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# A Green Hazardous Waste Location-routing Problem Considering the Risks Associated with Transportation and Population

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*ABSTRACT*

The researches on environmental and sustainability are an active topic, especially in the waste management. As such, the hazardous waste optimization is an active research topic in developing countries which may be integrated with carbon emissions and green subjects. This grand challenge motivates the current research to contribute a new multi-objective optimization model to address the green hazardous waste location-routing problem. The proposed multi-objective optimization model establishes four objectives simultaneously for the first time. In addition to the total cost and the greenhouse gas emissions of the transportation systems as the two main objectives, another objective function aims to minimize the risk of transportation of the hazardous waste alongside the waste residue associated with the people's exposure around transportation paths. Furthermore, the total risk linked with the population in a certain radius around the treatment and disposal centers is minimized. As the proposed model is complex with conflicting objectives, several multi-objective decision making (MODM) tools are employed and compared with each other based on different test problems associated with an industrial example. Based on the solution quality and the computational time, the technique for the order of preference by similarity to the ideal solution (TOPSIS) is selected as the strongest technique to assess the performances of all five MODM methodologies.

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## 1. INTRODUCTION

Industrial hazardous waste and disposal are an active research topic in developing countries. The logistics of hazardous waste management is naturally complex regarding the transport network; increasing sensitivity to the costs of environmental impact; the practical limitations that often govern the location of processing facilities [1], the source of waste streams, recycling options, and the complexities of transportation management [2]. Regarding the challenge of transportation management [3], the largest source of pollution and environmental concerns in the logistics system is a significant optimization problem within itself.

As known, hazmat, i.e., the industrial hazardous substances resulted from many manufacturing processes, is a dangerous and toxic posing risk to people most notably in developing countries [4]. Thus, the management of hazardous material substances including a series of actions such as systematically collecting, transporting, treating, recycling and disposing of hazardous substances, is very operational for governments and strategic for environmentalists [5]. The logistic activities of the hazmat motivated several studies to develop efficient optimization models and algorithms to be computationally manageable [6-8]. Although many studies have recently contributed to this research area, green hazardous waste optimization is still an open issue and scarce.

The current study has been motivated by the main needs and benefits of having an efficient green hazardous waste location-routing system that minimizes four

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objectives including the total cost, the total carbon emissions, as well as the risk associated with the transportation and the population in a certain radius around treatment and disposal centers. This study also considers a stochastic budget constraint estimated by a normal distribution to report more practical results for the first time. In addition, dealing with four conflicting objectives provides further practical results for the decision-makers of the hazardous waste management. Besides, based on the sustainable development paradigm which is of particular concern in developing countries, it is essential for managers to consider the risks of transportation and population to improve the reliability of the system as social factors in addition to the economic and environmental impacts of hazardous waste management. Hence, the present study can add some values to the literature.

As one of well-known studies in the area waste location-routing problem, with the supposition of the site and the flow of the hazardous waste between facilities as decision variables, a mathematical model was introduced by Cappanera et al. [9] to address the problems associated with the location and routing of the hazardous materials. In order to decompose the proposed model into location and routing sub-problems, they employed the Lagrangian relaxation approach and recommended a branch-and-bound solution method to reduce the gap existing among the lower and upper bounds by using an adaptive technique. Similarly, a multi-objective integer model was proposed by Nema and Gupta [10] for this problem. They took into consideration the location of the treatment centers as well as the disposal centers and the transportation routes whereby the hazardous wastes and the waste residues are transported from the origin nodes to the treatment and the disposal facilities as decision variables. This model was made by the purpose of reducing the overall transportation costs as well as reducing the risks associated with the transportation vehicles and facilities. Later in 2005, another multi-objective optimization approach for the hazardous waste location-routing problem was developed by Zhang et al. [11]. Their model aimed to reduce the total costs and the possible risks. They utilized a multi-objective optimization approach to help decision-makers in evaluating the location-routing decisions related to hazardous wastes. Furthermore, a mathematical model was proposed by Ahluwalia and Nema [12] to design an integrated computer waste management system by introducing a decision-support tool to select the optimal facility configurations related to the computer waste management. This included storing, treating, recycling, disposing and allocating the waste to the facilities. As an integer linear programming, their proposed model aimed to reduce environmental risks and the total costs. They used the Monte Carlo simulation technique to address the uncertainty of the amount of waste.

In a survey, Nagy and Salhi [13] conducted comprehensive research elaborating on the location-routing models and their exact and heuristic solution methods. A mathematical model was also developed by Emek and Kara [14] for the problems of the hazmat by considering variables such as disposal mode, the site of the disposal plants, as well as the routes whereby the hazmat was transported. Their research contributed to the body of knowledge by introducing a mathematical model that could select the disposal method to control air pollution and meet international standards. This was accomplished by using the Gaussian Plume equation to measure air pollution at the population centers.

As one of the earliest studies in the area of hazardous waste routing optimization with time windows, Berman et al. [15] proposed an optimization model that aimed at minimizing the network’s overall costs. They solved the problem using a branch-and-price algorithm. In order to evade exposing a given population with hazmat or to impose a security measure, sometimes, the transportation company of the hazardous materials aims to find a set of routes with almost equal performance such that it will be able to switch among various routes. For this problem, Dadkar et al. [16] used a K-shortest path algorithm in which the performance of the highway facility was stochastic and could change over time considering each objective function separately. To obtain a proper trade-off between the geographic diversity and the performance, they offered a Mixed Integer Linear Programming (MILP) to determine a subset of paths.

As indicated recently in the literature, there is still a great deal of interest in developing optimization models and algorithms to address hazardous waste optimization problems. Since there are many reviews in the area of logistics of industrial hazardous waste [1, 4, 17, 18]; here, only recent advances and relevant works in this research area are collected and exposed as follows.

