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A New Multi-objective Mathematical Model for Hazardous Waste Management Considering Social and Environmental Issues

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Abstract

Hazardous waste management incorporates collection, separation, treatment, recycling and disposal of hazardous wastes. In this paper, a new multi-objective mixed integer model is presented for hazardous waste collection problem. The model aims to minimize transportation and construction costs, and environmental and population risks in hazardous waste management systems. This model is applied in a case study of Iran in order to help decision makers to decide on the location of separation, treatment, recycle, disposal centers, and established technology in treatment center. Moreover, this paper specifies routes between different facilities in collection network. For addressing population and environmental impacts and economical costs, three objective functions including total costs, total population exposure risk, and environmental risks are considered. An augmented ε-constraint method is used to generate Pareto optimal solution for these conflicting objectives. Finally, proposed model is utilized in our case study and numerical results and some managerial insights are provided.

Keywords

Hazardous waste management, Mixed integer programming, Augmented ε-constraint, Pareto solutions and Multi-objective optimization.

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Introduction

Hazardous waste is a waste with properties that makes it potentially harmful to human health or environment (e.g., ignitability, corrosivity, reactivity, toxicity) (Farrokhi-Asl et al. 2017). The domain of hazardous waste is extensive and these wastes can be liquid, solid, and gas. Incomplete hazardous wastes management (HWM) causes substantial harm to human health and safety or to the environment (Alumur and Kara 2007). The aim of this study is to find an optimal set of solutions that considers three objectives of the problem, and simultaneously to determine rational network of separation, treatment, recycle and disposal centers. According to the European list of waste types, about half of waste types are categorized as hazardous wastes (Yilmaz et al. 2017). Due to this variety, hazardous waste (HW) separation in specific sites is an absolutely useful task and can help us to transport each class of HW to compatible center for treatment. This action can reduce operational costs. In this regard, HWs are classified in order to decrease the model complexity.

There are some difficulties in the modeling of HWs. These difficulties are derived from the simultaneous consideration of different aspects of HWs, including operational costs and environmental risks. Lack of attention to environmental effects of HWs can enhance the harmful effect of these hazardous materials. For example, if industrial or hospital wastes find their way into drinking water, thousands or millions of people will face serious risks. One liter of motor oil contaminates one million liters of water. According to statistics, on average, 100000 kg hospital waste is generated in Tehran. This volume of waste needs professional management system for an efficient treatment. Any neglect in this system causes a humanitarian disaster. In the current study, in addition to cost related objectives, there are two objective functions about population and environmental risks; minimizing total population risks around related sites and minimizing environmental risks considering the environmentally vulnerable areas, including river watershed basins, agricultural areas, coastal zones, and forestlands.

Another aspect of HWM is the existence of different kinds of hazardous waste which are in need of different types of technologies for being treated. By then, many papers in the literature have discussed how to allocate different kinds of hazardous waste to centers with compatible technology. However, in this study, there are several separation nodes where hazardous waste is separated and routed to appropriate treatment centers. This model minimizes costs and system's risks by answering the questions such as how we can manage hazardous wastes, where to open separation centers, where to open treatment centers with special technology, which area is appropriate for establishing recycle centers and which zones have an environmental ability for opening disposal centers.

The proposed hazardous wastes management model is demonstrated in Fig. 1. Distinct types of waste are generated in generation nodes. Afterward, HWs are separated in different classes in separation centers. Then, non-recyclable HWs are transported to appropriate treatment centers with suitable technology and recyclable ones are routed to recycle nodes. After the treatment of non-recyclable wastes, waste residues are transmitted to disposal centers and recyclable ones are routed to recycle centers. In recycling centers, after recycling operation, waste residues are also sent to disposal centers. With this method, HW's risk is reduced and useful materials could be extracted in recycle centers. The main contribution of this paper is developing a multi-objective model with environmental, population and economic perspectives which separates hazardous wastes in separation sites and can be applied in realistic, large-scale problems.

Data for this paper are gathered from the department of environment and waste management organization of Iran. Since environmental issues are important in this research, we got advice from the mentioned organization and obtained some useful statistics to select appropriate criterion for environmental factors. Statistic center of Iran is another organization which helped us to provide useful and latest statistics about the population of Iran.

The rest of this paper is formed as follows. In section 2, we discuss previous researches in this field and express hazardous waste problem literature review. Then, we compare this research with previous articles in this field. In section 3, we introduce the model and present the solution method. This section defines some key concepts to be used in the modeling and specifies the main problem assumptions and customizes an AGEMON approach to identify competitive efficient solutions. In section 4, a large-scale realistic case study constructed based on Iran provinces are is used to prove our model and expresses different scenarios to give appropriate insights to decision makers.

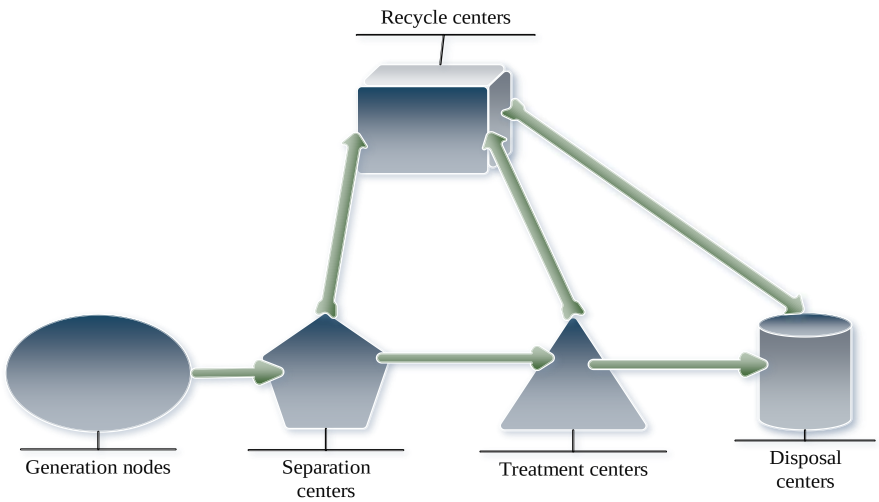

Fig. 1. Framework of the presented network

Literature review

In recent years, waste management problem has become more and more complex by considering new assumptions in real world cases (Achillas et al. 2013). In the literature, various mathematical models are investigated in order to cover different aspects of hazardous wastes.

Location-Routing Problem (LRP) modeling approach is very usual and common in hazardous waste management literature (Farrokhi-Asl et al. 2017; Rabbani et al. 2017; Samanioglu 2013). In addition to hazardous waste management, location-routing problem is used in many areas. This problem mixed two basic problems in logistics (Drexl and Schneider 2015). And in recent years, the number of multi-objective location-routing problem papers increased. (Rath and Gutjahr 2014; Govindan et al. 2014; Zhang et al. 2017) are some papers that applied this type of problem in their papers.

As we said earlier, one of the common areas for location-routing problem is HW area. Due to issues such as transportation costs, transportation risks are the features that can be seen in hazardous waste location-routing problems. For example, some papers focus on minimizing transportation costs in location routing problem. The hazardous materials transportation is an important, strategic and shrewd decision-making problem (Erkut and Verter 1998). Nema and Gupta (1999) expressed planning of hazardous waste management system involves allocation, treatment and disposal facilities and the selection of the transportation routes. Erkut and Ingolfsson (2005) focus on transportation risks and present a model that meets the axioms. Emek and Kara (2007) combined HW management with disposal methods. They propose a cost-based mathematical model that meets air pollution standards. Many other papers discuss Location-Routing problems and use this kinds of mathematical model for modeling hazardous wastes problem, and both exact and heuristic algorithms are used. Nagy and Salhi (2007) and Killmer, et al. (2001) studied uncertainty in HW problems and assumed that demand and variable production and transportation costs are uncertain.

