferring hazardous waste as well as the waste remainder are considered to design a proper waste collection system. The proposed model tries to minimize the whole costs of the waste management system, the total hazards from the facilities and transportation, together with the CO_2 emissions, simultaneously equipped with a real case study to show the applicability of the developed model. In order to show the sustainability importance, the outputs of the original model are compared with the model, not including sustainability. The outcomes illustrate that, under the lack of sustainability, total costs, transportation, and site risk along with the CO_2 emissions increase, demonstrating the importance of sustainability. Besides, the extracted managerial insights support managers in making better decisions in the hazardous waste management system.

1. Introduction

Hazardous waste that is produced by the industrial process can cause several impacts on humans, animals, and plants. Toxicity, reactivity, ignitability, and corrosiveness are the four kinds of waste categories, and if any waste possesses at least one of these categories, it is categorized as hazardous waste [1]. In recent years, population growth and industrial and technological developments have increased environmental impacts on our planet, which have raised government concerns regarding a hazardous waste management (HWM) system. An HWM system involves a multitude of tasks, such as collecting, transporting, recycling, treatment, and disposal of hazardous waste, as well as determining related routes for collecting hazardous waste and waste residues to deliver them between the facilities [2]. Due to various categories of physical and chemically hazardous waste, selecting suitable locations for the treatment, recycling, and disposal facilities as well as how to allocate these hazardous waste to the associated facilities, plays a crucial role in the HWM system and could be a challenging task [3]. To design an efficient HWM system, several perspectives, including environmental, economic, and social aspects, should be considered simultaneously, making it a more complex problem [4].

A sustainable hazardous waste management (SHWM) system is of utmost importance to guarantee human health and safety. In a waste management system (WMS), sustainability must be adequately and properly addressed to ensure its success [5]. However, it is essential to recognize that sustainability encompasses various factors, including environmental preservation, economic efficiency, and social acceptance. For instance, consider the examples of composting facilities in Delhi [6] and composting and incinerator facilities in Turkey [7]. These facilities were established with the primary goal of mitigating the adverse effects of solid waste on the environment, particularly by reducing open dumping. Although these facilities were operational, they faced challenges that led to their ultimate failure. One of the key reasons for their failure was the improper implementation of sustainability which led to their inefficiency and high operational costs, which hindered their long-term viability. So, an SHWM must be effective environmentally, inexpensive economically, and socially acceptable [8]. According to the definition of the World Summit of Sustainable Development (WSSD), sustainability is a trade-off between three items: economic profit, environmental conservation, as well as social development, which focuses on the significance of environmental preservation as one of the sustainability poles [9]. To address this issue, this paper considers waste residues and trans-

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portation systems as the two sources of releasing Greenhouse Gas (GHG) emissions and aims to minimize the CO_2 emissions from waste, waste residues, and transportation systems.

Social responsibility is another important pillar of sustainability that should be focused on. Due to the growing social responsibility concerns, many scientists have tried to deal with the environmental risks [10,11]. Numerous studies have been conducted in a waste management system considering risks such as population risk and transportation risk in their models as an objective required to be minimized [12], Samanlioglu [2,13,14]. However, few studies have considered the impact of social responsibility on their proposed models. This paper addresses the social responsibility issue by considering the transportation risk and site risk as an objective function to be minimized.

To prevent interaction between different types of incompatible waste, they should be carried out separately, including the emissions and the generation of heat. In this regard, an inhomogeneous fleet of vehicles is exploited to collect the waste in a divided fleet that is compatible with the load. The network in our problem comprises five components, including the generation nodes, a central depot, and three facilities (recycling, treatment, and disposal). Generation nodes are the nodes where hazardous waste is generated. The central depot is a location where hazardous waste is collected and stored temporarily before being further processed or transported to recycling, treatment, or disposal facilities. The recyclable amount of waste is shipped to the recycling facility. A recycling facility is responsible for processing hazardous waste materials in a way that allows for the extraction and reuse of valuable resources or the conversion of waste into usable products. In treatment facilities, hazardous waste undergoes various processes, such as chemical and physical, to reduce its hazardous properties or make it less harmful before final disposal or recycling. Finally, the disposable amount is transferred to the disposal facility. In addition, there is a capacity level for each facility that determines the effective utilization of these facilities. The capacity level includes three levels for each facility, which are determined by the amount of waste delivered to the facilities. In this paper, we propose an MINLP model in which the locations of the facilities and routing decisions are considered simultaneously in a sustainable hazardous waste location-routing problem (SHWLRP). In this regard, a new mathematical programming model is developed to minimize the total investment costs, transporting costs, CO_2 emissions from the transportation system, and waste residues. In addition, we aim to minimize transportation and site risks.

The remainder of this study is as follows: Section 2 presents the related literature review. Descriptions and mathematical formulations are presented in Section 3. In Section 4, the importance and the value of the proposed model are evaluated through a real case study. Finally, Section 5 provides some conclusions and suggests various future directions to further advance the paper.

2. Literature review

Three main objective functions are generally addressed by the researchers simultaneously to consider different aspects of the undesirable facility location problem in hazardous waste management; the minimization of costs, including construction and operational costs, the minimization of the transportation and facilities risks which the population around those geographic areas are being exposed to, and the maximization of the equity of the distribution risk which is obtained by a maximum zonal risk per unit. These goals were initially proposed in the facility location area by Ratick and White [15]. Then several scholars, such as Asgari et al. [16], Zhang and Zhao [17], and Zhao and Huang [18] evaluated simultaneously the balance between expenditures, risk, and the allocation of a fair risk. Since hazardous waste is enormously dangerous to the health of humans and the environment, several scholars have been persuaded to propose mathematical models to aid decision-makers in assessing hazardous waste. Two significant aspects of dealing with hazardous waste are the location of facilities and the routing of hazardous waste between the facilities [12]. Regarding the first aspect, the primary work associated with a semi-desirable or partially noxious facility location problem was developed by [19], in which they proposed the notion of an obnoxious facility on a network. [20] surveyed the location model maximization for obnoxious facilities. Later, concerns about the location of undesirable facilities have greatly raised as the magnitude of hazardous materials increased. For example, [21] developed a multi-objective mixed-integer programming model for sitting landfills. Minimizing the total costs, the risk to nearby population centers, the risk nearby to the ecosystem, and the inequity of risk distribution were four objectives that they considered in their paper. [22] addressed the undesirable facility location selection problem to determine an appropriate location to construct undesirable facilities in Istanbul. Benefits, opportunities, costs, and risks were taken into account as criteria to find the optimum locations. Regarding the second aspect, [23] investigated the vehicle routing problem through proposing a multi-objective approach for collecting hazardous waste. They applied a memetic algorithm to minimize the total traveling time and the number of vehicles for collecting the waste. [24] proposed a MILP model to minimize the length of the routes for collecting the waste to lessen the whole expenditures of the system in India. Louati [25], to collect solid waste from a municipality, proposed a generalized VRP model, including heterogeneous vehicles in time windows, and applied a MILP approach to reduce both the total traveling distances and operational hours of the vehicles. [26] developed a new method for the problem of hazardous material transportation in town areas in addition to minimizing the overall risk for the population.

Considering the location and routing decisions in an HWM leads to Hazardous Waste Location-Routing Problems (HWLRPs). The first HWLRP was proposed by [13]. They considered one type of hazardous waste and three objectives, including the time of traveling, the risk of transportation, and the risk of site. They proposed a goal programming model for determining the location and routing decisions. [27] studied a combined location-routing problem for minimizing the joint facility location, transportation route, cost, and perceived risks. [28] proposed a location model for an obnoxious facility location problem in which they simultaneously incorporated the routing decisions into their model. [29] considered a bi-modal transportation network including road and rail connections. They formulated a two-stage stochastic programming model for minimizing the costs and risks of transportation. [30] incorporated a multi-period HWLRP. They applied a multi-objective MINLP model to select the best route for collecting the waste. [31] developed a two-echelon multi-objective HWLRP. Finding the best routes of the vehicles for collecting hazardous waste to minimize the cost and risk was one of the leading purposes of their study. [32] addressed a hazmat routing-scheduling problem to minimize the risk in hazmat land transportation by simultaneously incorporating routing and scheduling approaches. The routing approach simultaneously divides the routes of transported hazmat, while the scheduling approach divides the transportation time slots on the same routes. Hassanpour et al. [33] addressed a time-dependent location-routing problem of hazardous material transportation, considering edge unavailability and time windows. Their study contributes to the optimization of hazardous waste transportation systems under time constraints, which is valuable in enhancing the efficiency and safety of hazardous waste management practices. Ouertani et al. [34] proposed a decision support system for addressing the dynamic hazardous materials vehicle routing problem. Their study offers insights into optimizing routing strategies for hazardous materials transportation.