Recently, Xie et al. [19] proposed a multi-modal location and routing problem for the transportation of hazmat materials. They elaborated on a case study in the north of China to address a model that considers multi-commodity flow. Most notably, they only considered the total cost as the objective function to be minimized. Alongside dealing with greater complexity in terms of the problem description, the limitations of considering just a single optimization objective function have also been manifested. Vidovi´c et al. [20] proposed an extended MILP model to optimize the economic benefits in a two-echelon logistics network that comprised the collection points, transfer stations, and end-users. Harijani et al. [21] applied a bi-objective MILP model to balance economic profit with qualitative, non-economic cost criteria. Another bi-objective MILP model was proposed by Asefi and Lim [22] to optimize transportation costs against time factors. Practical applications of bi-objective optimization have also been proposed to select the optimal locations and allocations of waste facilities in Tehran, Iran [23]. Tehran was also the case study location for the research by Edalatpour et al. [17] which optimized an overall economic and environmental cost against various aspects of a comprehensive waste management network, including recycling and remanufacturing. At last but not least, another case study in Tehran was examined by Rabbani et al. [1] who proposed a location-routing problem for the case of hazardous materials. Their mathematical model dealt with different types of incompatible waste and took into account the aspects related to adaptation/compatibility with the treatment technologies. Another contribution of their work was related to the use of a heterogeneous transportation system to collect wastes compatible with their loads. In another study, Mahmoudsoltani et al. [4] tackled another realistic and practical issue in the field of management of hazardous materials. They considered several types of transportation routes such as roads or pipelines in which two objective functions including the total cost and risk were considered to be minimized. To solve the problem, they utilized three well-known multi-objective evolutionary algorithms. Moreover, Ebrahimi [24] proposed a multi-objective optimization model considering the sustainability aspects based on the triple line to assess the tire supply chain with discount supposition. An epsilon constraint method was applied in their work to solve a real case of the tire industry in Iran. Mohammadi et al. [18] provided a mixed-integer nonlinear programming model for the locating-routing problem of hazardous wastes. The components of their proposed logistic network were the manufacturers of hazardous waste and the disposal centers. Their model considered the risk of facility failure in addition to the consideration of the accidents due to the transport of hazardous wastes. To handle these uncertainties, they applied a chance-constrained and possibilistic programming approach. They employed a metaheuristic algorithm to find a near-optimal solution to their NP-hard problem. Their model was validated by a case study in Iran. However, despite Mahmoudsoltani et al., [4] and Rabbani et al. [1], this model did not consider the possibility of transport for the hazardous waste by pipelines and the transportation time and the reliability of the routes being selected. They did not assume different types of vehicles with different capacities either.

More recently, Hu et al. [25] proposed a multi-objective optimization model to seek out the optimal routes for hazardous wastes with traffic restrictions. This paper assumed multiple paths between every possible origin-destination pair. Another contribution was to develop an adaptive weight genetic algorithm. In another recent paper published by Rabbani et al. [26], a stochastic multi-period industrial hazardous waste location-routing-inventory problem considering the risk of transportation was proposed. To solve their NP-hard problem, a sim-heuristic method by combining a non-dominated sorting genetic algorithm and Monte Carlo simulation was used. At last but not least, Pouriani et al. [27] developed a bi-level and robust optimization method to model the municipal solid waste management. Based on their proposed model, the establishment costs of solid waste collection centers were assumed at the lower level and the allocation of the waste to the various centers at the upper level. They validated their model in a case study in Babol, Iran. At last but not least, Delfani et al. [28] proposed a robust-possibilistic programming for a waste location-routing problem with the risk of transportation.

In order to have a conclusion, the aforementioned papers are classified based on the objective functions and the constraints utilized. This classification is given in the Electronic Supplementary Materials F1. The titles of the columns in this table are related to the type of the model, the objective functions, and the characteristics of the model. From the previous studies, there are six common objective functions including the total cost, carbon emissions, customer satisfaction, risk of transportation, risk of population, and the time of loading. The model's characteristics are related to the decisions obtained by the model based on the location, allocation, routing and inventory decisions. Some other suppositions are the use of uncertainty modeling such as stochastic or robust optimization, budget constraint, traffic restriction, technology selection for recycling, GIS model, multi-commodity and time windows. Based on these criteria, the following observations are identified:

- Fourteen studies considered multi-objective decision-making models.
- In addition to the total cost, the risk of transportation is well-studied as the second objective function in the literature.
- The location, allocation and routing decisions are considered in the majority of studies.
- Uncertainty modelling approaches are well-studied in many old and recent works.
- Carbon emissions are considered in three papers in addition to the current study.
- There is no study to consider the risk of transportation and population simultaneously.
- Only the present study considers the total cost, the risk of transportation and population in addition to the carbon emissions simultaneously.
- Inventory decisions, budget constraints, and traffic restrictions are still scarce in the literature.

Generally speaking, having increasing concerns about global warming, international rules urge the countries to minimize their total carbon emissions. Therefore, developing a green hazardous waste location-routing model seems worthy of investigation. To this end, this study establishes a multi-objective optimization model for the hazardous waste location-routing problem considering greenhouse gas emitted by the transportation system as well as the risks associated with transportation and population. Briefly, the main highlights of this research article can be listed as follows:

- A new multi-objective optimization model for a green hazardous waste location-routing problem is developed.
- Four objectives based on the total cost, the carbon emissions, the risk associated with the transportation and population are contributed simultaneously.
- A stochastic budget constraint is applied to the proposed problem.
- Five well-established MODM techniques are employed to solve the model
- The MODM techniques are ranked using the TOPSIS method.

The structure of the rest of this paper is as follows. In section 2, the problem is explicitly defined and the mathematical formulation of the problem is given. Section 3 introduces some solution approaches, where some comparison measures are defined. Computational results are provided in section 4 in which the TOPSIS method is used to rank the solution approaches. Section 5 contains the results of some sensitivity analyses to determine the impacts of varying the main parameters of the model on the values of the objective functions. Finally, conclusions alongside some recommendations for future research are given in section 6.

## 2. PROBLEM DESCRIPTION AND MATHEMATICAL FORMULATION

The flow of the hazardous wastes in the network starts from their origin (generation) nodes. Then, making use of different transportation modes, the non-recyclable hazmat is sent to the treatment facilities with well-suited machinery whereas the recyclable hazardous wastes are transported to the recycling facilities. The treatment facilities send the recyclable waste residues to the recycling facilities; on the other hand, the non-recyclable ones are sent to the disposal facilities. Besides, the waste residues of the recycling facilities are sent to the disposal centers. An overview of the hazmat management network is exhibited in Figure 1.

