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DESIGNING A LOGISTIC NETWORK FOR HOSPITAL WASTE MANAGEMENT: A BENDERS DECOMPOSITION ALGORITHM

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Abstract

Healthcare wastes are produced from all medical and therapeutic activities in hospitals and healthcare centres. Around 15-20% of these wastes are classified as infectious wastes that could be hazardous. Therefore, an effective approach is required for handling costs and environmental issues. In this paper, a bi-objective Mixed-Integer Linear Programming (MILP) model is presented for logistics of infectious and non-infectious wastes. The proposed bi-objective model aims to minimize network costs and the risk of exposure to contamination. In this respect, a multi-stage network consisting of hospitals, recycling centres, treatment centres, disposal centres, mainly covering the location-routing problem, is considered. To deal with computational complexity of the proposed model, a Benders Decomposition Algorithm (BDA) has been employed. The researchers were faced with two important questions: (1) whether the proposed model can be applied to real-world scenarios or not, and (2) how efficient is the proposed algorithm in solving standard test problems and real-world cases. To answer these questions, the outputs of the BDA have been compared with the optimal solutions provided by the CPLEX software. The results imply that the BDA has been able to achieve optimal solutions in less computation times. Moreover, the proposed model and algorithm have been applied to a real-world study in Alborz Province of Iran. The outputs demonstrate that the proposed model and algorithm can yield applicable solutions for the case study which have been approved by experts. The proposed model can be extended by considering compatibility of wastes in storage.

Keywords: Benders Decomposition Algorithm, infectious waste management, location-routing problem, mathematical programming

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1. Introduction

Since the Industrial Revolution, the volume and diversity of wastes had grown so high that led to a considerable threatening issue. This dramatic increase in waste amount has caused problems, most notably to the surroundings and well-being of community. Hence, waste management has attracted the attention of researchers, practitioners, and authorities. They provided various solutions for collecting, transporting, processing, recycling, and disposing wastes (Windfeld and Brooks, 2015). Health-related wastes are divided into infectious and non-infectious groups and embrace a wide range of materials. In other words, the term "waste" includes all wastes that are produced in healthcare centers, research centers, and medical laboratories. In addition, this category also comprises the wastes that are produced at homes for medical care (Chartier et al., 2014).

Designing an efficient supply chain network to manage wastes in the healthcare sector is one of the main challenges in this area, as lack of proper management in addition to environmental pollution, will cause serious problems for the hospitals and healthcare centers. In designing healthcare networks, humanitarian and environmental issues have great importance and should be considered in addition to

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cost minimization. In designing these networks, many strategic decisions must be made that inappropriate decisions lead to cost growth in the chain and increase the risk of the chain. These strategic decisions include selecting suitable locations for decontaminating, recycling, and getting rid of wastes. Moreover, suitable treatment technologies should be chosen for treatment centers to disinfect infectious wastes. Besides, paying attention to tactical decisions, such as routing the fleet will affect the amount of cost and the risk of getting infected (Nikzamir and Baradaran, 2020). This research offers a new mathematical model for tackling hospital wastes. Costs and risk of exposure to infectious materials are minimized in this model. The proposed model also selects the best available treatment technology to disinfect infectious wastes.

The location-routing problems (LRPs) are categorized as NP-hard problems, and therefore there is a necessity to use powerful methods to obtain appropriate solutions (Rabbani et al., 2018). This necessity motivated the researchers to develop a Benders Decomposition Algorithm (BDA) to deal with computational complexity of this problem. Several standard test problems have been generated to evaluate the BDA. By using the CPLEX software, we have solved the test problems and optimal results have been ensued. Then, the performance of the BDA has been compared with the optimal solutions acquired by the CPLEX. Both the model and the BDA were used to tackle a real case study. Hence, the applicability of the model and the BDA was demonstrated. This real case study is a waste collection network in Alborz Province in Iran. Once again, for the case study, the outputs of the BDA were validated by comparing to the optimal solutions of the CPLEX. The questions that challenge the researchers of this study are:

1. Is the proposed model suitable for real-world waste collection network?; 2 How efficient is the proposed BDA method in solving test problems and real-world cases?; 3) Are the outputs of the proposed model and algorithm offer feasible and practical solutions for real-world situations?

The remainder of the study is structured as follows: Section 2 reviews the background of the waste management problem. The problem's description and the proposed formulation are found in Section 3. In Section 4, the developed BDA is explicated. Thereafter, computational outputs come in Section 5. Section 6 is dedicated to a real case study. Section 7 concludes the paper and presents some directions for future studies.