Considering different types of risks is a usual concept in hazardous waste management papers. This concept helps the model to become more practical. And also some researchers have used Geographic Information Systems (GIS) in HW routing problems (Zhang, et al. 2000). They consider human population risks. Map algebra techniques, from GIS, allow them to combine concentration mathematically with the population distribution to estimate risks. Map algebra further allows them to apply these risk estimates to every link in the network. Dadkar et al. (2008) developed a K shortest path algorithm for the performance of each highway facility and also devised a mixed integer program. Another concept that is used abundantly in HW problems is the different types of risks (such as environmental risks, side risks, traditional risks, etc.) Fabiano et al., (2002) and Kara et al. (2003) are focused on hazardous waste transportation risks. Carotenuto et al. (2007) studied generating minimum transportation risks for HW between an origin and a destination. The study was mathematically formulated, and two heuristic algorithms were proposed as its solutions. Saat et al. (2014)

focused on hazardous material rail transportation and the model was used in conjunction with a GIS analysis of environmental characteristics to develop probabilistic estimates.

Some researchers related hazardous wastes to logistic topics. Hu et al. (2002) explained a cost-minimization model for a multi-time-step, multi-type hazardous-waste reverse logistics system, and Hicks et al. (2004) explore the definition and classification of waste from different viewpoints. This model presented the modeling of the material and the flow of waste from both a physical and cumulative cost perspective.

With the passage of time, authors considered more aspects of hazardous wastes problem and used multi-objective problems to model this type of problems. Also hazardous wastes solving method is a very important concept. There are various kinds of solving for multi-objective models (such as exact, meta-heuristic, fuzzy, etc.). Rakas et al. (2004) formulated a multi-objective model for undesirable facilities location problem. To solve the multi-objective problem, they combined two functions into one objective function with certain weight and summed and produced one object. Alçada-Almeida et al. (2009) introduced a mixed-integer, multi-objective programming approach to identify the locations and capacities of such facilities and used GIS, and generated a solution by weighted method. Alumur and Kara (2007) propose a multi-objective model for hazardous wastes management. In this paper, authors considered cost- effective and population risks. Unlike some prior models, their model included some constraints which were incorporated. The purpose of that model was to answer the questions like: where to open treatment and disposal centers and with what technologies, how to transport different types of hazardous waste and waste residues with what compatible treatment technologies and to which disposal centers.

Using fuzzy approach is one of the newest methods joined with hazardous wastes problems. Wang et al. (2008) explained a multi-objective mathematic model. The main aim of tht research is to find the location of treatment centers and transport sites for hazardous wastes. Based upon the fuzzy satisfactory levels of objectives, a bi-fuzzy algorithm is proposed. According to model solving approach, an analysis is conducted on the locations and some of these centers and that how to assign the generation centers to transfer sites. Pamučar et al. (2016) used both fuzzy and heuristic methods for solving multi-objective HW transportation problem. That paper considered cost and risk assessment in the multi-objective selection of routes for the transport of hazardous wastes on a network of city roads. That model was based upon the application of an Adaptive Neuro-Fuzzy Inference System. Using an adaptive neuro-fuzzy network trained with an Artificial Bee Colony (ABC) algorithm, the values of the cost and risk criteria were integrated into a single CR value by means of which the worthiness of each branch in the network is expressed.

Like other areas, especially multi-objective problems, hazardous waste meta-heuristic algorithms are used to create solutions. Caballero et al. (2007) developed a multi-objective location routing problem and solved it with a multi-objective meta-heuristic procedure. To solve this problem, a Meta heuristic algorithm, MOAMP, has been used (based on tabu search). Pradhananga et al. (2014) presented a bi-objective hazardous material vehicle routing and scheduling problem with Time Windows. An ant colony system-based meta-heuristic algorithm used to solve the model and generate Pareto optimal solutions.

Finally, the last approach for solving hazardous waste mathematical model is exact solutions. Samanlioglu (2013) focused on industrial hazardous wastes (hazmats). In this paper a multi-objective model is developed. This model can help decision makers to decide on the locations of treatment nodes, recycle nodes, disposal nodes and the transportation of various types of industrial hazardous wastes to compatible treatment nodes. Total costs minimization and population considerations are the main objects of this model. A lexicographic weighted Tchebycheff formulation is used to discover solutions for the model. Their data are about the Marmara region and are obtained by utilizing Arcview 9.3 GIS software and Marmara region geographical database. Yilmaz et al. (2017) presented a multi-objective mixed integer Location-Routing problem for hazardous wastes management. In this model, both environmental and population risks were considered. The solution method generated Pareto optimal curve for two conflicting objectives. ε-constraint method was used in this study.

For a better comparison of this paper with other papers in the literature and to display the contributions of our work, Table 1 is prepared. In this table, with some parameters like population, environmental risks and solution method we make comparisons between papers. There are many papers about hazardous wastes and many researchers have been studying this subject. But in Table 1, we investigate some papers that have a large similarity with our research. Also, early papers in this field cannot help us to make a fair comparison and cannot challenge our research. Therefore, we do not consider them in Table 1.

A lot of information can be extracted from Table1. Although, population and environmental considerations are very important, authors in many papers have neglected these risks in their works. As can be seen in Table1, less than 10% of papers have considered population and environmental risks, simultaneously. Moreover, there is not any paper in the literature that considers separation node for hazardous waste. This is a significant fact in modeling this problem and can help the better management of similar waste collection networks. In separation centers, hazardous waste is separated according to hazardous waste classes. Consequently, we face categorized hazardous waste that planning and transportation of which become easier and more efficient. Another fact that can be understood from Table1 is about the approaches to solve the problem. There are so many solving methodologies for multi-objective problems, but this study is the first one in the literature of waste management that uses augmented ε-constraint method. Augmented ε-constraint is an extension of classical ε-constraint method and it is a new exact solving approach that generates a set of efficient solutions for the multi-objective problems. As such, using separation centers, a different type of solving method, simultaneous consideration of population and environmental risks, and verification of presented model by applying it in real cases are the main contributions of this paper. Iran is one of the developing countries in the world and increasingly needs to have a hazardous waste management system nowadays. Furthermore, Iran is one of the populated countries in the Middle East with a special environment and eco-system. So suggesting an integrated system is really essential for this country. To the best of our knowledge, there is not any paper in the literature that selects Iran for its case study.