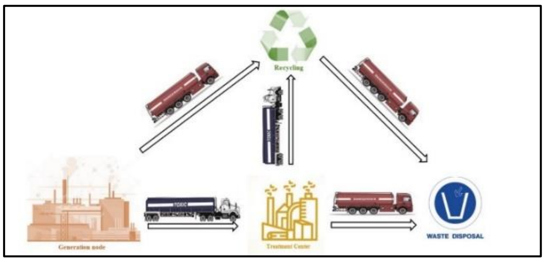

**Figure 1.** An overview of the hazmat management network

As discussed earlier, this study follows a sustainable development paradigm for developing countries. Sustainability seeks to optimize the economic, environmental, and social impacts simultaneously. These goals conflict with each other in the majority of cases. As a result, a solution obtained by optimizing one objective does not cover all sustainability factors. Hence, multi-objective decision-making is needed. This study minimizes the total cost as the economic factor and carbon emissions as environmental impacts. To cover the social objectives, the current work focuses on the risks of transportation and population as two conflicting objectives.

Currently, up to our knowledge, there is no similar model to solve the location, routing, and transportation problems in a hazardous waste management network that simultaneously considers the greenhouse gas emissions in addition to the risks associated with transportation and population. As such, a multi-objective mathematical model is aimed for the green hazardous waste location-routing problem at hand to answer the following questions:

- ✓ Which technology could be established in which treatment centre?
- ✓ Which vehicle of a type and capacity could be used to route hazardous waste to treatment centres?
- ✓ Where to locate the disposal facilities?
- ✓ How to route waste residues to disposal facilities?
- ✓ Where to locate recycling facilities?
- ✓ Which vehicle type and capacity should be used to transport the produced hazardous waste from the generation nodes and the waste residues to the recycling centres?
- ✓ How many vehicles of different types are required in each hazardous waste generation node to transport hazardous waste to treatment centres?
- ✓ How many vehicles of different types are required in each hazardous waste generation node to transport hazardous waste to recycling centres?
- ✓ How many vehicles of different types are required in each treatment centre to transport hazardous waste to recycling centres?

The notations are given in Electronic Supplementary Materials F2. The developed mathematical model of the problem that simultaneously minimizes four objective functions Z1, Z2, Z3 and Z4 alongside proper constraints is presented as follows:

$$\begin{aligned} Min\, Z1 = & \sum_{w}\sum_{g}\sum_{t}\sum_{v} c_{gtv} x_{wgtv} \\ & + \sum_{t}\sum_{d} cz_{td}\, z_{td} \\ & + \sum_{h}\sum_{d} cv_{hd} v_{hd} \\ & + \sum_{g}\sum_{h}\sum_{v} cr_{ghv} l_{ghv} \\ & + \sum_{t}\sum_{h}\sum_{v} crr_{thv} k_{thv} \\ & + \sum_{q}\sum_{t} fc_{q,t}\, f_{qt} \\ & + \sum_{d} fd_{d} dz_{d} \\ & + \sum_{h} fh_{h} b_{h} \end{aligned} \tag{1}$$

$$Min\,Z2=\sum_{w}\sum_{g}\sum_{t}\sum_{v} popgt_{gt}x_{wgtv} + \sum_{t}\sum_{d} poptd_{td}z_{td} \tag{2}$$

$$Min\,Z3=\sum_{w}\sum_{q}\sum_{t} popa_{qt}y_{wqt}+\sum_{d} popb_{d}dis_{d} \tag{3}$$

$$Min\,Z4=\sum_{w}\sum_{g}\sum_{t}\sum_{v} n_{wgtv}dgt_{gt}cc_{v} + \sum_{g}\sum_{h}\sum_{v} n_{ghv}dhv_{gh}cc_{v} + \sum_{t}\sum_{h}\sum_{v} n_{thv}dth_{th}cc_{v} \tag{4}$$

*s.t.*

$$gen_{wg}=\alpha_{wg}gen_{wg}+\sum_{t}\sum_{v}x_{wgtv} \qquad \forall g,w \tag{5}$$

$$\sum_{w}\alpha_{wg}gen_{wg}=\sum_{h}\sum_{v}l_{ghv} \qquad \forall g \tag{6}$$

$$\sum_{g}\sum_{v}x_{wgtv}=\sum_{q}y_{wqt} \qquad \forall w,t \tag{7}$$

$$\sum_{w}\sum_{q}y_{wqt}(1-r_{wq})(1-\beta_{wq})=\sum_{d}z_{td} \qquad \forall t \tag{8}$$

$$\sum_{w}\sum_{q}y_{wqt}(1-r_{wq})(\beta_{wq})=\sum_{h}\sum_{v}k_{thv} \qquad \forall t \tag{9}$$

$$\sum_{t}\sum_{v}k_{thv}+\sum_{g}\sum_{v}l_{ghv}=\mathrm{hr}_{h} \qquad \forall h \tag{10}$$

$$\mathrm{hr}_{h}(1-\gamma_{h})=\sum_{d}v_{hd} \qquad \forall h \tag{11}$$

$$\sum_{h}v_{hd}+\sum_{t}z_{td}=dis_{d} \qquad \forall d \tag{12}$$

$$\sum_{w}y_{wqt}\le tc_{qt}f_{qt} \qquad \forall q,t \tag{13}$$

$$\sum_{w}y_{wqt}\ge tcm_{qt}f_{qt} \qquad \forall q,t \tag{14}$$

$$y_{wqt}\le tc_{qt}Com_{wq} \qquad \forall w,q,t \tag{15}$$

$$dis_{d}\le dc_{d}dz_{d} \qquad \forall d \tag{16}$$

$$dis_{d}\ge dcm_{d}dz_{d} \qquad \forall d \tag{17}$$

$$\mathrm{hr}_{h}\le rc_{h}b_{h} \qquad \forall h \tag{18}$$

$$\mathrm{hr}_{h}\ge rcm_{h}b_{h} \qquad \forall h \tag{19}$$

$$n_{wgtv}\ge\frac{x_{wgtv}}{Cap_{v}} \qquad \forall w,g,t,v \tag{20}$$

$$n_{ghv}\ge\frac{l_{ghv}}{Cap_{v}} \qquad \forall g,h,v \tag{21}$$

$$n_{thv}\ge\frac{k_{thv}}{Cap_{v}} \qquad \forall t,h,v \tag{22}$$

$$P\left\{\sum_{w}\sum_{g}\sum_{t}\sum_{v}n_{wgtv}\,\mathrm{Cos}\,t_{v}+\sum_{g}\sum_{h}\sum_{v}n_{ghv}\,\mathrm{Cos}\,t_{v}\sum_{t}\sum_{h}\sum_{v}n_{thv}\,\mathrm{Cos}\,t_{v}\le Budget\right\}\ge\psi \tag{23}$$