Due to various types of hazardous waste in the real world, many works have tried to address those types differently. For example, Samanlioglu [2] proposed different kinds of industrial hazardous waste network designs. She presented a new multi-objective model to minimize total costs, transportation, and site simultaneously. [35] and [3] are two other works that addressed a location-routing model to consider different categories of hazardous waste. They suggested waste-waste and waste-technology compatibility constraints and presented a multi-objective goal programming model to find the locations of the disposal and treatment centers as well as the transportation routes to these facilities. [36] and [37] described an HWLRP with recycling, treatment, and disposal facilities. [37] addressed waste-waste compatibility to guarantee that a type of waste is not collected with incompatible waste and all these types are collected with an inhomogeneous fleet of vehicles. Furthermore, [36] divided the generation nodes into two distinctive types of centers. The first type is where waste is produced, and the second type is where the waste is collected. Aydemir-Karadag [38] formulated a mathematical model for a profit-HWLRP in which multiple types of waste were taken into account. They considered two treatment technologies, including chemical treatment and incineration, to deal with different categories of waste delivered to facilities in accordance with its classification. Jafari et al. [39] addressed the time-dependent location-routing problem for hazardous material (hazmat) transportation with stop en route, focusing on a case study for fossil fuel distribution. Their model mainly selects the best facility to assign to customers, finds the optimal route to serve the customers, and determines a schedule for arrival and departure time from nodes. Hassanpour et al. [40] examined infectious waste management strategies amid a pandemic, focusing on a stochastic location-routing problem with chance-constrained time windows. The findings shed light on optimizing waste disposal processes during public health emergencies, contributing to the development of robust and adaptive waste management frameworks.

As discussed earlier, the environmental aspect is one of the essential pillars of sustainability. The environmental perspective was rarely taken into account in the HWM literature. [41] formulated a solid waste management problem in which the global warming and cost-profit factor were considered to obtain optimal planning for the waste system. They considered a scenario-based design process to estimate greenhouse gas emissions. [42] proposed an integrated solid waste management with regard to two objective functions, including total cost minimization and the minimization of carbon dioxide (CO_2) emissions.

Table 1 presents a comparative analysis of the published studies that were particularly focusing on the field of HWLRPs from 1989 to 2020. According to this table and the reviewed studies in this section, it has been found that little attempts have been made to consider all three components (economic, environmental, and social) simultaneously in the HWLRP literature. In addition, to the best of our knowledge, capacity planning of the facilities has not been taken into consideration in the HWLRP area. However, due to a constant change in the relationships between waste generation and the availability of facility capacities, it is important to have capacity planning for the effective utilization of facilities [43]. To overcome these shortcomings and fill these failed gaps, this paper develops a model which considers three aspects of sustainability at the same time and also formulates the capacity planning for each facility. The main contributions of this paper, which distinguish our work from the previous studies in this area, are as follows.

- Developing a sustainable location-routing hazardous waste management system with capacity planning for each facility;
- Introducing a new environmental objective function to minimize the impact of CO_2 emissions in location-routing hazardous waste management;
- Considering a heterogeneous vehicle fleet to prevent interactions between different waste types.

In this study, we propose a novel approach to design a sustainable hazardous waste management (HWM) system that addresses location-routing challenges while considering capacity planning for each facility involved. The HWM system encompasses waste collection, transportation, recycling, treatment, and disposal processes. By integrating capacity planning into the model, we aim to optimize the utilization of facilities and ensure efficient waste processing while considering future waste generation trends. To further enhance the sustainability of the proposed HWM system, we introduce a new environmental objective function that focuses on reducing the environmental impact of CO_2 emissions associated with waste transportation and processing. By minimizing CO_2 emissions, we aim to mitigate the system's contribution to climate change and enhance its overall environmental performance. This objective function is integrated into the location-routing model, allowing us to optimize waste management efficiency and environmental sustainability simultaneously.

3. Problem description

In this section, first, the description of the proposed HWLRP and the assumptions characterized by the given problem are presented. Then, the mathematical model of the concerned HWLRP is formulated using an MINLP approach under the foregoing assumptions. In the end, the augmented ε-constraint method is applied to transform the HWLRP into a single-objective problem.

3.1. Description

Fig. 1 presents a schematic view of the structure of the considered HWLRP and the links between the facilities and generation nodes. The network of the developed HWRLP includes generation nodes, recycling, disposal, and treatment facilities, and a central depot. Also, there are potential facilities for each set of facilities that can be selected to open in the future and a set of existing facilities for each facility. Hazardous waste is produced at a generation node, and this can be hospitals, factories, and collection centers. There are many potential nodes where recycling facilities and treatment facilities can be established. A link that connects two adjacent facilities shows the physical roads in which the waste is transported between the facilities and generation nodes through these roads.

The presented model can handle different kinds of waste that are incompatible with each other. Four types of waste have been considered in this paper. These four types are (I) recyclable waste, (II) non-recyclable waste that it is suitable for incineration technology, (III) non-recyclable waste but it is suitable for chemical technology, and (IV) waste that is non-recyclable but it is compatible with both technologies. An inhomogeneous fleet of vehicles is considered to collect incompatible waste in different vehicles to avoid interactions between incompatible types of waste. There is a limitation for the vehicle that carries a specific type of waste associated with its capacity and the length of the tour it travels. In this location-routing problem for collecting the waste, each vehicle starts from the central depot, and after unloading the waste, it comes back to the central depot.

Hazardous waste is accumulated at generation nodes. The accumulated waste is collected with a compatible vehicle, and then the recyclable amounts are shipped to the recycling facilities, and the non-recyclable amounts are transferred to the treatment facility. Again, at the treatment facility, the amount of waste residues that are recyclable is delivered to recycling facilities, and the remaining ones which are

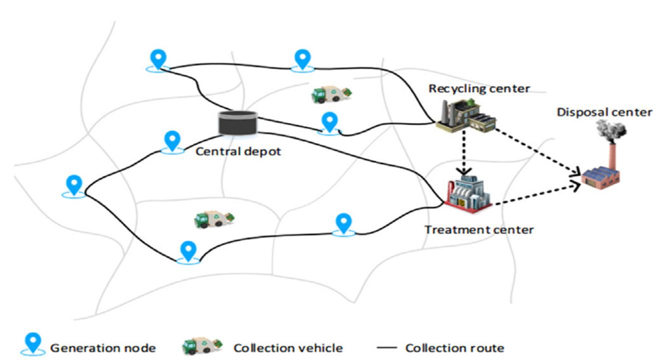

Fig. 1. The framework of a hazardous waste management system.

Table 1
Most relevant literature on the hazardous waste location-routing problem.

Study	Decision variable			Objective function			Vehicle		Compatibility	
	Location	Allocation/Routing	Capacity	Total cost	Risk	CO_2 emission	Homogenous	Heterogeneous	Waste-Waste	Waste-Technology
Zografros and Samara [13]	√	√		√	√		√			
List and Mirchandani [44]	√	√		√	√					
Stowers and Palekar [28]	√	√			√		√			
Current and Ratick [12]	√	√		√	√		√			
Nema and Gupta [35]	√	√		√	√		√		√	√
Alumur and Kara [1]	√	√		√	√		√			√
Zhang and Zhao [17]	√	√		√	√		√			
Samanlioglu [2]	√	√		√	√		√			√
Jiahong Zhao and Verter [45]	√	√		√	√		√			√
Ghezavati and Morakabchian [36]	√	√		√	√		√			
Zhao et al. [46]	√	√		√	√		√			
Asgari et al. [16]	√	√		√	√		√			
Yilmaz et al. [47]	√	√					√			√
Farrokhi-Asl et al. [48]	√	√						√		
Rabbani et al. [37]	√	√		√	√			√	√	√
Aydemir-Karadag [38]	√	√		√						√
Zhao and Huang [18]	√	√					√			
Rabbani et al. [30]	√	√		√	√			√		
Yu et al. [14]	√	√		√	√		√			
Yu et al. [31]	√	√		√	√					
This study	√	√	√	√	√	√		√	√	√

non-recyclable are sent to disposal facilities. Also, waste residues at recycling facilities are routed to the disposal facility.

We optimize the SHWLRP by considering total costs, total risks, and CO_2 emissions minimization. The total costs include the total transportation cost and the total investment cost of opening facilities. The second objective deals with reducing the total risks. The total risks are composed of transportation risk and site risk. The exposure of the population within the transportation routes is defined as transportation risk. Site risk is defined as the risk that the population around the treatment and disposal facilities is facing. This risk is measured by the number of loads at each facility and the population living around the facilities within a given radius.

While addressing the economic and social aspects of the system, to design a sustainable hazardous waste management system, the environmental aspect should be incorporated as well. In this regard, we design an environmental-friendly HWLRPs by minimizing CO_2 emission.

The main assumptions to facilitate the model formulation can be summarized as follows.

- The parameters are considered to be deterministic.
- All the recycling, treatment, and disposal facilities have limited capacities.
- Each generation node is served only one time by one vehicle for each type of waste.
- The amount of possible facilities that can be opened is bounded.
- The transportation costs for the vehicles are related to the distance they traveled.
- Two kinds of treatment technology exist, and at each treatment center, at most, one of them is allowed to be established.