Table1. Comparison between papers in the literature

		Risks			Solving approach			
							Exact solution	
	Multi -objective	population	environmental	Separation centers	fuzzy	Meta heuristic	others	Augmented ε-constraint
Hicks et al. (2004)							✓	
Sibel Alumur (2007)	✓	✓					✓	
Caballero et al. (2007)	✓					✓		
Alçada-Almeida et al. (2009)	✓						✓	
Wang et al. (2008)	✓				✓			
Xie et al. (2012)	✓		✓			✓		
Xu, et al. (2013)	✓		✓			✓		
Mehrjerdi and Nadizadeh (2013)	✓				✓	✓		
Samanlioglu (2013)	✓	✓					✓	
Pradhananga et al. (2014)	✓		✓			✓		
Pamučar et al. (2016)	✓	✓			✓	✓		
Yilmaz et al. (2017)	✓	✓	✓				✓	
Vidović, et al. (2016)	✓					✓		
Ardjmand et al. (2016)	✓		✓			✓		
Saxena et al. (2016)	✓		✓			✓		
Farrokhi-Asl et al. (2017)	✓	✓	✓			✓		
Hong et al. (2017)	✓	✓	✓			✓		
Chiou (2017)	✓		✓			✓		
Rabbani, et al. (2017)	✓	✓	✓			✓		
Dinler and Güngör, (2017)	✓		✓		✓			
This Paper	✓	✓	✓	✓				✓

All in all, in this paper a new mathematical multi-objective mixed integer location/routing model with three objectives are developed and in addition to total cost, population and environmental risks are minimized. The model is solved by means of augmented ε-constraint method. The main aim of the applied methodology is to find a set of efficient solutions called Pareto solutions and help decision makers to take appropriate decisions. The formulation is implemented in Iran, and considering various kinds of hazardous wastes and different types of technologies for treating them and using separation and recycling centers make this model so practical.

Materials and methods

This paper's main question is how to route hazardous waste and how to locate the facilities in potential centers. After waste treatment, the danger of waste decreases and becomes appropriate for disposing or recycling. In separation centers, hazardous wastes are divided into different classes according to their type and their risk type. This facility improves the integration of the hazardous waste network and reduces corresponding costs and risks. Some treatment operations enable waste to be ready for recycling and some other operations decline the danger of the hazardous waste. A portion of hazardous wastes in separation centers is routed to recycle centers and some of the hazardous waste after treating is sent to the recycle centers. Recycle centers are useful facilities to create value added products from recyclable hazardous waste. Eventually, residual hazardous waste is routed to disposal centers. The most usual type of disposal facility is a landfill.

The multi-objective mixed integer programming model consists of g generation hazardous waste nodes. Each of this generation nodes generates a different amount of hazardous waste. Hazardous waste is transported to the separation centers where it is separated into different classes. Afterwards, in terms of their kind and recyclability rate, wastes are routed to the treatment or recycle centers. Disposal nodes are in the end of the route for the residue amount of hazardous wastes. In the following sections, mathematical formulations are declared.

Mathematical formulation

Nomenclature

G = {1, 2, … , g}	hazardous waste generation centers, $G \subset$ N
T = {1, 2, … , t}	hazardous waste treatment centers, $T \subset$ N
S = {1, 2, … , s}	hazardous waste separation centers, $S \subset$ N
D = {1, 2, … , d}	hazardous waste disposal centers, $D \subset$ N
R = {1, 2, … , r}	hazardous waste recycling centers, $R \subset$ N
W = {1, 2,… , w}	hazardous waste types, $W \subset$ N
Q = {1, 2, … , q}	treatment technologies, $Q \subset$ N

Parameters

$C_{i,j}$	cost of transporting a single unit of hazardous waste on route(i,j) , $i \in G, j \in S$
$Ct_{i,j}$	cost of transporting a single unit of hazardous waste residue on route $(i,j), i \in S, j \in T$
$Cre_{i,j}$	cost of transporting a single unit of waste residue on route $(i,j), i \in T, j \in D$
$Crr_{i,j}$	cost of transporting a single unit of waste residue on route $(i,j), i \in R, j \in D$
$Cr_{i,j}$	cost of transporting a single unit of recyclable waste on route $(i,j), i \in S, j \in R$
$Crre_{i,j}$	cost of transporting a single unit of recyclable waste remnant on route $(i,j), i \in T, j \in R$
Fcs_i	fixed cost of opening a separation at node $i \in S$
$Fct_{i,q}$	fixed cost of opening a treatment technology $q \in Q$ at node $i \in T$
Fcd_i	fixed cost of opening a disposal center at node $i \in D$
Fcr_i	fixed cost of opening a recycling center at node $i \in R$
$Pops_i$	number of residents around node $i \in S$
$Popt_i$	number of residents around node $i \in T$ with technology $q \in Q$
$Popd_i$	number of residents around node $i \in D$
$Popr_i$	number of residents around node $i \in R$
$Gen_{w,i}$	amount of hazardous waste type $w \in W$generated at generation node $i \in G$
$Rec_{w,i,j}$	amount of hazardous waste type $w \in W$received in separation center from generation node $i \in G, j \in S$

$\alpha_{w,i}$ portion of recycling of hazardous waste type $w \in W$ separated at separation node $i \in S$

$\beta_{w,i,q}$ portion of recycling of hazardous waste type $w \in W$ treated at treatment node $i \in T$ with technology $q \in Q$

$\delta_{w,i,q}$ portion of clump reduction of hazardous waste type $w \in W$ treated at treatment node $i \in T$ with technology $q \in Q$

γ_i portion of total hazardous waste recycled at node $i \in R$

Sc_i capacity of separation at node $i \in S$

Sc_i^m minimum amount of hazardous waste required to establish separation center at node $i \in S$

$Tc_{q,i}$ capacity of treatment technology $q \in Q$ at node $i \in T$

$Tc_{q,i}^m$ minimum amount of hazardous waste required to establish treatment technology $q \in Q$ at node $i \in T$

Dc_i capacity of disposal center $i \in D$

Dc_i^m minimum amount of waste residue required to establish a disposal center at node $i \in D$

Rc_i recycling capacity of node $i \in R$

Rc_i^m minimum amount of waste required to establish a recycling center at node $i \in R$

$$C_{w,q} = \begin{cases} 1 \text{ if waste type } w \in W \text{ is compatible with technology } q \in Q \\ 0 \quad otherwise \end{cases}$$

$$\varphi_i = \begin{cases} 10 \quad \text{if disposal center is stablished in critical area(like river, jungle, etc) } i \in D \\ 1 \quad otherwise \end{cases}$$

Decision variables

$u_{i,j}$ amount of hazardous waste transported $i \in G, j \in S$

$x_{w,i,j}$ amount of hazardous waste type $w \in W$ transported $i \in S, j \in T$

$z_{w,i,j}$ amount of waste residue type $w \in W$ transported $i \in T, j \in D$

$o_{w,i,j}$ amount of recyclable waste type $w \in W$ transported $i \in S, j \in R$

$p_{w,i,j}$ amount of recyclable waste residue type $w \in W$ transported $i \in T, j \in R$

$qq_{w,i,j}$ amount of waste residue type $w \in W$ transported $i \in R, j \in D$

$Sep_{w,i}$ amount of hazardous waste type $w \in W$ separated at $i \in S$

$Tre_{w,i,q}$ amount of hazardous waste type $w \in W$ treated at node i∈ T with technology $q \in Q$

$Dis_{w,i}$ amount of hazardous waste type $w \in W$residue disposed at node $i \in D$

$Hr_{w,i}$ amount of hazardous waste type $w \in W$recycled at node $i \in R$

$$Se_i = \begin{cases} 1 & \text{If separation center is stablished at node } i \in S \\ 0 & otherwise \end{cases}$$

$$Tr_{q,i} = \begin{cases} 1 & \text{If treatment technology } q \in Q \text{ is stablished at node } i \in T \\ 0 & otherwise \end{cases}$$

$$Di_i = \begin{cases} 1 & \text{If disposal center is stablished at node } i \in D \\ 0 & otherwise \end{cases}$$

$$Re_i = \begin{cases} 1 & \text{If recycle center is stablished at node } i \in R \\ 0 & otherwise \end{cases}$$

This mathematical model is multi-objective location routing problem and is categorized as an NP-hard problem (Alumur and Kara 2007). In Fig. 2, the parameters, decision variables and notations are demonstrated. This Fig helps to understand the relation between variables and routing hazardous wastes between centers.