$$x_{wgtv}\ge 0 \qquad \forall w,g,t,v \tag{24}$$

$$l_{ghv}\ge 0 \qquad \forall g,h,v \tag{25}$$

$$k_{thv}\ge 0 \qquad \forall t,h,v \tag{26}$$

$$y_{wqt}\ge 0 \qquad \forall w,q,t \tag{27}$$

$$z_{td}\ge 0 \qquad \forall t,d \tag{28}$$

$$v_{hd}\ge 0 \qquad \forall h,d \tag{29}$$

$$dis_{d}\ge 0 \qquad \forall d \tag{30}$$

$$\mathrm{hr}_{h}\ge 0 \qquad \forall h \tag{31}$$

$$f_{qt}\in\{0,1\} \qquad \forall q,t \tag{32}$$

$$b_{h}\in\{0,1\} \qquad \forall h \tag{33}$$

$$dz_{d}\in\{0,1\} \qquad \forall d \tag{34}$$

$$n_{wgtv}\ge 0,\ \mathrm{int} \qquad \forall w,g,t,v \tag{35}$$

$$n_{ghv}\ge 0,\ \mathrm{int} \qquad \forall g,h,v \tag{36}$$

$$n_{thv}\ge 0,\ \mathrm{int} \qquad \forall t,h,v \tag{37}$$

As mentioned earlier, the first objective function Z1 is established to minimize the overall costs including the total transportation expenditures and the fixed establishment costs as imposed on the treatment, disposal, as well as recycling centers. The second objective function Z2 is meant to minimize the transportation risk of hazardous waste as well as waste residues associated with the people's exposure around transportation paths. The third objective function Z3 is aimed to minimize the total risk related to the population living in a certain distance around treatment and disposal centers. Finally, the fourth objective function Z4 is defined to lessen the total carbon emission of the transportation system. Besides, Constraints (5-7) balance the flow of the hazardous waste from the generation nodes to the treatment and recycling facilities and waste residue from the treatment facilities to the recycling centers. Constraints (8-9) take into account the recycling proportion of the hazardous waste treated by treatment technologies and recycled hazardous waste proportion at the recycling centers. Constraint (10) ensures that the total amount of the waste recycled at each recycling center is equal to the flow arriving from the treatment facilities and the generation nodes to that recycling center. Constraint (11) determines the quantity of the waste residue sent from each recycling center to each disposal center. Constraints (12) guarantee that the sum of the waste sent to each disposal center is equal to the incoming flow from treatment centers and recycling nodes. Meanwhile, Constraints (13-19) present the capacity constraints of the treatment, the recycling, and the disposal nodes and the minimum required quantity of the hazardous waste and waste residue to establish or open the treatment, recycling and disposal facilities. Constraints (20-22) determine the number of each type of transportation vehicle in each center while considering the capacity of each type of vehicle. Constraint (23) presents the budget constraint which is assumed to limit the total fixed cost of the transportation system. As it is assumed in this research that the budget follows a normal distribution [25]. Constraint (23) can be written as follows:

$$\begin{aligned}&\sum_{w}\sum_{g}\sum_{t}\sum_{v} n_{wgtv}\,\mathrm{Cos}\,t_v\\&+\sum_{g}\sum_{h}\sum_{v} n_{ghv}\,\mathrm{Cos}\,t_v \sum_{t}\sum_{h}\sum_{v} n_{thv}\,\mathrm{Cos}\,t_v\\&+Z_{\psi}\sigma_{Budget} \le \mu_{Budget}\end{aligned} \tag{38}$$

## 3. SOLUTION METHODS

An ideal solution for the recommended multi-objective optimization model shown in expressions (1-37) is capable of simultaneously minimizing all the objective functions; nonetheless, as these functions are typically in conflict with each other in most of the cases, an ideal solution cannot be determined [28-30]. In these cases, the decision-maker tries to find solutions that make good trade-offs among the objective functions. Such solutions are known as Pareto or efficient solutions.

There are two general methodologies to obtain efficient solutions of a multi-objective optimization problem, namely the multi-objective decision making (MODM) and the multi-objective optimization methods [29]. The first category of the solution methods aims to optimize the problem based on different approaches including minimization of the weighted deviation of the objective functions from the goals (the decision-maker specifies the best objective functions value) [30, 31]. In this method, the multi-objective optimization problem is changed to a single-objective optimization problem using some criteria. The second class of the solution methods provides numerous Pareto solutions to enable the decision-makers to choose a preferred one. As choosing a preferred solution among a certain set of Pareto solutions is cumbersome in many cases, in this research five MODM methods [30-32] have been selected to optimize the proposed multi-objective optimization problem. While in this paper an individual optimization method is first used to solve four single-objective optimization problems separately with the objective function values $Z_i^*; i = 1, 2, 3, 4$ representing their ideal solutions, these MODM methods are described as follows.

Due to page limitation, the details of the Lap-metric, goal attainment method (GA), Max-Min method, the goal programming method (GP) and the weighted sum method (WSM) are given in Electronic Supplementary Materials F3. The performances of the aforementioned five MODM methods are assessed in this paper in terms of the four averages they obtain for the four objective functions of the problem along with their required computational time (CPU-time) in seconds when they are used to solve some randomly-generated problems using the CPLEX solver provided in the GAMS software. Note that all experiments have been done on an INTEL Core 2 CPU with a 2.4 GHz processor and 2 GB of RAM.