3.2. Model formulation

We propose a multi-objective MINLP for an HWLR, which simultaneously determines the locations of the facilities, the routing decision, and the amounts of loads that are operated at each facility. The sets, indices, parameters, and decision variables of the model are shown in the following.

Sets:	
$N(V,A)$	The transportation network of nodes V and arcs A
G	Set of generation nodes $G = 1,2,\dots,g$
R	Set of recycling centers $R = 1,2,\dots,r$
R'	Existing recycling center $R' \in R$
T	Set of treatment centers $T = 1,2,\dots,t$
T'	Existing treatment center $T' \in T$
D	Set of disposal centers $D = 1,2,\dots,d$
D'	Existing disposal center $D' \in D$
W	Hazardous waste types $W = 1,2,\dots,w$
Q	Treatment technologies $Q = 1,2,\dots,q$
F	Depots $F = 1,2,\dots,f$
K	The fleet of collection $K = 1,2,\dots,k$
H	Set of available capacity levels for establishing facilities $H = 1,2,\dots,h$
Parameters:	
c_{ij}	Transporting cost for one unit of waste on link $(i,j) \in A$,
ft_{qih}	Investment cost of establishing a treatment facility with technology q with a capacity level of h at the node $i \in T$
fr_{ih}	Investment cost of establishing a recycling facility with a capacity level of h at the node $i \in R$
fd_{ih}	Investment cost of establishing a disposal facility with a capacity level of h at the node $i \in D$
d_{wi}	Quantity of waste type $w \in W$ accumulated at the generation node $i \in G$
Ptr_{ij}	Transportation risk on link $(i,j) \in A,\ \ i \in T,\ \ j \in R$
Ptd_{ij}	Transportation risk on link $(i,j) \in A,\ \ i \in T,\ \ j \in D$
Prd_{ij}	Transportation risk on link $(i,j) \in A,\ \ i \in R,\ \ j \in D$
s_{rh}	Operating risk of a recycling center with a capacity level of h at the candidate node $r \in R$

(continued on next column)

s_{th}	Operating risk of a treatment center with a capacity level of h at the node $T \in T$ with technology $q \in Q$
s_{dh}	Operating risk of a disposal center with a capacity level of h at the candidate node $d \in D$
Pc_{ij}	Maximum allowable risk tolerance capacity on link $(i.j) \in A$
β_{wq}	The ratio of recyclable hazardous waste type w which is treated with technology $q \in Q$
r_{wq}	The ratio of reduction of mass for the hazardous waste type w which is treated with technology $q \in Q$
γ_i	The ratio of total waste that is recycled at the node $i \in R$
tc_{qjh}	The capability of treatment technology $q \in Q$ with a capacity level of h at the node $j \in T$
tc^m_{qj}	Minimum quantity of waste needed for establishing a treatment technology $q \in Q$ at the node $j \in T$
rc_{jh}	Maximum capacity of recycling center with a capacity level of h at the node $j \in R$
rc^m_j	Minimum quantity of waste required for establishing a recycling facility at the node $j \in R$
dc_{jh}	Maximum capacity of a recycling center with a capacity level of h at the node $j \in D$
dc^m_j	The minimum amount of waste residues required for opening a disposal facility at the node $j \in D$
com_{wq}	Waste compatibility with technology $q \in Q$; 1 if compatible; 0 otherwise
Qr_{wi}	CO_2 emissions per one kg of waste type $w \in W$ to be recycled in the recycling center $i \in R$
Qt_{wqi}	CO_2 emissions per one kg of waste type $w \in W$ to be treated in the treatment center with technology $q \in Q,\ \ i \in T$
Qd_{wi}	CO_2 emissions per one kg of disposed waste type $w \in W$ at the node $i \in D$
QTr_{wij}	CO_2 emissions per one km and one kg from the transportation of waste type $w \in W$ to be recycled on link $(i,j) \in A,\ \ i \in T,\ \ j \in R$
QTd_{wij}	CO_2 emissions per one km and one kg from the transportation of waste type $w \in W$ to be disposed of on link $(i,j) \in A,\ \ i \in T,R,\ \ j \in D$
dis_{ij}	Travel distance by a truck for delivering waste on link $(i,j) \in A$
ve_{wk}	Waste compatibility with vehicle $v \in V$; 1 if compatible; 0 otherwise
a_{qi}	Availability of the treatment technology $q \in Q$ at the existing treatment facility $i \in T'$;1 if available; 0 otherwise
δ_w	The vehicle capacity that is compatible with waste type $w \in W$
μ_w	Vehicle's maximum traveling distance compatible with waste type $w \in W$
Variables:	
x_{ijk}	1 if vehicle $k \in K$ visited node j just after node i; 0 otherwise
z_{ij}	Quantity of waste residues delivered on link $(i,j) \in A,\ \ i \in T,\ \ j \in D$
k_{ij}	Quantity of recyclable waste residues delivered on link $(i,j) \in A,\ \ i \in T,\ \ j \in R$
v_{ij}	Quantity of waste residues transported through a link $(i,j) \in A,\ \ i \in R,\ \ j \in D$
xr_i	Quantity of waste recycled at the node $i \in R$
xt_{wi}	Quantity of hazardous waste type $w \in W$ treated at the node $i \in T$
xd_i	Quantity of waste residues disposed at the node $i \in D$
e_{ik}	Traveled distance by vehicle $k \in K$ after the node i
lo_{ik}	Vehicle's load $k \in K$ after node i
r_{ih}	1 if a recycling facility with a capacity level of h is located at the candidate node $i \in R$; 0 otherwise
t_{qih}	1 if a treatment facility with a capacity level of h is located at the candidate node $i \in T$ with technology $q \in Q$; 0 otherwise
d_{ih}	1 if a disposal facility with a capacity level of h is located at the candidate node $i \in D$; 0 otherwise

3.2.1. Proposed mathematical model

The formulation of a mathematical programming model for an HWLRP with respect to the aforementioned notations is as follows, which extends the mathematical model proposed by Rabbani et al. [37].

$$
\begin{aligned}
Min f_1(x) = {} & \sum_{i\in G}\sum_{j\in T\cup R\cup D}\sum_{k\in K} c_{ij}x_{ijk}lo_{ik} + \sum_{i\in T}\sum_{j\in D} c_{ij}z_{ij} + \sum_{i\in R}\sum_{j\in D} c_{ij}v_{ij} \\
& + \sum_{i\in T}\sum_{j\in R} c_{ij}k_{ij} + \sum_{q\in Q}\sum_{i\in T-T'}\sum_{h\in H} ft_{qih}t_{qih} + \sum_{i\in D-D'}\sum_{h\in H} fd_{ih}d_{ih} \\
& + \sum_{i\in R-R'}\sum_{h\in H} fr_{ih}r_{ih}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
Min f_2(x) = {} & \sum_{i\in T}\sum_{j\in R} Ptr_{ij}k_{ij} + \sum_{i\in T}\sum_{j\in D} Ptd_{ij}z_{ij} + \sum_{i\in R}\sum_{j\in D} Prd_{ij}v_{ij} \\
& + \sum_{w\in W}\sum_{(i,t)\in T}\sum_{h\in H} s_{th}xt_{wi} + \sum_{(r,i)\in R}\sum_{h\in H} s_{rh}xr_i + \sum_{(d,i)\in D}\sum_{h\in H} s_{dh}xd_i
\end{aligned} \tag{2}
$$

$$Minf_3(x) = \sum_{w\in W}\sum_{i\in R} Qr_{wi}xr_i + \sum_{w\in W}\sum_{i\in R}\sum_{q\in Q} Qt_{wqi}xt_{wi} + \sum_{w\in W}\sum_{i\in D} Qd_{wi}xd_i + \sum_{w\in W}\sum_{i\in T}\sum_{j\in R} QTr_{wij}dis_{ij}k_{ij} + \sum_{w\in W}\sum_{i\in T,R}\sum_{j\in D} QTd_{wij}dis_{ij}(z_{ij}+\upsilon_{ij}) \tag{3}$$

subject to:

$$\sum_{i\in F}\sum_{j\in G} x_{ijk} = 1\forall k \in K \tag{4}$$

$$\sum_{i\in FG} x_{ijk} - \sum_{i'\in GRT} x_{ji'k} = 0\forall j \in G, k \in K \tag{5}$$

$$\sum_{j\in GRT}\sum_{k\in K} x_{ijk}ve_{wk} = 1\forall i \in G, w \in W \tag{6}$$

$$\sum_{i\in G} x_{ijk} - \sum_{i'\in F} x_{ji'k} = 0\forall j \in RT, k \in K \tag{7}$$

$$x_{ijk} \le \sum_{w\in W}\sum_{q\in Q}\sum_{h\in H} ve_{wk}com_{wk}t_{qih}\forall i \in G, j \in T, k \in K \tag{8}$$