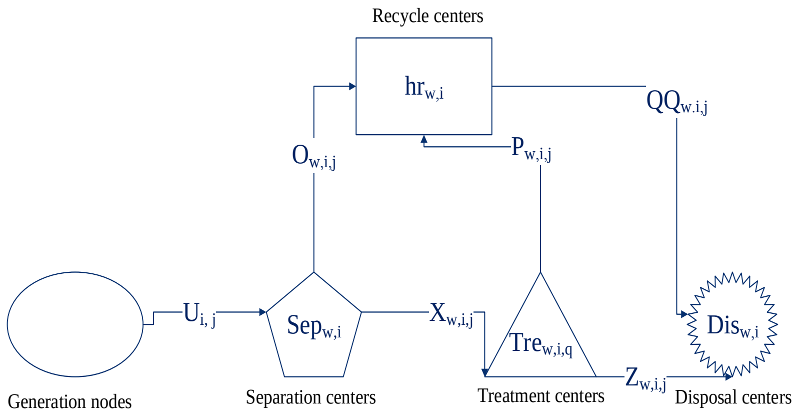

Fig. 2. Decision variables and notation of the model

This paper aims to present the model helping us to manage hazardous wastes and to generate Pareto solution (a set of efficient solutions) for offering to the decision makers. The proposed model has three objective functions. The first one is minimizing the cost, the second one is minimizing population exposure risks (population consideration) and the third one is minimizing environmental risks (environment consideration). This multi-objective mixed integer location routing problem is as follows:

$$f_1(x) = \sum_{i\in G}\sum_{j\in S} C_{i,j}\, U_{i,j} + \sum_{i\in S}\sum_{j\in T}\sum_{w\in W} Ct_{i,j}\, x_{w,j,j} + \sum_{i\in T}\sum_{j\in D}\sum_{w\in W} Cre_{i,j}\, z_{w,i,j} + \sum_{i\in R}\sum_{j\in D}\sum_{w\in W} Crr_{i,j}\, qq_{w,i,j} + \sum_{i\in S}\sum_{j\in R}\sum_{w\in W} Cr_{i,j}\, o_{w,i,j} + \sum_{i\in T}\sum_{j\in R}\sum_{w\in w} Crre_{i,j}\, p_{w,i,j} + \sum_{i\in S} Fcs_i\, Se_i + \sum_{i\in T}\sum_{q\in Q} Fct_{i,q}\, Tr_{i,q} + \sum_{i\in D} Fcd_i\, Di_i + \sum_{i\in R} Fcr_i\, Re_i \quad (1)$$

$$f_2(x) = \sum_{i\in G}\sum_{j\in S}\sum_{i\in R} Popt_i\, Tre_{w,i,q} \sum_{i\in R}\sum_{i\in R} Popd_i\, Dis_{w,i} + \sum_{i\in R}\sum_{i\in R} Popr_i\, Hr_{w,i} \quad (2)$$

$$f_3(x) = \sum_{i\in D}\sum_{w\in W} Dis_{w,i}\, \varphi_i \quad (3)$$

S.T.

$$Gen_{w,i} = \sum_{j \in S} u_{i,j} \qquad \forall w \in W, i \in G \qquad (4)$$

$$\sum_{i \in G} u_{i,j} = \sum_{w \in W} \sum_{i \in G} Rec_{w,i,j} \qquad \forall j \in S \qquad (5)$$

$$\sum_{i \in G} u_{i,j} = \sum_{w \in W} Sep_{w,i} \qquad \forall j \in S \qquad (6)$$

$$\sum_{i \in G} \sum_{j \in S} Rec_{w,i,j} \left(1 - \alpha_{w,j}\right) = \sum_{i \in S} \sum_{j \in T} x_{w,i,j} \qquad \forall \ w \in \ W \qquad (7)$$

$$\sum_{i \in G} \sum_{j \in S} \alpha_{w,j} \, Rec_{w,i,j} = \sum_{i \in S} \sum_{j \in R} o_{w,i,j} \qquad \forall \mathrm{w} \in \mathrm{W} \qquad (8)$$

$$\sum_{i \in S} x_{w,i,j} = \sum_{q \in Q} Tre_{w,j,q} \qquad \forall \ w \in W, \forall \ j \in T \qquad (9)$$

$$\sum_{w \in W} \sum_{q \in Q} Tre_{w,i,q} \left(1 - \delta_{w,i,q}\right)\left(1 - \beta_{w,i,q}\right) = \sum_{w \in W} \sum_{j \in D} z_{w,i,j} \qquad \forall \ i \in T \qquad (10)$$

$$\sum_{w \in W} \sum_{q \in Q} Tre_{w,i,q} \left(1 - \delta_{w,i,q}\right)\beta_{w,i,q} = \sum_{w \in W} \sum_{j \in R} P_{w,i,j} \qquad \forall \ i \in T \qquad (11)$$

$$\sum_{w \in W} \sum_{i \in S} o_{w,i,j} + \sum_{w \in W} \sum_{i \in T} p_{w,i,j} = \sum_{w \in W} Hr_{w,j} \qquad \forall j \in R \qquad (12)$$

$$\sum_{w \in W} Hr_{w,i} \left(1 - \gamma_i\right) = \sum_{w \in W} \sum_{j \in D} qq_{w,i,j} \qquad \forall i \in R \qquad (13)$$

$$\sum_{w\in W}\sum_{i\in R} qq_{w,i,j} + \sum_{w\in W}\sum_{i\in T} z_{w,i,j} = \sum_{w\in W} Dis_{w,j} \qquad \forall j \in D \qquad (14)$$

$$\sum_{w\in W} Sep_{w,i} \leq Sc_i Se_i \qquad \forall i \in S \qquad (15)$$

$$\sum_{w\in W} Sep_{w,i} \geq Sc_i^m Se_i \qquad \forall i \in S \qquad (16)$$

$$\sum_{w\in W} Tre_{w,i,q} \leq Tc_{q,i} Tr_{q,i} \qquad \forall q \in Q, \forall i \in T \qquad (17)$$

$$\sum_{w\in W} Tre_{w,i,q} \geq Tc_{q,i}^m Tr_{q,i} \qquad \forall q \in Q, \forall i \in T \qquad (18)$$

$$Tre_{w,i,q} \leq Tc_{q,i} C_{w,q} \qquad \forall w \in W, \forall q \in Q, \forall i \in T \qquad (19)$$

$$\sum_{w\in W} Dis_{w,i} \leq Dc_i Di_i \qquad \forall i \in D \qquad (20)$$

$$\sum_{w\in W} Dis_{w,i} \geq Dc_i^m Di_i \qquad \forall i \in D \qquad (21)$$

$$\sum_{w\in W} Hr_{w,i} \leq Rc_i Re_i \qquad \forall i \in R \qquad (22)$$

$$\sum_{w\in W} Hr_{w,i} \geq Rc_i^m re_i \qquad \forall i \in R \qquad (23)$$

$$\sum_{i\in S}\sum_{j\in T} x_{w,i,j} = \sum_{i\in T}\sum_{j\in D} z_{w,i,j} \qquad \forall w \in W \qquad (24)$$

$$\sum_{i\in S}\sum_{j\in R} o_{w,i,j} + \sum_{i\in T}\sum_{j\in R} p_{w,i,j} = \sum_{i\in R}\sum_{j\in D} qq_{w,i,j} \qquad \forall w \in W \qquad (25)$$

$$u_{i,j} \geq 0 \qquad \forall i \in G, \forall j \in S \qquad (26)$$

$$x_{w,i,j} \geq 0 \qquad \forall w \in W, \forall i \in S, \forall j \in T \qquad (27)$$