## 4. COMPUTATIONAL RESULTS

Here, various test problems with diverse sizes are generated randomly. Table 1 tabulates the main parameters of the problems alongside the probability distributions used to generate random numbers. Note that the range of these parameters is taken from some case studies in Tehran as provided in the literature [1, 17, 23].

The generated problems are classified based on their sizes in terms of the indices (***g-t-w-d-h-q-v***) in Table 2. Besides, for every individual problem of small, medium and large sizes, three randomly-generated test problems are solved utilizing the aforementioned five MODM methods. As observed in Table 2, the average of each objective function value alongside the average CPU-time of each MODM method in solving these three randomly generated test problems in each size are reported. In addition, Figures 2-6 present a schematic view of the average values of the four objective functions as well as the CPU-time required by the five MODM methods in solving various test problems with different sizes.

The results in Table 3, as well as Figures 2-6, show that each solution method performs differently in terms of the five performance measures. That is why the TOPSIS method is utilized in the next section to choose an ideal solution algorithm.

**TABLE 1.** The main parameters of the problems

| Parameters | Distribution | Parameters | Distribution |
|---|---|---|---|
| $c_{gtv}$ | ~ Uniform (100,300) | $\beta_{wq}$ | ~ Uniform (0.2,0.7) |
| $cz_{td}$ | ~ Uniform (200,500) | $\gamma_h$ | ~ Uniform (0.2,0.3) |
| $cv_{hd}$ | ~ Uniform (50,200) | $tc_{qt}$ | ~ Uniform (1000,10000) |
| $cr_{ghv}$ | ~ Uniform (100,500) | $tcm_{qt}$ | ~ Uniform (20,100) |
| $crr_{thv}$ | ~ Uniform (50,500) | $Com_{wq}$ | ~ Uniform (0,1) |
| $fd_d$ | ~ Uniform (10000,30000) | $dc_d$ | ~ Uniform (1000,10000) |
| $fh_h$ | ~ Uniform (20000,40000) | $dcm_d$ | ~ Uniform (20,100) |
| $popgt_{gt}$ | ~ Uniform (100,300) | $rc_h$ | ~ Uniform (1000,10000) |
| $poptd_{td}$ | ~ Uniform (100,300) | $rcm_h$ | ~ Uniform (20,100) |
| $popa_{qt}$ | ~ Uniform (100,300) | $Cap_v$ | ~ Uniform (20,50) |
| $popb_d$ | ~ Uniform (100,300) | $\mathrm{Cos}t_v$ | ~ Uniform (100,500) |
| $dgt_{gt}$ | ~ Uniform (50,200) | *Budget* | ~Normal (15000,2000) |
| $cc_v$ | ~ Uniform (50,100) | $\alpha_{wg}$ | ~ Uniform (0.2,0.7) |
| $dhv_{gh}$ | ~ Uniform (50,200) | $r_{wq}$ | ~ Uniform (0.2,0.5) |
| $gen_{wg}$ | ~Uniform (100,500) | | |

**TABLE 2.** Results of solving various test problems

| Problem Size (*g-t-w-d-h-q-v*) | Method | Average $Z_1$ | Average $Z_2$ | Average $Z_3$ | Average $Z_4$ | Average CPU-Time |
|---|---|---|---|---|---|---|
| 5-5-3-5-5-3-2 | LP-Metric | 2673792.4 | 1493328.4 | 1484020.3 | 1304265.8 | 0.138 |
| | GA | 4520147.4 | 1927929.4 | 3855707.2 | 1090713.5 | 0.127 |
| | Max-Min | 4294688.5 | 2545882.8 | 2545882.8 | 3113495.1 | 0.112 |
| | GP | 3006386.2 | 1536061.1 | 1502934.9 | 1112638.2 | 0.139 |
| | WSM | 2895391.7 | 1720062.7 | 1490646.9 | 1084632.2 | 0.231 |
| 7-5-4-5-6-3-3 | LP-Metric | 3079834.1 | 1200036.5 | 1863539.3 | 1049942.6 | 0.250 |
| | GA | 4510677.3 | 2350515.4 | 3582271.6 | 5106643.2 | 0.128 |
| | Max-Min | 4181865.6 | 2776617.0 | 3036346.6 | 5028571.0 | 0.115 |
| | GP | 3233271.9 | 1163624.2 | 1821913.1 | 828606.4 | 0.212 |
| | WSM | 3149844.6 | 1224772.1 | 1819318.1 | 825386.2 | 0.137 |
| 10-7-4-7-8-5-3 | LP-Metric | 4755457.3 | 2814150.9 | 3510891.4 | 2372599.5 | 0.182 |
| | GA | 7066914.4 | 5209634.4 | 5209634.4 | 5287528.9 | 0.245 |
| | Max-Min | 8444197.8 | 5201881.0 | 5967626.7 | 7215629.0 | 0.290 |
| | GP | 4679416.3 | 2666911.5 | 3662147.6 | 3759724.7 | 0.250 |
| | WSM | 4734098.6 | 2789542.5 | 3498010.8 | 2367611.6 | 0.144 |
| 15-7-5-9-10-7-5 | LP-Metric | 8039154.6 | 4620117.0 | 4726292.5 | 2736342.5 | 0.366 |
| | GA | 12038899.2 | 8669810.7 | 8669810.7 | 9058031.2 | 0.355 |
| | Max-Min | 13704599.5 | 8642904.6 | 8642904.6 | 13079368.9 | 0.462 |
| | GP | 6853345.7 | 3805444.6 | 4824182.1 | 5388340.3 | 0.362 |
| | WSM | 7955229.1 | 4160111.4 | 4626702.7 | 2808197.6 | 0.475 |
| 20-8-5-10-10-10-5 | LP-Metric | 10318085.9 | 5760664.5 | 7166290.8 | 4428706.9 | 0.355 |
| | GA | 21618144.5 | 9862342.6 | 19724533.6 | 179219761.7 | 0.710 |
| | Max-Min | 18574876.9 | 14029805.3 | 14029805.3 | 20206683.4 | 0.494 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | GP | 10104969.2 | 5740334.0 | 6816704.1 | 6334490.5 | 1.500 |
| | WSM | 12426432.7 | 6482507.9 | 6976094.6 | 3252852.8 | 0.360 |
| 30-10-7-10-10-10-5 | LP-Metric | 17445805.3 | 10243985.7 | 12901088.8 | 10005779.0 | 83.224 |
| | GA | 40148141.9 | 17057454.0 | 32696605.2 | 250919945.7 | 20.083 |
| | Max-Min | 32611138.3 | 24407695.5 | 24407695.5 | 34621963.8 | 1.527 |
| | GP | 21306976.5 | 11173706.2 | 13076542.7 | 6949640.7 | 7.362 |
| | WSM | 20563552.7 | 12826761.5 | 12903291.1 | 6662785.9 | 79.152 |
| 40-15-10-15-15-10-10 | LP-Metric | 33221311.5 | 18853507.7 | 26124301.1 | 13938957.4 | 6.412 |
| | GA | 107019894.3 | 34614866.6 | 69229581.6 | 173206953.7 | 88.327 |
| | Max-Min | 78844422.2 | 50245262.6 | 51897268.8 | 58495892.6 | 37.030 |
| | GP | 36504031.0 | 19841243.0 | 26164440.5 | 11450607.3 | 29.490 |
| | WSM | 36251328.4 | 22087066.6 | 25887735.1 | 10995666.7 | 5.819 |
| 50-25-15-20-25-10-15 | LP-Metric | 75186465.4 | 35187220.7 | 55151734.7 | 41337166.2 | 1384.650 |
| | GA | 174753873.7 | 102331023.6 | 110323366.4 | 949672115.8 | 7233.314 |
| | Max-Min | 169836264.1 | 98540049.2 | 108687709.2 | 148843120.0 | 1100.457 |
| | GP | 70559920.7 | 34393191.6 | 52218221.1 | 323809940.1 | 821.461 |
| | WSM | 74837305.5 | 37235454.0 | 52278461.4 | 40406202.4 | 261.762 |