$$x_{ijk} \le \sum_{w\in W} ve_{wk}\frac{\left(\left(2-\sum_{q\in Q}com_{wq}\right)r_j\right)}{2}\forall i \in G, j \in R, k \in K \tag{9}$$

$$e_{ik} - e_{jk} + \sum_{w\in W} ve_{wk}\left((\mu_w + dis_{ij})x_{ijk} + (\mu_w - dis_{ij})x_{jik}\right) \le \sum_{w\in W} ve_{wk}\mu_w\forall i,j \in GRT \tag{10}$$

$$\sum_{i\in F} dis_{ijk}x_{ijk} \le e_{jk} \le \sum_{w\in W} ve_{wk}\left(\mu_w + \sum_{i\in F}(dis_{ij}-\mu_w)x_{ijk}\right)\forall j \in G, k \in K \tag{11}$$

$$e_{ik} \le \sum_{w\in W} ve_{wk}\mu_w - \sum_{j\in F} dis_{ij}x_{ijk}\forall j \in RT, k \in K \tag{12}$$

$$lo_{ik} - lo_{jk} + \sum_{w\in W} ve_{wk}\delta_w x_{ijk} \le \sum_{w\in W} ve_{wk}(\delta_w - d_{jw})\forall i,j \in G, k \in K \tag{13}$$

$$\sum_{w\in W} d_{wi}ve_{wk} \le lo_{ik} \le \sum_{w\in W} ve_{wk}\delta_w\forall i \in G, k \in K \tag{14}$$

$$\sum_{i\in F}\sum_{w\in W} x_{ijk}d_{wj}ve_{wk} \le lo_{jk}\forall j \in G, k \in K \tag{15}$$

$$lo_{jk} \le \sum_{w\in W} ve_{wk}\left(\delta_w + \sum_{i\in F}(d_{wj}-\delta_w)x_{ijk}\right)\forall j \in G, k \in K \tag{16}$$

$$xt_{wj} = \sum_{k\in K}\sum_{i\in G} x_{ijk}lo_{ik}ve_{wk}\forall j \in T, w \in W \tag{17}$$

$$\sum_{w\in W} xt_{wj} \le \sum_{q\in Q}\sum_{h\in H} tc_{jh}t_{qjh}\forall j \in T \tag{18}$$

$$\sum_{w\in W} xt_{wj} \ge \sum_{q\in Q}\sum_{h\in H} tc^m_{jh}t_{qjh}\forall j \in T \tag{19}$$

$$xr_j = \sum_{w\in W}\sum_{k\in K}\sum_{i\in G} x_{ijk}lo_{ik}ve_{wk} + \sum_{i'\in T} k_{i'j}\forall j \in R \tag{20}$$

$$\sum_{w\in W}\sum_{q\in Q} xt_{wi}(1-r_{wq})\beta_{wq} = \sum_{j\in R} k_{ij}\forall i \in T \tag{21}$$

$$xr_j \le \sum_{h\in H} rc_{jh}r_{jh}\forall j \in R \tag{22}$$

$$xr_j \ge rc^m_j\sum_{h\in H} r_{jh}\forall j \in R \tag{23}$$

$$\sum_{w\in W}\sum_{q\in Q}\sum_{h\in H} xt_{wi}t_{qih}(1-r_{wq})(1-\beta_{wq}) = \sum_{j\in D} z_{ij}\forall i \in T \tag{24}$$

$$xr_i(1-\gamma_i) = \sum_{j\in D}\upsilon_{ij}\forall i \in R \tag{25}$$

$$xd_i = \sum_{j\in T} z_{ji} + \sum_{j'\in R}\upsilon_{j'i}\forall i \in D \tag{26}$$

$$xd_i \le \sum_{h\in H} dc_{ih}d_{ih}\forall j \in D \tag{27}$$

$$xd_i \ge dc^m_i\sum_{h\in H} d_{ih}\forall j \in D \tag{28}$$

$$\sum_{w\in W}\sum_{i\in G} d_{wi} = \sum_{w\in W}\sum_{j\in T} xt_{wj} + \sum_{j\in R} xr_j \tag{29}$$

$$\sum_{q\in Q}\sum_{h\in H} t_{qih} \le 1\forall i \in T \tag{30}$$

$$\sum_{h\in H} t_{qih} = a_{qi}\forall q \in Q, i' \in T \tag{31}$$

$$\sum_{h\in H} r_{ih} = 1\forall i \in R' \tag{32}$$

$$\sum_{h\in H} d_{ih} = 1\forall i \in D' \tag{33}$$

$$ptr_{ij}k_{ij} + ptd_{ij}z_{ij} + prd_{ij}\upsilon_{ij} \le Pc_{ij}\forall (i,j) \in A \tag{34}$$

$$\begin{aligned} &xd_j \ge 0, z_{ij} \ge 0\forall j \in D, i \in T\\ &xt_{wi} \ge 0, k_{ij} \ge 0\forall i \in T, j \in R, w \in W\\ &xr_i \ge 0, \upsilon_{ij} \ge 0\forall i \in R, j \in D\\ &lo_{ik} \ge 0\forall i \in G, k \in K\\ &e_{ik} \ge 0\forall i \in (f \cup G), k \in K \end{aligned} \tag{35}$$

$$\begin{aligned} &x_{ijk} \in \{0,1\}\forall i \in (f \cup G), \forall j \in (G \cup R \cup T), k \in K\\ &r_{ih} \in \{0,1\}\forall i \in R, h \in H\\ &t_{qih} \in \{0,1\}\forall i \in T, q \in Q, h \in H\\ &d_{ih} \in \{0,1\}\forall i \in D, h \in H \end{aligned} \tag{36}$$

The objective functions (1), (2), and (3) are associated with the total costs, the total risks, and the CO_2 emissions, respectively, in the proposed HWLRP. The first objective function is composed of seven parts, in which the first part indicates the transportation cost of waste collection. The next three parts express the transportation of the waste residues. The last three parts show the fixed cost of opening recycling, treatment, and disposal facilities, respectively. The second objective function minimizes the total risk, including transportation and site risks. The transportation risk is related to the amount of waste residues transferred between the facilities, where the first three terms of the objective function (2) indicate them. The site risk can be described analogously to the transportation risk, except that it depends on the amount of waste that is available at each facility. The third objective function, which is an environmental-friendly objective, minimizes the CO_2 emissions from the whole hazardous waste management system.

Eq. (4) indicates that all the vehicles should start from the central depot. Eq. (5) guarantees that each vehicle leaves from and arrives at the same node, which is one of the main constraints in the vehicle routing problem. Eq. (6) ensures that all generation nodes are visited once by a vehicle for collecting each type of waste. Eq. (7) requires that the vehicles return to the central depot after they empty their load. Eq. (8) ensures that all vehicles with collected waste can unload their waste in a treatment facility, provided that their waste is compatible with the technology at that treatment facility. Eq. (9) shows that all vehicles with recyclable collected waste should empty their load at the recycling facilities before going back to its origin. Eqs. (10) and (12) guarantee that the traveled distance by a heterogeneous fleet does not transgress the permissible amount. Eqs. (13)-(16) require to eliminate sub-tours in the problem under consideration. Eq. (17) computes the amount of waste handled at each treatment facility. Eqs. (18) and (19) represent the minimum and maximum amount of waste and waste residues that are necessary for establishing a treatment facility.

Eq. (20) calculates the amount of waste that is processed at each treatment facility. The flow of waste residues between treatment facilities and recycling facilities is indicated in Eq. (21). Eqs. (22) and (23) indicate the maximum and minimum quantity of waste and residues of waste that are needed for establishing a recycling facility. The flow of waste residues from the treatment and recycling facilities to disposal facilities is shown in Eqs. (24) and (25). Eq. (26) measures the quantity of waste at disposal facilities. Eqs. (27) and (28) show the minimum and maximum quantity of waste and residues of waste that are needed for establishing a disposal facility. Eq. (29), which is a balanced equation, ensures that all the demand at different source nodes must be supplied. Eq. (30) states that establishing more than one treatment technology is not allowed at the transfer station. All the existing facilities are determined by Eqs. (31)-(33). Eq. (34) asserts that the transportation risk does not allow to exceed the maximum allowable tolerance capacity. Finally, Eqs. (35) and (36) impose the binary and non-negative constraints of the decision variables.

3.3. Model linearization

The developed mathematical model has a non-linear term in the first objective function. Therefore, to solve the proposed model, the non-linear term should be transformed into linear equivalences. For this purpose, we used an exact linearization method proposed by (Azadeh et al. 2017). The non-linear term is a multiple of the binary variable x_{ijk} and the continuous variable lo_{ik} in the first objective function. One of the easiest ways to prevent these non-linearities is to define a new continuous variable and three auxiliary constraints in the presented model. In this context, we replace the non-linear term with a new continuous variable xl_{ijk}. In the following, three auxiliary constraints should be added to the original model to guarantee that this reformulation yields the same result as the original model.

$$xl_{ijk} \le BMx_{ijk};(i,j) \in N, k \in K \tag{37}$$

$$xl_{ijk} \le lo_{ik};(i,j) \in N, k \in K \tag{38}$$

$$xl_{ijk} \ge lo_{ik} - \left(1 - x_{ijk}\right)BM;(i,j) \in N, k \in K \tag{39}$$

where BM is a large number.