$z_{w,i,j} \geq 0$	$\forall w \in W, \forall i \in T, \forall j \in D$	(28)
$o_{w,i,j} \geq 0$	$\forall w \in W, \forall i \in T, \forall j \in R$	(29)
$p_{w,i,j} \geq 0$	$\forall w \in W, \forall i \in T, \forall j \in R$	(30)
$qq_{w,i,j} \geq 0$	$\forall w \in W, \forall i \in R, \forall j \in D$	(31)
$Sep_{w,i} \geq 0$	$\forall w \in W, \forall i \in S$	(32)
$Tre_{w,i,q} \geq 0$	$\forall w \in W, \forall i \in T, \forall q \in Q$	(33)
$Dis_{w,i} \geq 0$	$\forall w \in W, \forall i \in D$	(34)
$Hr_{w,i} \geq 0$	$\forall w \in W, \forall i \in R$	(35)
$Se_i \in \{0,1\}$	$\forall i \in S$	(36)
$Tr_{q,i} \in \{0,1\}$	$\forall i \in T, \forall q \in Q$	(37)
$Di_i \in \{0,1\}$	$\forall i \in D$	(38)
$Re_i \in \{0,1\}$	$\forall i \in R$	(39)

Equation (1) calculates the cost of the network. The costs involve hazardous waste transportation costs and fixed costs of opening separation, treatment, recycle and disposal centers. This objective function aims to reduce extra expenses and generate affordable model. The next equation, namely Equation (2), minimizes population exposure risks. The population around the treatment, recycle and disposal centers should be minimized. The main goal of this equation is paying attention to human health. The last but not least function discusses environmental considerations. In this function, landfills should not be placed in sensitive environment locations such as bandwidth of rivers, near jungle areas and so forth. The harmful impact of disposing hazardous waste to the environment will be minimized with this function. On the other hand, paying attention to probable environmental damage in order to minimize this probability is this function's goal.

The constraints (4) - (7) relate to collecting the hazardous waste from generation nodes, routing them to separation centers and finally separating them. Constraints (8)-(12) are subjected to show flow balance between separation, treatment and recycling centers. A percentage of hazardous waste after separating is routed to recycle centers and others are sent to the treatment centers. This scenario happens in treatment centers. Some of hazardous wastes after treating are sent to recycle centers and the rest is transmitted to disposal centers. Constraint (13) declares that after recycling in recycle centers wastes residue are routed to disposal centers. Constraint (14) provides a balance between recycle centers, treatment centers and disposal centers. Constraints (15)-(23) guarantee the capacity limitation of the separation, treatment, recycle and disposal centers, respectively. For establishing these centers, the amount of the hazardous wastes should be more than the certain amount; each of them has a capacity and cannot accept more than their capacity. Constraint (24) declares that there is a balance between the separation and treatment of non-recyclable hazardous wastes. Also, Constraint (25) affirms that there is a balance between recycle centers' input and output. Constraints (26)-(35) express non-negative variables and constraint (36)-(39) represent binary variables. This model has fundamental differences with similar models which are developed in this field. The most important difference is using separation nodes in this model. On the other hand, the number of main nodes in this paper is more than previous articles. And also the solution method in this paper is a newer approach that generates efficient Pareto solution. In next section, we discuss this solution method.

Solution approach

In this paper, a multi-objective mathematical programming (MOMP) is formulated. The model has three object functions; so, multi objective approaches are more appropriate in order to solve the problem. The aim of these approaches is generating efficient Pareto solution. This Pareto solution should be trustworthy enough to help decision makers through giving a whole picture of the problem. Augmented ε-constraint is a novel method to solve multi-objective mathematical model with avoiding redundant iterations (Mavrotas, 2009). Augmented ε-constraint (AGEMON) method has several steps presented as follows:

Step1. Determine pay-off table for augmented ε-constraint model in order to calculate the range of objective functions. *n* denotes the number of objective functions.

Step 2. Determine upper and lower bounds of each objective functions.

Step 3. Calculate the range of objective functions one by one from payoff table.

Step 4. Choose desirable st_i to the partition range of each function by using (st_i-1) average equitant net spots. Then specify (st_i+1) net spot. Run the model (st_1+1)* (st_2+1)*…… (st_n+1) times.

Step 5. Use GAMS software to obtain Pareto solution based on above steps.

Step 6. Select some of the Pareto solutions.

Step 7. Decision maker should choose some solutions from solutions in step 6 according to his/her criteria.

Step 8. If the solutions are desirable, the process will be finished; otherwise, calculate new payoff table and return to step 1.

These steps show that AGEMON method is an interactive method and decision maker's ideas are important. Fig. 3 illustrates the algorithm's flow chart. The augmented ε-constraint model was proposed by Mavrotas (2009) as follows:

$$\text{Min } (f_1(x) + eps * s_2 + s_3 + \cdots + s_n))$$

s.t.

$$f_2(x) - s_2 = e_2,$$

$$f_3(x) - s_3 = e_3,$$

$$\ldots\ldots$$

$$f_n(x) - s_n = e_n$$

$$x \in S \text{ and } s_i \in R^+$$

7. Benefits of the aforementioned approach in comparison to other multi objective approaches are:

8. Using AUGEMON method results in efficient solutions.

This method is flexible to decision maker's desire and need.