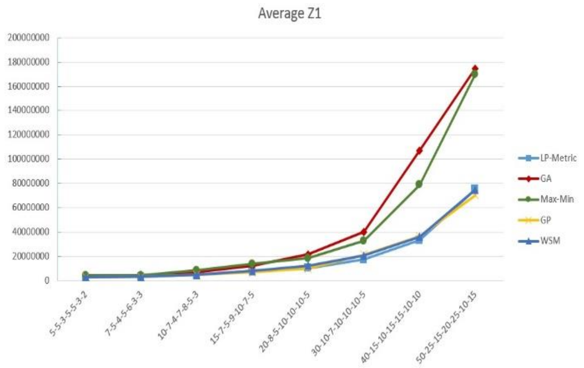

**Figure 2.** The average values of the first objective function

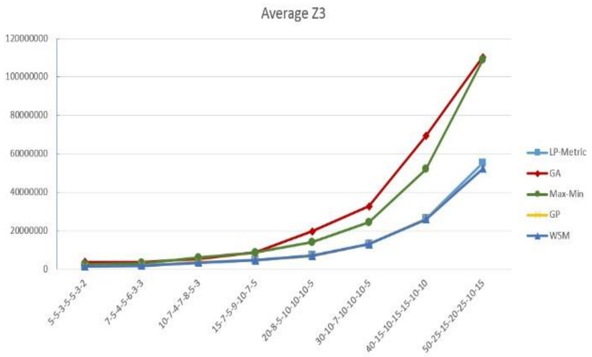

**Figure 4.** The average values of the third objective function

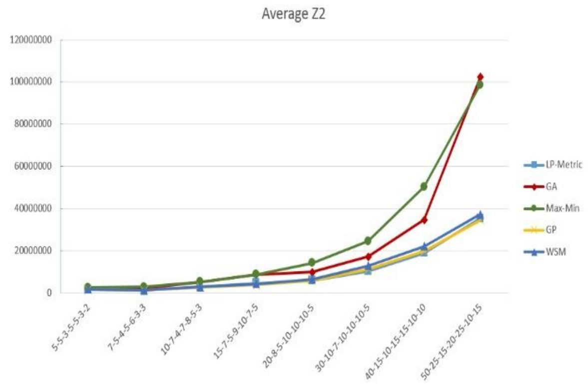

**Figure 3.** The average values of the second objective function

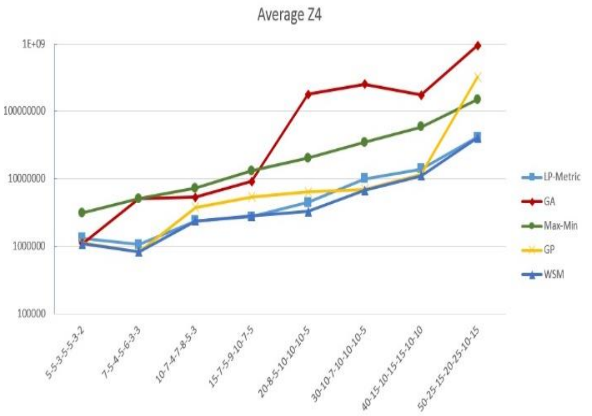

**Figure 5.** The average values of the fourth objective function

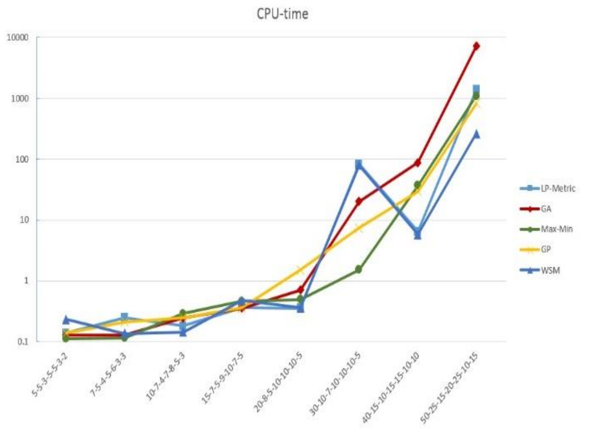

**Figure 6.** The average of the CPU Time

### 4. 1. TOPSIS Method

The TOPSIS has been introduced as a method to analyze multi-criterion decision making (MCDM) problems [31, 32]. Its main aim is to determine a substitute having the shortest (lengthiest) distance from the positive (negative) ideal solution. This study uses the TOPSIS method to provide a comparison between the performances of five multi-objective techniques and to rank them.