3.4. Conversion to a single objective model

Several methods, including ε-constraint, weighted metrics, goal programming, and lexicographic methods, are commonly applied to deal with MOPs. In this study, the augmented ε-constraint method introduced by Mavrotas [49] is used to deal with the proposed MOP. The decision to use the "ε-constraint" method for converting the three objective functions into a single objective is based on its effectiveness in handling multi-objective optimization problems. The "ε-constraint" method is a widely recognized and well-established approach for solving multi-objective optimization problems in the literature [50]. Compared to other methods, such as the weighted sum method or the goal programming approach, the "ε-constraint" method provides a more comprehensive and versatile way to explore the trade-offs among multiple objectives. It allows decision-makers to examine different levels of priority assigned to each objective, offering a more nuanced understanding of the solution space. Furthermore, the "ε-constraint" method is better suited for handling non-linear and non-convex objective functions, which are often encountered in hazardous waste location-routing problems. Its ability to capture the Pareto-optimal solutions efficiently makes it a suitable choice for balancing economic, environmental, and social considerations in hazardous waste management.

In the augmented ε-constraint method, one of the objective functions of the problem is optimized, and the rest of the objective functions are moved to the constraints as follows:

$$Max\left(g_1(x) + eps \times \left(s_2/r_2 + s_3/r_3 + \ldots + s_p/r_p\right)\right)$$

subject to:

$$g_k(x) - s_k = \varepsilon_k k = 1, 2, \ldots, p; x \in S; \varepsilon_k \in R^+ \tag{40}$$

where $g_2(x), \ldots, g_p(x)$ are the objective functions, S is the solution space of the problem, and the vector x contains the decision variables and the values $g_1(x)$,. $\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_p$ give the right-hand sides of the limited objective functions. Moreover, $r_1, r_2, \ldots, r_p$ give the ranges of the corresponding objective functions, and $s_1, s_2, \ldots, s_p$ represent the auxiliary variables of the relevant constraints. The value *eps* is taken from $[10^{-6}, 10^{-3}]$.

When using this method, specifying the most excellent amounts of ε_k is important. To obtain these values, the worst and best amounts of the considered objective functions should be determined. To do this, we solve the problem using the objective function for which one wishes to obtain the best value. For getting the worst value of an objective function, the problem is solved with other objective functions, and the attained values are kept. Then the worst value of the saved amounts is taken as the worst amount of this objective function. Through searching for the worst and best amounts of the corresponding objective functions, a suitable amount of ε_k could be specified. To do so, the value ε_k is changed between the best and worst obtained values, and then the resulting problem will be solved. Now, the amount of the first objective function at each level of ε_k is investigated to obtain the best one.

Using the above description, the multi-objective model can now be transformed into an equivalent single-objective model in the following way:

$$\begin{aligned} Min f_1(x) = &\sum_{i\in G}\sum_{j\in T\cup R\cup D}\sum_{k\in K} c_{ij}x_{ijk}lo_{ik} + \sum_{i\in T}\sum_{j\in D} c_{ij}z_{ij} + \sum_{i\in R}\sum_{j\in D} c_{ij}v_{ij} \\ &+ \sum_{i\in T}\sum_{j\in R} c_{ij}k_{ij} + \sum_{q\in Q}\sum_{i\in T-T'}\sum_{h\in H} ft_{qih}t_{qih} + \sum_{i\in D-D'}\sum_{h\in H} fd_{ih}d_{ih} \\ &+ \sum_{i\in R-R'}\sum_{h\in H} fr_{ih}r_{ih} + \left(\sum_{s\in S-\{1\}} w_s^1\delta_s^1\right) - \left(eps \times \left(s_2/r_2 + s_3/r_3\right)\right) \end{aligned} \tag{41}$$

subject to:

$$\begin{aligned} &\sum_{i\in T}\sum_{j\in R} Ptr_{ij}k_{ij} + \sum_{i\in T}\sum_{j\in D} Ptd_{ij}z_{ij} + \sum_{i\in R}\sum_{j\in D} Prd_{ij}v_{ij} + \sum_{w\in W}\sum_{(i,t)\in T}\sum_{h\in H} s_{th}xt_{wi} \\ &+ \sum_{(r,i)\in R}\sum_{h\in H} s_{rh}xr_i + \sum_{(d,i)\in D}\sum_{h\in H} s_{dh}xd_i + \left(\sum_{s\in S-\{1\}} w_s^2\delta_s^2\right) + s_2 = \varepsilon_2 \end{aligned} \tag{42}$$

$$\begin{aligned} &\sum_{w\in W}\sum_{i\in R} Qr_{wi}xr_i + \sum_{w\in W}\sum_{i\in R}\sum_{q\in Q} Qt_{wqi}xt_{wi} + \sum_{w\in W}\sum_{i\in D} Qd_{wi}xd_i \\ &+ \sum_{w\in W}\sum_{i\in T}\sum_{j\in R} QTr_{wij}dis_{ij}k_{ij} + \sum_{w\in W}\sum_{i\in T,R}\sum_{j\in D} QTd_{wij}dis_{ij}\left(z_{ij} + v_{ij}\right) \\ &+ \left(\sum_{s\in S-\{1\}} w_s^3\delta_s^3\right) + s_3 = \varepsilon_3 \end{aligned} \tag{43}$$

$$S_k \in R \tag{44}$$

Eqs. (4)-(36)

In the following section, we show how this single-objective model will be solved by the solution method proposed above.

4. Case study

For the validation of the proposed model, a real-world case study is considered in Babol City, which is located in the northwest of the Mazandaran province, Iran. This city, with an area of 310 km^2 and a total population of 531,930, is the most populated city in Mazandaran province, Iran. This city has been selected for the case study as it has many hospitals, clinics, and industrial companies that generate a considerable amount of hazardous waste.

To the best of our knowledge, there is no practical and strategic plan for collecting hazardous waste and recycling or disposing of them in the city council. A considerable amount of generated waste is transferred to a forest area in the south of Babol, which is geographically located next to a river. Therefore, it is necessary to make a strategic plan for collecting the waste and treating it in an organized way, which is the main purpose of our investigation. Based on the political divisions that are available on the Mazandaran Province Statistics Center (MPSC) website, Babol is divided into six main population districts, including Central (I), Laleabad (II), Gatab (III), Bandpey-ye Gharbi (IV), Babol Kenar (V) and Bandpey-ye Shargi (VI). Fig. 2 shows the geographical map of Babol City, and its population districts are numbered from (I) to (VI). Based on (MPSC), there are 13 demand nodes within these six districts, and all districts are candidate locations for establishing facilities. In this paper, the amount of hazardous waste that is generated from industrial processes and health sectors is taken into account. According to Babol Waste Management Organization's official data for the year 2019, the amount of waste generated from industrial processes and health sectors was 131,980 tons, where 36% of them were considered hazardous waste (BMWMC 2020).

4.1. Data set

In this study, all the input data we used are from the official reports of the Babol Waste Management Organization for the year 2019. The cost unit is a million Tomans (the currency of Iran, where 1 US Dollar is equal to 30,000 Tomans), the distance unit is the kilometer, and the waste unit is the ton. The distances between each node and its facilities are measured by applying Google Maps. The amount of hazardous waste produced by industrial processes and health sectors in 2019 was a total of 47,513 tons, and only 20% of the produced hazardous waste was transferred to facilities, and the remaining one was disposed of improperly. Since a large amount of hazardous waste is not suitable for recycling when directly delivered from the demand nodes, a small percentage of it is sent to a recycling facility. According to the data obtained from the existing facilities, the percentage for each type of hazardous waste that is sent to corresponding facilities is shown in Table 2. Based on the research that is done by [1], the amount of waste residues that are sent to the recycling facility from a chemical treatment facility is 30%, and this amount of waste residues that are delivered to the recycling facility after an incineration treatment is 0% because they are only ashes. In addition, according to [1], since the incineration process aims to reduce the volume of mass, the reduction of mass in this process is 80%, while this amount for chemical treatment is 20%, since the chemical treatment aimed to reduce the hazardous characteristic of the waste. According to the data obtained from the existing facilities, after the recycling process, 5% of the waste residues have been sent to disposal facilities.

Table 2
The percentages of each category of hazardous waste.