9. Some accelerated issues are obtained from the mentioned method (the early existence of the loops)

10. The AUGEMON method is effective for both continuous and discrete variables.

11. Decision makers can use this model as an interactive way to find the most desirable Pareto optimal solution.

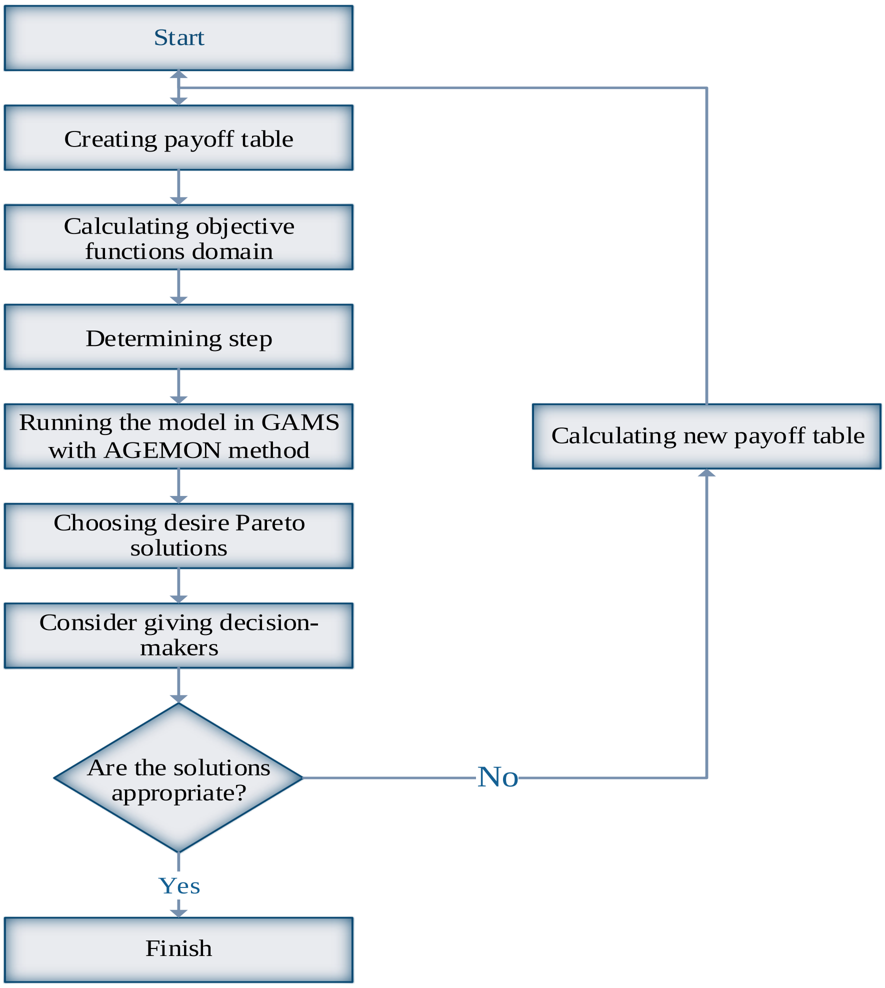

Fig. 3. AUGMECON method flow chart

Application in Iran

This paper's model is applied in a real case in Iran. The data is obtained from related government and non-government organizations and geographical information system (GIS). Iran has 31 provinces.

We consider each province as a generation node; therefore, there are 31 generation nodes in this case study. Population of these provinces, population density and distance between generation nodes are obtained by GIS. The provinces are sorted according to their population as follows: Tehran, Khorasan-Razavi, Isfahan, Fars, Khuzestan, East-Azerbaijan, West-Azerbaijan, Mazandaran, Kerman, Sistan and Baluchestan, Gilan, Alborz, Kermanshah, Golestan, Hamadan, Lorestan, Hormozgān, Kurdistan, Markazi, Ardabil, Qazvin, Qom, Yazd, Bushehr, Zanjan, Chahar Mahaal and Bakhtiari, North-Khorasan, Kohgiluyeh and Boyer Ahmad, Semnan, South-Khorasan, and Ilam.

In Fig. 4, the amount of hazardous waste is shown based on the generated waste of each province. Some of these provinces have a special environmental condition. For example, Gilan province has dense forests, and environmentally particular conditions. In this study, like other studies, there are some assumptions. These assumptions help us to model the problems simpler which are according to hazardous waste literature. These assumptions are as follows:

6. All nodes generate all kinds of hazardous waste. (w=7, $\forall\ g \in G$).

7. All provinces (nodes) are candidate for establishing separation, treatment, recycle and disposal centers.

8. Because of Iran's climate variability, we can see various ecosystems. According to purpose of this paper, environmental considerations are important. Regarding the environmental regulations, we want to minimize the number of disposal centers in the following provinces: Khuzestan, Mazandaran, Gilan, Gulestan, Hurmozgan, Ardebil, Bushehr and Chahar Mahaal and Bakhtiari (nodes), which have special environmental conditions and it is better not to dispose hazardous waste in them.

9. Similar to Samanlioglu (2013), the amount of each kind of hazardous waste generation is the same. Also, with respect to Yilmaz et al. (2017), in this paper, we discuss 7 classes and 7 kinds of hazardous waste. First group of hazardous waste needs treatment (incineration) after separation, then they are routed to disposal facilities. For instance, engine oils are in these classes and because of the hazard level, the second group is sent to disposal centers after separation. Some types of batteries are categorized in this type. The

next group is routed to treatment centers (chemical or physical treatment), and then they are transported to landfills. The fourth type is like the third one. The difference is that after treating this class faces recycle centers, and then they are sent to disposal centers. For example, wastes from chemical industries and hospital wastes are placed in third and fourth categories, simultaneously. The fifth group is similar to the first group, but the treatment technology is different, and chemical or physical treatment happens. Wastes that are generated in treatment and recycle processes are the examples of this hazardous wastes type. The next type of hazardous waste after separating is routed to recycle center and after that disposal nodes. Some kinds of metals generated in industrial factory are placed in this class. The last ones are hazardous wastes sent to landfills after separation. Any hazardous wastes which cannot be placed in previous classes are in the last class. Yilmaz et al. (2017) and European list of waste use this classification.

10. For calculating hazardous wastes and residue transportation cost, the fuel costs and distance are the main parameters. The fuel costs in Iran is about 0.25$/liter, and on average each vehicle consumes 10liter per Km. Similar to Alumur and Kara, (2007) the costs of transporting 1unit hazardous waste are 42% more than transporting 1unit of residue. The reason of the difference is technology requirements and special vehicles for transporting hazardous wastes.

11. By examining real existing centers and consulting with officials in these centers, we assume that the fixed costs to establish separation, treatment, recycle and disposal centers are 50, 50, 50, 10 million dollars, respectively.

12. One of the most important assumptions in this paper is determining bandwidth (the minimum distance from potential centers to urban and rural areas). Like ReVelle et al. (1991), Alumur and Kara (2007) and Samanlioglu (2013), population exposure bandwidth is about 800 meters. This means people who live closer than 800 meters from treatment, recycle and disposal centers are in risks and the population in this area should be minimized. Observance of this rule can improve community health. The population density information is obtained, and in Fig. 5 you can see this population distribution.

13. Because in this study there are separation centers, recycling rate can be improved. In other studies and from existing centers, the recycling rate of different types of hazardous wastes is approximately 10%, but with the help of separation centers, recycling rate can be improved, and in this study the recycling rate of each hazardous waste type is considered 20%.

14. In this case, there are two kinds of technologies in treatment centers including chemical and incineration technologies.

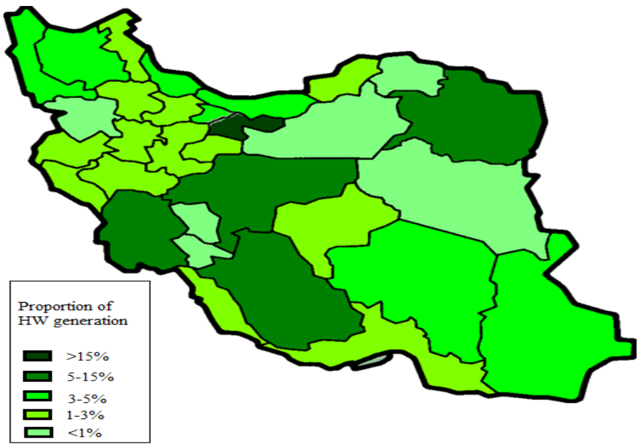

Fig. 4. Total hazardous wastes generation

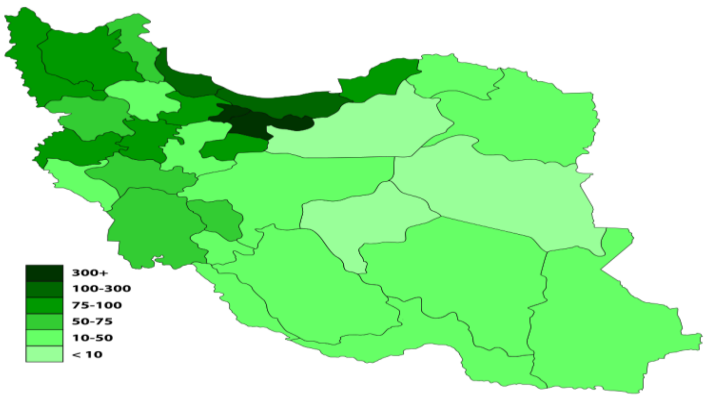

Fig. 5. Provinces of Iran by population per square kilometer

According to Iran’s data, the model is solved by AGEMON method with GAMS software. As previously noted, the problem is a minimization problem with three objectives. In Table 2 , each objective function is minimized, separately without the consideration of other objective functions. For using AGEMON method, the data of this table is neccessery. With this table, we can determine upper and lower bounds of each objective function and choose the appropriate step for AGEMON.