The first step involved in the TOPSIS method is to construct a decision matrix based on the MCDM methods (the aforementioned five solution methods) in the rows and the criteria (the aforementioned five performance measures) in the columns as shown in Table 3. Then, the other main steps shown in Figure 7 are taken in order to rank the methods in terms of all criteria simultaneously.

**TABLE 3.** The decision matrix

| Method | Average $Z_1$ | Average $Z_2$ | Average $Z_3$ | Average $Z_4$ | Average CPU-Time |
|---|---|---|---|---|---|
| LP-Metric | 19339988.3 | 10021626.4 | 14116019.9 | 9646719.99 | 184.447 |
| GA | 46459586.6 | 22752947.1 | 31661438.8 | 196695212 | 917.911 |
| Max-Min | 41311506.6 | 25798762.3 | 27401904.9 | 363255590.5 | 142.560 |
| GP | 19531039.7 | 10040064.5 | 13760885.8 | 44954248.5 | 107.597 |
| WSM | 20351647.9 | 11065784.8 | 13685032.6 | 8550416.93 | 43.510 |

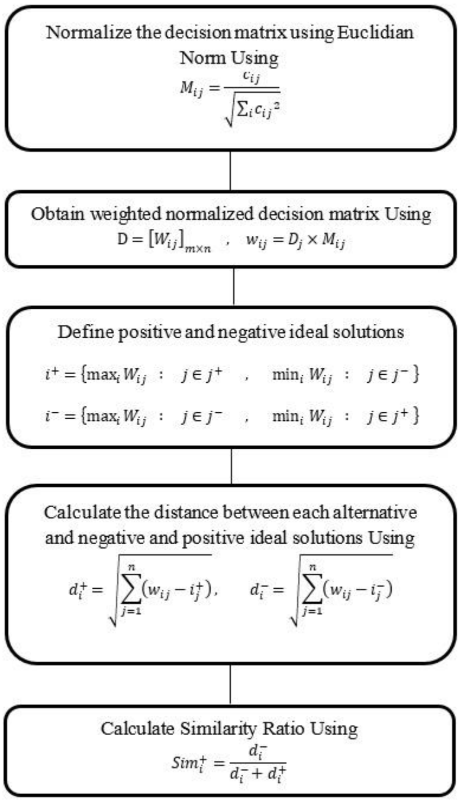

**Figure 7.** The main steps involved in the TOPSIS method [31]

In this regard, Table 4 summarizes the outcome of using the TOPSIS method to rank the solution methods.

As an MODM method with the largest similarity ratio is preferred by the TOPSIS approach, the results in Table 5 indicate that the LP-Metric with the similarity ratio of 0.5968 is the best solution method to solve the proposed MIP model of the problem at hand. Then, the GA, Max-Min, GP, and WSM are respectively the strongest methods.

## 5. SENSITIVITY ANALYSES

To investigate the impacts of the variations of the main parameters including $gen_{wg}$ (produced hazardous waste at generation nodes), $tcm_{qt}$ (Minimum required hazardous waste to open a treatment technology at a treatment center), Budget (total available budget), and $a_{wg}$

**TABLE 4.** The outcome of using the TOPSIS method

| | Ranking | Similarity Ratio |
|---|---|---|
| LP-Metric | 1 | 0.5968 |
| GA | 4 | 0.4532 |
| Max-Min | 5 | 0.4407 |
| GP | 3 | 0.5350 |
| WSM | 2 | 0.5501 |

(recycling hazardous waste proportion of a hazardous waste generated at a generation node) involved in the proposed model on the values of the four objective functions, some sensitivity analyses are carried out in this section. The variations are defined on the parameters at -50, -25, +25 and +50%. Table 5 tabulatizes the results of these sensitivity analyses.

The results in Table 5 indicate that a raise to $gen_{wg}$ significantly increases the values of all objective functions. In addition, a raise in $a_{wg}$ reduces such values, except the fourth objective function at +25%. Therefore, increasing $a_{wg}$ in real-world situations can significantly reduce the risk and the total costs of the hazardous waste management chain. Figures 8-11 present the results of the sensitivity analysis graphically.

Based on these results, a comprehensive discussion is provided in Electronic Supplementary Materials F4.

**TABLE 5.** The results of some sensitivity analyses

| Parameter | Change (%) | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ |
|---|---|---|---|---|---|
| $gen_{wg}$ | -0.50 | 3188728.083 | 1577780.467 | 2134800.210 | 811187.831 |
| | -0.25 | 4679161.857 | 2365633.986 | 3202200.315 | 1159575.453 |
| | +0.25 | 7328448.686 | 3942723.310 | 5337000.524 | 1810316.231 |
| | +0.50 | 8620702.546 | 4731267.972 | 6404959.368 | 2137879.202 |
| $tcm_{qt}$ | -0.50 | 6036194.825 | 3154178.648 | 4269600.420 | 1470499.116 |
| | -0.25 | 6036194.825 | 3154178.648 | 4269600.420 | 1470499.116 |
| | +0.25 | 6047022.743 | 3154178.648 | 4269600.420 | 1470499.116 |
| | +0.50 | 6223474.230 | 3154178.648 | 4269600.420 | 1490667.691 |
| Budget | -0.50 | 6374325.825 | 3155835.203 | 4269600.420 | 1665141.275 |
| | -0.25 | 6374325.825 | 3155835.203 | 4269600.420 | 1665141.275 |
| | +0.25 | 5837475.464 | 3154178.648 | 4269600.420 | 1470499.116 |
| | +0.50 | 6025591.583 | 3154178.648 | 4269600.420 | 1470499.116 |
| $\alpha_{wg}$ | -0.50 | 6019803.386 | 4174292.853 | 4649144.417 | 1479600.475 |
| | -0.25 | 5931821.639 | 3575031.875 | 4459372.418 | 1438653.828 |
| | +0.25 | 5954363.759 | 2733518.653 | 4079828.421 | 1594639.432 |
| | +0.50 | 5864064.226 | 2312582.902 | 3890056.422 | 1476272.281 |