Percentage (%)	Waste types			
	(I)	(II)	(III)	(IV)
Industrial process	15%	13%	20%	5%
Health sectors	10%	30%	15%	8%

The generated hazardous waste, which is gathered in the demand nodes, is collected by 12 trucks. Each truck collects only one type of waste because the waste should be collected separately to prevent interaction between them (BMWMC 2020). According to the categories of waste, the vehicles, with respect to their capacities and distance limitation, deliver them to the corresponding facility. The transportation cost is calculated based on the distance that a vehicle travels to collect and deliver the hazardous waste and waste residues to the facilities, which are 0.01 Million Tomans per kilometer. For the establishment cost of each facility, we applied the judgment of three senior experts in the Babol Real Estate Consultants Association. The investment cost of each potential facility depends on the capacity of each facility, and it is also different for each region due to the difference in the price of the land, which is summarized in Table 3.

According to the amount of generated waste in the selected regions, three capacity levels, including 5 (low-level),10 (medium-level), and 15 (high-level) tons per day, are considered for each facility. The region, where its waste production is in the range of [0–600] tons, is considered to be low-level, [601–1700] and [1700–3500] are medium-level and high-level, respectively. For the region in which its waste generation is in a low-level range, the capacity level of 5 is assigned to its facilities, and the capacity levels of 10 and 15 are assigned to medium-level and high-level regions, respectively. Table 4 indicates the amount of generated hazardous waste in each district. The locations of the existing facilities in each district are shown in Table 5. In addition, there are also two existing recycling facilities, including Juybar and Amol, which are located in the North and West of Babol, respectively.

During the operation and transportation of hazardous waste, many substances like CO_2 are emitted into the air. Table 6 shows the amount of produced CO_2 emissions by the transportation and the operations of recycling, treatment, and disposal facilities according to the available data and the dependable scientific report in the footnote of Table 6.

The location risk (LR) and transportation risk (TR) of each category of hazardous waste are measured by the risk method proposed by [3]. The values of risk consequence and risk probability are shown in Table 7

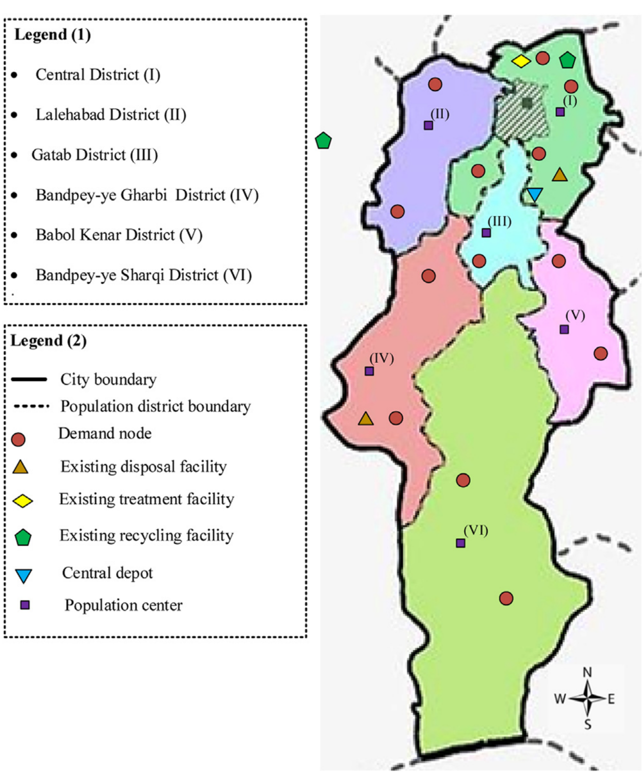

Fig. 2. The geographical map of Babol city.

Table 3
The establishment costs of each potential facility (million Tomans).

District		I	II	III	IV	V	VI
Capacity levels	5	1572	1275	1463	1098	1137	847
	10	1932	1583	1892	1386	1408	1230
	15	2241	1987	2340	1791	1853	1596

Table 4
The amounts of generated hazardous waste (HW) in each region.

District	I	II	III	IV	V	VI
Amount of HW	13,746	8190	7120	8961	5167	4329

Table 5
The locations of the existing facilities.

	Types of facility		
	Recycling	Treatment	Disposal
The location of the facility	(I)	(I)	(I), (IV)

Table 6
The amounts of CO_2 emissions from the transportation and operations of the facilities.

Types of facilities	CO2 emission (kg emissions/t of HW)
Recycling	438
Treatment (Incineration)	1000
Treatment (Chemical)	291
Disposal	300
Transportation	1.17

Source: [51]

Table 7
The values of risk consequence and risk probability for each facility.

Facilities	Risk	
	Risk outcome (×104 people)	Probability of Risk (×10–6)
Recycling	[0.01,3.32]	20
Treatment (incineration)	[0.01,3.32]	50
Treatment (chemical)	[0.01,3.32]	60
Disposal	[0.01,3.32]	30

for each type of facility. The population densities for the six districts are shown in Table 8.

The values presented in Table 7 are collected based on information obtained from the works of [1] and [3]. Specifically, we used data reported in their papers as a reference to populate Table 7 with the relevant parameters and corresponding values. Similar to Alumur and Kara [1], the location risk of each waste facility type in each city is assessed using the traditional risk method [3], calculated as the product of the city risk consequence and the city risk probability.

The city risk consequence is standardized as the number of people exposed within a 2.5 km radius of the city, represented by the formula city risk consequence = 6.25p (km^2) * city population density (people/km^2). The city risk probability is assumed to be identical for all types of waste facilities in each city. Moreover, the transportation risk is the product of three factors, including the waste risk potential, the link risk consequence, and the link risk probability. The waste risk potential is measured by an AHP, which is shown in Table 9 [46].

Table 9
Risk potentials for hazardous waste and waste residue.

Waste type	Potential risk
(I)	0.05
(II)	0.2
(III)	0.2
(IV)	0.2
Disposable hazardous waste	0.1
Waste residues at a treatment facility which is recyclable	0.05
Waste residues at a treatment facility which is disposable	0.1
Waste residues at a recycling facility which is disposable	0.1

Table 10
The optimal solution for the facility locations in the real case study.

District	Facility	Number of facilities	Capacity
1	Recycling	1	High-level
	Treatment (incineration)	1	High-level
2	Recycling	1	Medium-level
	Treatment (chemical)	1	High-level
3	Recycling	1	Low-level
	Treatment (incineration)	1	High-level
4	Treatment (chemical)	1	Medium-level
5	Treatment (chemical)	1	High-level
6	Recycling	2	Low-level, High-level
	Treatment (incineration)	1	Low-level
	Treatment (chemical)	1	Medium-level
	Disposal	1	High-level

4.2. Optimal solution for the case

The proposed single-objective model with the real-world case study's input parameters is solved using the CPLEX solver in the GAMS v. 24.1 optimization software, and the optimal solutions are illustrated in Fig. 3 and Table 10.

The solution reveals that the existing facilities do not satisfy the need for recycling, treatment, and disposal operations of the total generated waste in the studied districts. Due to the amount of generated waste, a need for a new disposal facility was clear, and according to the optimal solution, a new high-level disposal facility was opened. As expected, a high-level facility is selected for establishment in the most populated district in which the amount of generated waste is high.

The optimal routes of a heterogeneous fleet of vehicles for collecting the waste and the transportation stages are shown in Tables 11 and 12. For representing the optimal solution of the case study in Table 11, all

Table 8
The population densities for each district.

	District					
	I	II	III	IV	V	VI
Population density (people/Km2)	501–700	351–500	401–600	251–400	151–250	0–200

Table 11
The optimal routes for collecting the waste.

Waste type	Vehicle no.	Optimal route	Load's quantity (ton)	Route length (km)
Recyclable	1	0→6→4→2→8→9→0	738.3	37
	2	0→11→13→18→17→20→16→12→0	951.7	48
	3	0→22→30→28→24→25→0	671.6	83
Non-recyclable (incineration)	4	0→6→4→2→8→5→0	945.1	39
	5	0→11→13→18→17→20→15→0	1062.5	42
	6	0→22→30→28→24→29→19→0	837.1	89
Non-recyclable (chemical)	7	0→6→4→2→8→14–0	884.2	49
	8	0→11→13→18→17→20→21→0	1129.1	43
	9	0→22→30→28→24→26–0	840.7	85
Non-recyclable (incineration & chemical)	10	0→6→4→2→8→5→0	652.4	39
	11	0→11→13→18→17→20→21→0	746.8	43
	12	0→22→30→28→24→29→19→0	563.9	89

Table 12
The optimal decisions for transporting the waste residues and operations at the facility centers.