Table 2. Each objective optimal value and corresponding other objective values

	Min $f_1(x)$	Min $f_2(x)$	Min $f_3(x)$
$f_1(x)$	4222.268*	5425.418	7062.268
$f_2(x)$	8.424	1.428*	6.816
$f_3(x)$	15.424	16.524	14.424*

* indicates optimal value for each objective function

In this model, we need gaining Pareto optimal solutions that optimize three function simultaneously. Pareto optimality means that no solution can be made better off without making any other solution worse off (Diebold and Bichler, 2017) . After famous Italian engineer and economist, Vilfredo Pareto, this concept was named Pareto optimality or Pareto efficiency. Here and in this case, there are 31 generation nodes and 31 potential centers to establish separation, treatment, recycle and disposal centers. All kinds of constraints were declared in mathematical model. Table 3 displayed 15 Pareto solutions and located different centers to potential nodes. In this table, according to 15 efficient Pareto solutions, the location of separation, treatment, recycle and disposal centers has been found. In all of those solutions, costs, population and environmental considerations are considered and decision makers can choose between those solutions. A number of efficient solutions give the right to decision makers to choose.As can be seen in Table 3, there are two types of treatment centers with two technologies. Separating hazardous wastes before sending them to appropriate treatment centers can help different types of hazardous wastes. Because of that, in this case the number of treatment centers is less than similar aspers.

Table 3. Location of establishing centers, based on Pareto solutions

Solution Nimber	Location of				
	Separation centers	Treatment centers Tech 1	Treatment centers Tech2	Recycle centers	Disposal centers
1	2-3-7-8-12-15-20-23	25	28	3-4-5-6-7-27-28-29-30-31	29-30-31
2	4-6-13-17-18-20-28-31	27	31	5-6-7-25-26-27-28-29-30-31	29-30-31
3	1-5-8-11-14-22-24-31	31	31	2-3-4-5-6-7-28-29-30-31	28-30-31
4	1-2-7-8-15-20-22-28	30	31	1-2-3-4-5-6-7-28-29-31	29-30-31
5	3-5-8-15-19-22-23-26	25	31	3-4-5-6-7-26-27-28-29-30-31	28-30-31
6	2-5-11-13-16-17-26-31	31	30	4-5-6-7-26-27-28-29-30-31	29-30-31
7	2-3-5-7-9-12-23-29	27	31	1-2-3-4-5-6-7-29-30-31	28-30-31
8	2-4-10-11-15-26-28-31	31	31	6-7-24-25-26-27-28-29-30-31	28-29-31
9	2-3-9-14-15-24-26-28	31	31	4-5-6-7-26-27-28-29-30-31	28-30-31
10	8-15-17-23-25-26-27-31	28	30	3-4-5-6-7-27-28-29-30-31	29-30-31
11	1-3-4-5-10-11-16-30	31	23	5-6-7-25-26-27-28-29-30-31	29-30-31
12	1-7-11-12-18-19-20-28-30	31	31	1-2-3-4-5-6-7-29-30-31	28-29-30-31
13	1-8-9-18-22-23-24-28	24	31	2-3-4-5-7-8-28-29-30-31	28-30-31
14	4-9-10-15-16-17-27-28	23	31	3-4-5-6-7-27-28-29-30-31	29-30-31
15	1-2-7-8-15-20-22-28	31	30	1-2-3-4-5-6-7-28-29-31	29-30-31

Costs, environmental and population considerations are tangible in Table 3. The second function is about population risks. In most of Pareto solution, we can see separation centers established in populated provinces and treatment and disposal centers usually located in provinces with sparsely populated nodes. And about environmental consideration, AGEMON method doesn't allocate disposal centers to provinces with special environmental conditions. These results displayed in Tables 2 and 3 are the results with separation centers. The model with separation nodes does not exist in previous articles and these results are reasonable. The number of separation, treatment, recycle and disposal centers that the model and solution approach proposed is sensible and proportional with constraints. Fig. 6 shows scattering of centers in Iran's provinces. For creating this table, 100 Pareto solutions have been evaluated. The results are completely logical and so the centers which have been allocated to the considerations are met.

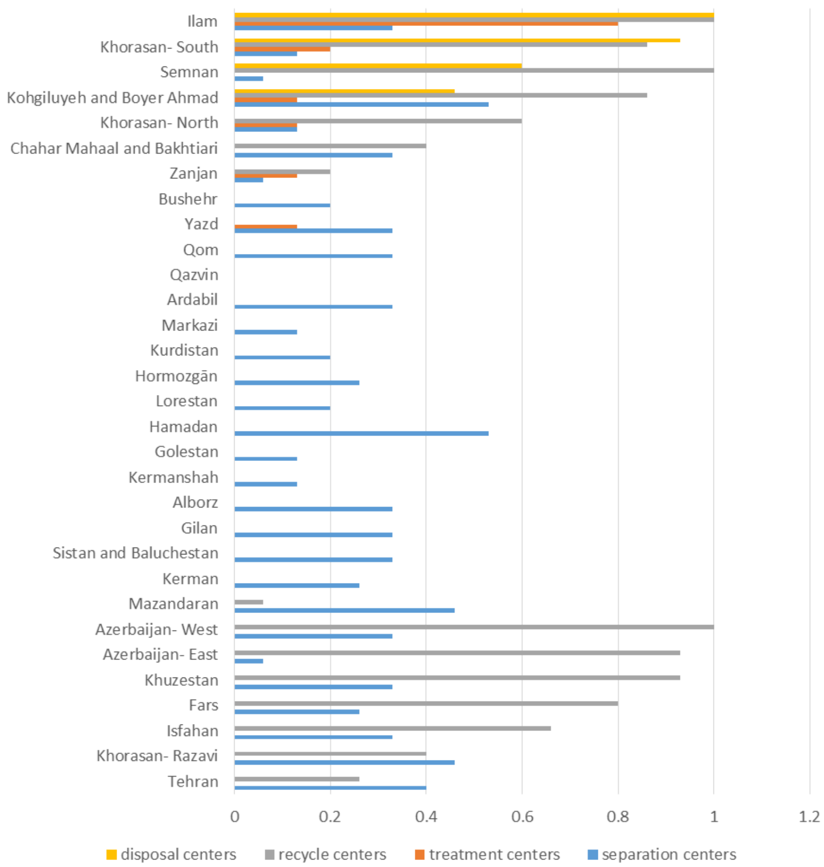

Fig. 6. Scattering of centers in Iran's province

The outputs of chart1 show that most of the treatment, recycle and disposal centers with their harmful impacts are established in low population provinces. And they are usually established in provinces that their environment does not have special conditions. On the other hand, recycle and separation centers are usually established in populated provinces because of economic saving. These populated provinces generate more than other provinces and transporting this amount of hazardous waste for recycling and separating is not logical. And the model also displayed this logical hypothesis.