2. Literature review

In this section, the literature related to the waste collection networks is reviewed in two classes of hazardous materials transportation and healthcare wastes. At the end of this section, the novelties of this research has been elaborated as well.

2.1. Hazardous materials transportation

Because of infectious components of hazardous materials, these substances endanger the surroundings and lives of people. Due to the fact that unpleasant incidents during transportation of hazardous substances can endanger the surroundings and well-being of people, the risk of transporting hazardous materials should be assessed (Hu et al., 2018). There is a considerable number of studies on transportation risks of hazardous substances. Samanlioglu (2013) addressed the location-routing problem for handling hazardous wastes in Marmara, Turkey. Ardjmand et al. (2015) proposed a mathematical model for location and routing of facilities and disposal sites with consideration of risk and shipping costs. They used a Genetic Algorithm (GA) to solve their model. In another study, Ardjmand et al. (2016) developed a stochastic model to locate, transport, and allocate hazardous substances. Zhao et al. (2016) investigated the performances of different multi-objective optimization algorithms on handling regional hazardous wastes. Faghih-Roohi et al. (2016) presented a dynamic formulation to estimate the transportation risk of hazardous materials in the supply chain. They also developed an analytical solution algorithm for routing of hazardous materials with consideration of optimal times. Wang et al. (2018) presented a bi-objective vehicle routing model for transportation of hazardous substances to minimize the risk of any vehicle and shipping costs.

To solve this problem, they proposed a two-phase method inspired from the ε-constraint technique. Due to the impact of hazardous materials on human life, Mahmoudsoltani et al. (2018) developed a mathematical model for locating the facilities and routing the fleet of vehicles to ensure safe transportation of hazardous materials. They applied three multi-objective methods to solve the problem.

Hu et al. (2018) investigated the balance between the cost and the risk of transporting hazardous materials considering the fuzzy demands of retailers. In this research, a three-tier supply chain problem was considered, including suppliers, manufacturers, and retailers. Bula et al. (2019) developed a bi-objective model for designing a transportation network of hazardous materials using vehicle routing issues. They created a trade-off between transportation costs and the risk of selective routes. Rabbani et al. (2019) offered a multi-objective formulation for managing industrial waste. They integrated the NSGA-II and Monte Carlo Simulation to deal with stochastic environment of the problem. To detect the most appropriate vehicle in an intuitionistic fuzzy environment, Büyüközkan et al. (2019) suggested a Multi-Attribute Decision Making (MADM) approach consisting of Analytical Hierarchy Process (AHP) and Višekriterijumsko kompromisno rangiranje (VIKOR) under group decision making.

Kolekar and Agrawal (2019) investigated on the employed optimization algorithms used in the literature for the waste management problem. We reviewed the most relevant studies to the current research, however, there are other related researches that studied the transportation of different materials such as the hazardous ones: Batta and Chiu (1988); Baradaran et al. (2019); Chen and Lin (2009); Du et al. (2016); Du et al. (2017); Erkut and Ingolfsson (2000); Kundu et al. (2017); Li and Liu (2016); Zografos and Androutsopoulos (2004); List et al. (1991); Olapiriyakul et al. (2019); Pradhananga et al. (2010); Pradhananga et al. (2014); Verma and Verter (2007); Yuan et al. (2015); Zografos and Androutsopoulos (2008).

2.2. Healthcare wastes

Researches in the field of waste management can be classified into various ways; one of the most common classifications is the type of wastes. Based on the composition of these materials, it is possible to select and design a suitable method for disposal of these wastes (Altin et al., 2003). In order to design a hospital waste disposal system, it is essential to know the amount of wastes and their compositions. The production and composition of waste materials rely on the number and sort of sections in each hospital, the number of hospitalized patients and outpatient treatment (Komilis et al., 2011). Alagöz and Kocasoy (2008) examined the methods of isolation, collection, temporary storage, and transportation of the wastes inside and outside of the healthcare centers in Istanbul, Turkey. Al-Khatib and Sato (2009) investigated healthcare waste management in the West Bank, the Palestinian Territory. Having reviewed international requirements, they discovered that the global and local standards are remarkably different. Thus, they concluded that this issue should be significantly addressed.