Waste residues transportation		Waste operation			
Route	Load's quantity (ton)	Facility	The quantity operated waste at each facility	Facility	The quantity operated waste at each facility
14→12	164.5	1	133.1	19	2083.5
21→16	157.3	3	1715.5	21	1632.3
26→25	98.7	5	2150.8	23	6294.7
14→7	1050.9	7	10,340.9	25	1548.2
21→27	1183.1	9	1593.4	26	1841.9
26→23	1095.5	10	–	27	7296.5
9→7	720.8	12	1826.1	29	1235.1
12→7	985.3	14	1974.8		
16→27	542.2	15	2341.6		
25→23	938.6	16	1796.7		

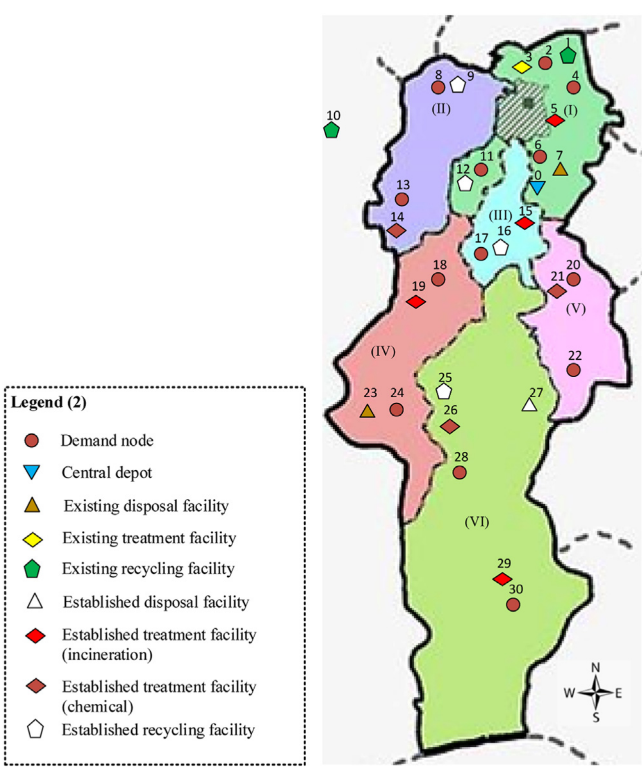

Fig. 3. The schematic illustration of the optimal solution for the real case study.

of the facilities in the schematic illustration are listed from 0 to 30. As one can see, Table 11 illustrates the optimal collection routes for each type of waste, where each vehicle begins from the central depot, continues its path to collect the generated waste from the demand nodes, and then it goes to the corresponding facility (recycling or treatment facility) to empty its load, and finally, it returns to the central depot. For example, truck No.1, as indicated in Table 11, starts its route from the central depot, then goes to the demand nodes 4, 6, 2, and 8 to collect the generated waste, and since the collected waste type is recyclable waste, it unloads its load at the recycling center 9 and terminates at the central depot. To verify the feasibility of the model, the quantity of collected waste and the length of the tour are measured. After operating the waste at the treatment facilities, the recyclable percentage of the waste is shipped to the recycling facility, and the remaining one is sent to the disposal facility. Moreover, at the recycling facility, a percentage of disposable waste is delivered to the disposal facility. Table 12 indicates the optimal decisions related to this stage of the problem. It is noteworthy to mention that recycling number 10, which is one of the two existing recycling facilities, was excluded from the network in the optimal solution since no amount of generated waste is delivered to this facility. In the optimal solution, due to the transportation costs, transportation and location risks, and CO_2 emissions, it was more sustainable to establish a new recycling facility than to transport hazardous waste to this facility. The optimal function values are 34,481 million Tomans, 5218.4 km * people, and 23,381.4 tons, for the costs, risks and CO_2 emissions, respectively, when separately, each objective function is minimized.

4.3. Sensitivity analysis and discussion

The case study results are based on the assumptions on the values of some parameters, such as the capacity level and the amount of generated waste accumulated at the demand nodes. To evaluate the sensitivity of the results to these parameters, different values of these parameters are considered as input parameters. The results and analyses are indicated in the following.

4.3.1. Non-sustainabile model

To indicate the impacts of sustainability, the results of the sustainable model are compared with the outputs of the non-sustainable one. In

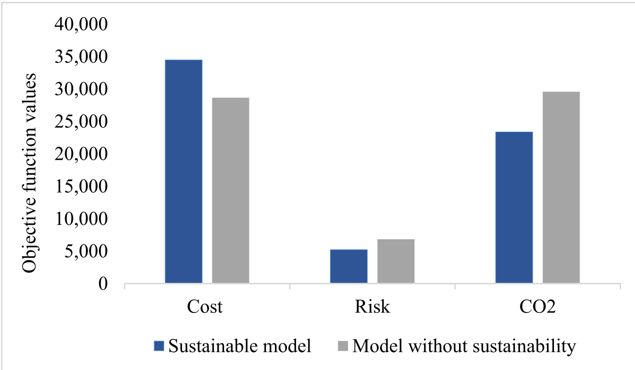

Fig. 4. A comparison of the objective function values.

the obtained optimal solution for the sustainable model, three recycling centers (recycling centers 12, 16, and 25) are established. Moreover, treatment center 15 is excluded from the optimal solution of the model without sustainability.

The optimal quantities of the objective functions in the model without sustainability are 28,639 million Tomans, 6831 km * people, and 29,571.1 tons, for the costs, risks, and CO_2 emissions, respectively, when each objective function is individually minimized. Fig. 4 shows a comparison of the objective function values of the sustainable model with the model without sustainability.

The sustainable model's results are then compared to the results of the non-sustainable model. The comparison indicates that considering the optimal values of the objective functions, the cost of establishing facilities and transportation decreased, but the site and transportation risk, along with the CO_2 emissions, increased. Since the risk and CO_2 emissions are too critical in the management system of hazardous waste, each of which can pose a big threat to the system, it is not desirable to run a model without sustainability. These findings imply the significance of sustainability in the HWLRP.

4.3.2. Impact of capacity level

As mentioned earlier, according to the generated waste in each region, the facilities were established with different capacity levels. Next, to investigate the impact of the capacity level on the facility, three scenarios were considered associated with those decision variables, which are related to the capacity level. These three scenarios are as follows: (1) remove the capacity level from the model, (2) increase the capacity level, and (3) decrease the capacity level. Then the results obtained by solving the model associated with each scenario are compared with the outcomes attained through the considered original capacity level. In the first scenario, the obtained results indicate that under the condition that the problem does not consider capacity planning, the total costs of the system, with the inclusion of investment costs, are raised by 5.88%. This matter happened because, in this instance, one more facility, a recycling facility, was established in the district (V). In addition, the second (minimizing site and transportation risk) and third (minimizing CO_2 emissions) considered objective functions are increased by 3% and 1.5%, respectively. In the second scenario, when the capacity level is increased to (10,15,20), the total costs of the system decreased by 6.3% because recycling facility 16 and treatment facilities 15 and 26 were excluded from the optimal solution. However, the values of risk and CO_2 minimization objective functions increased by 2% and 1.8%, respectively. Finally, in the last scenario in which the capacity level is decreased to (4,7,10), the obtained result indicates that under the condition of a decreasing capacity level, the overall costs of the system, comprising transportation and investment cost, increased by 8.4%. This matter mainly happens because by decreasing the capacity level, 1 recycling and 2 treatment facilities were added to the system. Moreover, the second and third objective functions increased by 2.5% and 2.1%, respectively. Fig. 5 shows the increase and decrease of the three objective functions under three scenarios compared to the original capacity level condition. Finally, one can conclude that taking the capacity level into account for the facilities prevents imposing additional costs, and it also decreases the risks and CO_2 emissions, which in turn contributes to having a more sustainable system.

4.3.3. Impact of the amount of generated waste

In our case study, the input parameters, for instance, the amount of generated waste, are taken from the Babol Waste Management Organization's official reports. Even though the amount of generated waste in the case study was from the official report of the Babol Waste Management Organization, this amount is a fixed amount. Some unprecedented happening may change the amount of generated waste in the health sec-

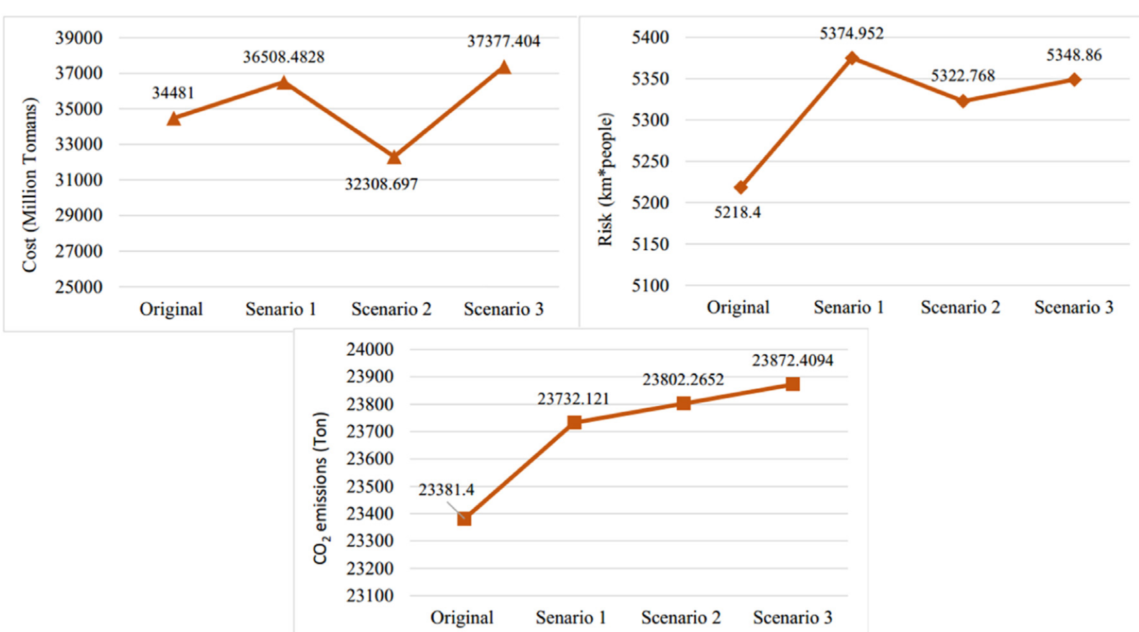

Fig. 5. Sensitivity analysis of the objective function values w. r. t. changes in the capacity level.