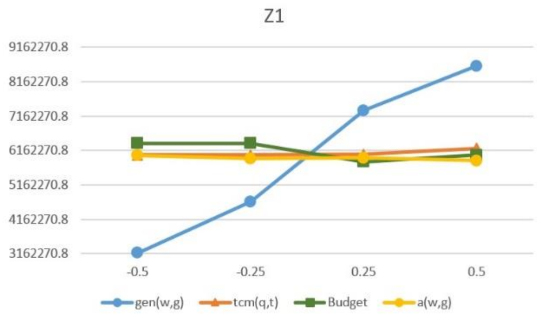

**Figure 8.** Variations of the first objective function value

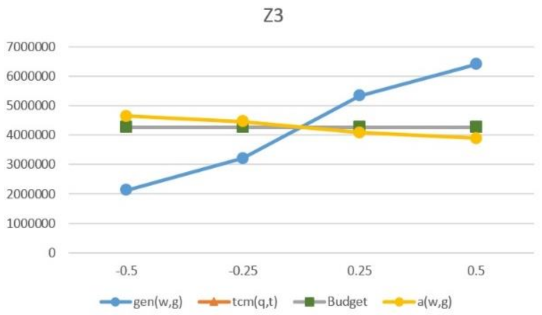

**Figure 10.** Variations of the third objective function value

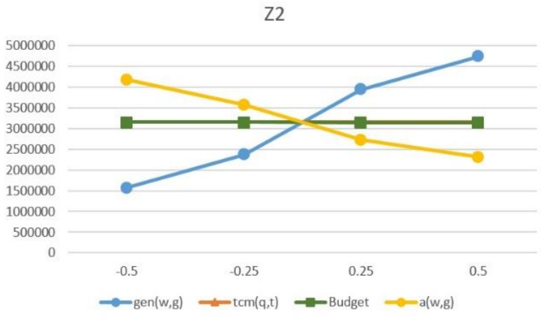

**Figure 9.** Variations of the second objective function value

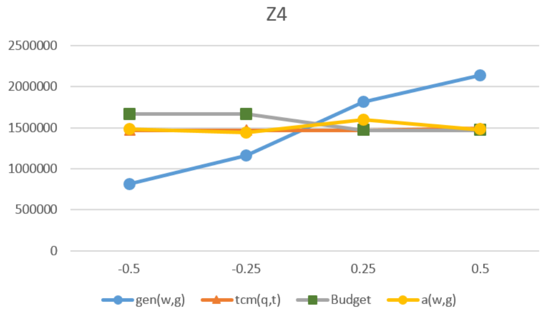

**Figure 11.** Variations of the fourth objective function value

## 6. CONCLUSION

In this research article, a multi-objective optimization model was introduced for a green hazardous waste location-routing problem. Four conflicting objective functions were took into account to minimize the total costs, the risk of transportation of the hazmat and the waste residues associated with the residents' exposure around the transportation routes, the total risk related to the population in a certain radius around the treatment facilities and the disposal facilities along with the total carbon emission of the transportation system. Five MODM methods were utilized to solve the multi-objective optimization problem. Besides, various randomly generated test problems of different sizes were solved, based on which the performances of the solution methods were assessed in terms of four solution quality measures as well as their computational times. As the methods performed differently, the TOPSIS method was used to determine the superior MODM method considering equal weights for each comparison measure. Lastly, some sensitivity analyses were conducted to determine the most essential parameters affecting the values of the objective functions. The results confirmed that the amount of hazardous waste produced at generation nodes plays the most significant role in the proposed problem and the considered objective functions.

This study provides several new avenues for future studies. Using inventory decisions and policies is another topic that can increase the problem complexity. With regards to the formulation of the proposed problem, developing a robust optimization model would be of great importance as well. Regarding the solution algorithm, this study applied five well-established MODM techniques from the literature to analyze the objective functions. In this regard, using a new hybrid MODM technique can be considered in future works. In addition, as the proposed model is NP-hard, it is highly recommended to use efficient heuristics [33, 34] such as Lagrangian [35] or novel metaheuristics such as the social engineering optimizer and the red deer algorithm [33, 36-38] to solve the location-routing optimization problem at hand. Finally, several other sustainbaility dimensions such as job oppurtunities can be added [39].

## 7. APPENDIX

Electronic Supplementary Materials are available in the online version as an attachment.

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## Persian Abstract

### چکیده

تحقیقات در مورد محیط زیست و پایداری یک موضوع فعال است ، به ویژه در مدیریت پسماند. به همین ترتیب ، بهینه سازی زباله های خطرناک یک موضوع تحقیقاتی فعال در کشورهای در حال توسعه است که ممکن است با انتشار کربن و افراد سبز ادغام شود. این چالش بزرگ انگیزه تحقیقات فعلی برای کمک به یک مدل جدید بهینه سازی چند هدفه برای رسیدگی به مسئله مسیریابی محل زباله های خطرناک سبز است. مدل بهینه سازی چند هدفه پیشنهادی برای اولین بار همزمان چهار هدف را تعیین می کند. علاوه بر هزینه کل و انتشار گازهای گلخانه ای سیستم های حمل و نقل به عنوان دو هدف اصلی ، هدف هدف دیگر این است که خطر حمل زباله های خطرناک در کنار پسماندهای زباله مرتبط با قرار گرفتن در معرض مردم در اطراف مسیرهای حمل و نقل را به حداقل برساند. علاوه بر این ، کل خطر مرتبط با جمعیت در یک شعاع خاص در اطراف مراکز درمان و دفع به حداقل می رسد. از آنجا که مدل پیشنهادی پیچیده با اهداف متناقض است ، چندین ابزار تصمیم گیری چند هدفه (MODM) استفاده شده و براساس مشکلات آزمون مختلف مرتبط با یک مثال صنعتی با یکدیگر مقایسه می شوند. بر اساس کیفیت راه حل و زمان محاسباتی ، روش ترتیب ترجیح با شباهت به محلول ایده آل (TOPSIS) به عنوان قوی ترین تکنیک برای ارزیابی عملکرد هر پنج روش MODM انتخاب شده است.