For the convenience of decision makers, in Fig 7, the locations of the separation, treatment, recycle and disposal centers are shown in 4 scenarios. The first one is when costs considerations are important. The second one is about the importance of individual population considerations. The third one is checked when just the satisfaction of environmental considerations is important. And the fourth is our purpose. The aim of this paper was generating Pareto solutions that could meet costs, population and environment considerations altogether. Samanlioglu (2013) is also used these types of Figs in his paper. In Fig 7, this difference is tangible. But in this research separation nodes are used and the model is more complex from the previous one and the application is for Iran. In other words, we solve three single objective problems and one multi-objective problem. When three objects are minimized together like when AGEMON is used, the Pareto solutions indicate all considerations. Although in these solutions costs are not at least possible, but population and environment health are respected. In the 21st century, dealing properly with hazardous wastes is really important and is an aspect beyond economic issues. We tried in this case to generate solutions that respond to these concerns. And AGEMON method was compatible with big data and created these Pareto solutions.

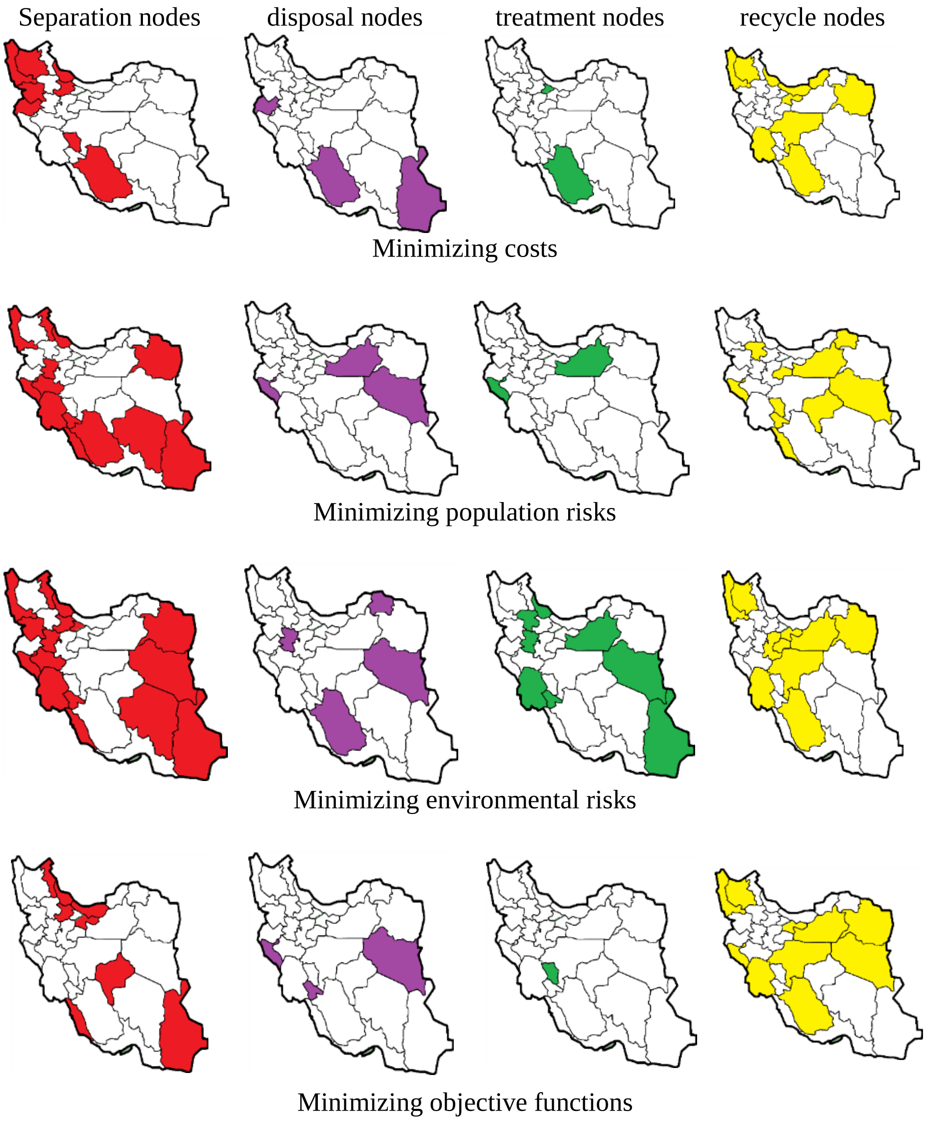

Fig. 7. Location of establishing centers, in four scenarios

Conclusion

In this paper, a new multi-objective mixed integer mathematical model was presented. The model was compatible with large-scale problems and the data related to a real case in Iran was used in this study. Moreover, the model considered the different classes of hazardous wastes, different technologies of treatment centers, the establishment of separation centers and the use of recycle centers. For solving this model and obtaining efficient Pareto solutions, a new mathematical method was introduced and solved by means of augmented ε-constraint. AGEMON is one of the best exact solving methods which can solve our model by GAMS software. The main aim of this paper was generating appropriate Pareto solutions that can help decision makers in designing a hazardous waste collection network. AGEMON generates these efficient solutions and we validated these results with Iran's data. Furthermore, this research answered to other questions, like the location of separation, treatment, recycle and disposal centers, the calculation of the optimum number of these centers and so forth. The main contribution of this study was establishing separation centers before treatment and recycle centers. With separating hazardous wastes and sending different classes of hazardous wastes to appropriate treatment centers, the costs will be lower and harmful impacts of hazardous wastes for humans and the environment are reduced. Discussing the separation of hazardous waste did not exist in literature. Using AGEMON for solving the model and implementing the model in a real case in Iran were other contributions of this study. The model had three objective functions which had conflicting goals. Minimizing costs, minimizing environmental damage and minimizing population harm for human health were our objectives with different constraints.

This paper benefited from an exact solution algorithm (AGEMON). The results in the case study were logical and validated the model formulations and proved the ability of implementing this model in large-scale instances. In the current study and for the convenience of the decision makers, the model is implemented in four different scenarios, and in each scenario one aspect of the problem is bolded. In hazardous wastes management, costs, population risks and environmental risks are valuable and without the consideration of each term, the problem is incomplete. In this paper, we tried to propose a model in which the importance of humans' health and the environment health is equal to economic considerations. So establishing disposal nodes in Tehran, Esfahan, Fars and other big provinces is not appropriate, and the model established these nodes in provinces like Ilam, Semnan and etc. But separation and recycle centers need to be in crowded provinces. As you saw in Fig. 6, the model results also approve this reasonable result. One of the most important results of this model and its solving approach is that, the results are a kind of preparation for different conditions with different criterion. Like every scientific research, this paper has some limitations. One of the main limitations in this paper was about data. For the case study, we needed exact data about hazardous waste systems in Iran, but in some parts obtaining clear data was difficult. Another restriction was the exact classification of hazardous waste in different types, because some categories had similarities and sometimes separating them to different groups was arduous.

Although this research improved the mathematical model and added separation centers, in the future, researchers can improve this model by the consideration of real world cases limitations in the model. Using fuzzy approach and surveying the problem in uncertainty will improve this study and allow the model to be more consistent with the real world.

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