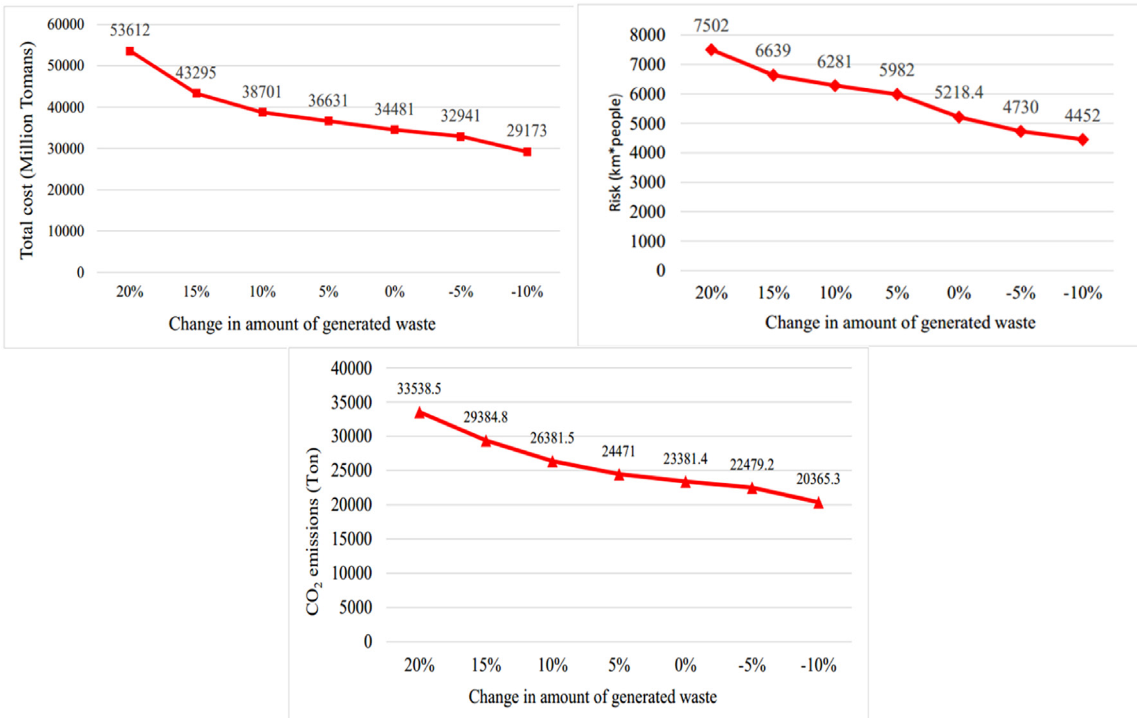

Fig. 6. Sensitivity analysis of objective functions value w. r. t. changes in the amount of generated waste.

tor or industrial processes. For instance, nowadays, a widespread pandemic, COVID-19, affects the whole world, and it causes the generation of a considerable amount of infectious waste, which is characterized as hazardous waste. This shows the importance of evaluating the sensitivity of the model in dependence on the amount of generated waste. In order to evaluate the sensitivity of the model depending on the amount of generated waste, the original amount was both decreased and increased by some percent to see its impact on the value of the objective function. According to the data from Fig. 6, there is a direct correlation between the change and the values of the objective functions. To be more specific, the results indicate that a minor shift in the waste amount can have a positive effect on all objectives.

4.4. Managerial and theoretical insights

The purpose of our study was the design of a proper HWMS with regard to the total costs, transportation, site risk, and CO_2 minimization. According to previous works in the hazardous waste management field, the lack of a strategic plan and proper financial assignment are the main concerns in Babol City [52]. Based on the optimal results of this study, the following points would help the managers in the Babol Municipal Waste Management Center (BMWMC) to improve the HWMS.

- A lack of recycling, treatment, and disposal facilities leads to improper disposal of hazardous waste, which poses a major threat to both the environment and human beings. To remove these threads, many facilities at each center should be established. Fig. 3 and Table 10 present the optimal solutions which can help the managers in finding the best locations. For example, a new treatment center (treatment center 21) should be established in the district (V).
- In the existing network, most of the transportation routes are among the most populated areas to shorten the length of the routes for delivering the waste; however, it increases the associated transportation risk. It is recommended that BMWMC uses the optimal route, as shown in Table 11, for collecting the waste. For instance, truck number 1, which delivers recyclable waste, should start from the central depot, then it goes to the demand nodes 6, 4, 2, and 8, respectively, and then unloads its waste at treatment facility 5, and finally, it returns to the central depot.
- As an independent organization, BMWMC tries to minimize its total costs without considering the risk of CO_2 emissions, which causes a major problem for our environment or health. As we showed in Section 4.3.1, considering other factors like risk and emission can lead to a better solution, even though the cost increases. Therefore, it is recommended that the government helps BMWMC with its financial aid to take these critical factors into account.

Also, the proposed model for the hazardous waste location-routing problem offers several theoretical benefits. It integrates sustainability aspects by simultaneously considering economic, environmental, and social dimensions, ensuring a comprehensive waste management system. The model focuses on minimizing CO_2 emissions from waste, waste residues, and transportation systems, contributing to environmental conservation and climate change mitigation. Additionally, the model introduces capacity planning for facilities, optimizing resource allocation and operational efficiency. It addresses different types of hazardous waste and their incompatibility, promoting safer waste handling and transportation. Through a real case study, the model provides practical insights and managerial implications, as well. Overall, the model fills research gaps and enables decision-makers to explore trade-offs between objectives, supporting the design of efficient and sustainable hazardous waste collection systems.

5. Concluding remarks and future study

This research developed a mixed-integer nonlinear programming (MINLP) model to handle the problem of hazardous waste location-routing under sustainable conditions. Having used a network with multiple types of hazardous waste, a multi-objective model is designed for the on-hand problem. The proposed plan specifies the locations of the facilities, the transportation routes for collecting the generated waste and delivering it to the facilities, and the quantity of various types of waste and waste deposits transported between the facilities.

To illustrate the validation of the developed plan, a real-world case study in Babol City was presented. The case study includes six districts and 13 demand nodes, where the generated waste is accumulated at these nodes and then collected with a heterogeneous fleet of vehicles to transfer them to the associated facilities. The model was solved with the CPLEX solver in the GAMS optimization software v. 24.1. In the optimal solution, four new recycling facilities, seven new treatment facilities, and one new disposal facility with defined capacity levels were added to the existing network. To demonstrate the importance of sustainability, the results are compared before and after sustainability. The results showed that in the model, without considering sustainability, total costs, transportation, and site risks along with the CO_2 emissions increased, which is not desirable for a waste management system. These results emphasized the importance of sustainability in an HWMS. In addition, to investigate the sensitivity of the model, a sensitivity analysis was performed on two parameters, including the capacity level and the amount of generated waste. The results showed that when the capacity level is removed or decreased, the values of all three objective functions increase. When the capacity level increased, the total costs decreased because fewer facilities were established. However, the risk and CO_2 emissions increased. Moreover, there was a positive correlation between the amount of generated waste and the three objective function values, which means when the amount of generated waste increases (decreases), the values of all three objective functions increase (decrease). Finally, some managerial insights for hazardous waste management authorities are extracted from the final results.

In the future, this study can be extended in several ways. First, since many parameters, such as the amount of generated waste, are unknown, a stochastic version of the study is a good venue to address uncertainty. Second, future works can be conducted by developing and implementing meta-heuristic algorithms for solving large-sized problems. Third, incorporating time window limitations on the vehicle routes can be another features for extending the model. Another stream could be taking different objectives into account simultaneously and employing techniques such as revised multi-choice goal programming in which a particular aspiration level should be satisfied for each objective [53]. Finally, due to the global outbreak of the COVID-19 pandemic, which increases the amount of hazardous waste in health sectors and hospitals, considering this pandemic for the design of an efficient hazardous waste collection system will lessen the spread of COVID-19. Eq. (1)-(3), Eq. (11), Eq, (37)-(44)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.susoc.2023.11.001.

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