The use of mathematical programming models in management of hospital wastes, especially transportation, has been of interest to the researchers and practitioners. Shih and Chang (2001) developed a mathematical programming model to perform the task of routing and scheduling the fleet. They used a two-stage solution approach to solve the problem. In order to evaluate the efficiency and effectiveness of the proposed approach, it was implemented for the data of 348 hospitals in Tainan, Taiwan. Shanmugasundaram et al. (2012) analysed the use of Management Information Systems (MIS), Geographic Information System (GIS), spatial distribution of large waste sites, location of centralized treatment facilities, and the design of optimal transportation routes for waste collection in Laos. Shi (2009) developed an MILP model with the goal of minimizing costs in order to design a reverse logistics network for hospital wastes. This network includes the levels of hospitals, collection centers, processing centers, and factories, which locates several centers for collections and processing. Nolz et al. (2014) presented an inventory routing problem for waste collection. They used a two-stage probabilistic model. The first stage deals with determining optimal route of each vehicle. The second stage determines the number of batches allocated to each pharmacy. Hachicha et al. (2014) modelled the routing problem under uncertainty for transportation of hospital wastes in Tunisia. Their model aimed to minimize transportation costs considering the limited capacity of vehicles. Naji-Azimi et al. (2016) offered a VRP model with multiple trips. Mantzaras and Voudrias (2017) developed a mathematical model for managing costs of hospital waste collection. Thakur and Ramesh (2017) developed an approach based on the analytical hierarchy process and Grey Theory to choose the appropriate strategies for waste disposal in the health sector. They chose a disposal strategy at the waste site based on several criteria such as access to expertise, excessive dependency, transportation, and related risks, government regulations, environmental factors, and economic factors. Hajar et al. (2018) developed a formulation for on-site gathering of medical waste materials. An approach based on the AHP and GA was proposed by Wichapa and Khokhajaikiat (2018) for the LRP. Çetinkaya et al. (2019) used the multiple regression method to build a prediction model. This model estimates the amount of medical wastes produced by the healthcare centers existing in Aksaray city, Turkey. Zamparas et al. (2019) evaluated the handling techniques of infectious wastes by means of a multi-criteria model. Babaee Tirkolaee et al. (2019) considered the collection of urban wastes as a VRP with multiple trips and developed a mathematical model for this problem. Their model has been solved by a Simulated Annealing (SA) algorithm. Aung et al. (2019) used the Multi-Criteria-Decision-Analysis (MCDA) methods to model a framework for evaluating medical waste mangament attributes. Wang et al. (2019) developed a waste recycling network for medical wastes by means of a two-stage approach. In the first stage, they used the Grey prediction model to estimate the amount of wastes generated in hospitals. The second stage proposes a multi-objective optimization model for minimizing environmental degradation and costs, simultaneously. To service a set of hospitals, Khoukhi et al. (2019) addresssed the MT-VRPTW with simultaneous pickup and delivery. The researchers presented a genetic algorithm which employs the route-first cluster-second approach to minimize total costs. Yu et al. (2020) designed a reverse logistic network for managing medical wastes in epidemic outbreaks. Lou et al. (2020) developed a management tool based on a weighted graph model for disposal of municipal wastes.

2.3. Novelties of this study

Reviewing considerable number of studies in the waste management problem persuaded the researchers of this paper that there is a necessity to design a network that embraces harmful and un-harmful wastes, concurrently. To model this network, a new linear programming formulation has been offered. The objectives of the developed formulation consider economic and environmental perspectives, simultaneously. The proposed model considers the routing of a heterogeneous number of vehicles that visit hospitals to gather wastes. Through this model, proper locations for facilities are selected as well. Due to high number of constraints and variables that incorporate real-world characteristics of the waste management problem, the proposed model became significantly complex. To solve such a complex model, the authors were led to develop a powerful tool which can provide appropriate and applicable solutions. Therefore, a Benders decomposition algorithm has been developed which is usually used for solving large linear programming problems. According to our investigations, the effectiveness of the BDA has not been examined for the problem with the aforementioned characteristics. Hence, as another contribution of this research, the performance of the Benders decomposition algorithm has been evaluated as well.

3. Problem description and proposed model

The proposed network considers different elements including hospitals and centers of treatment, recycling, and disposal. Infectious waste collection vehicles move from treatment centers to hospitals and return to treatment centers after collecting all infectious wastes. In treatment centers, the infectious wastes are treated and recyclable ones are transferred to recycling centers and the rest is buried in disposal centers. Then, the recycling centers also dispose of a fraction of the waste that cannot be recycled, and the remainder will be recycled. On the other hand, vehicles that collect non-infectious wastes travel from recycling centers to hospitals. They will ultimately return to recycling centers. The continuation of this network will be like infectious wastes (Fig. 1) illustrates the structure of the proposed network. Since the operating costs of this system is significantly important for organizations, we have added the minimization of costs as an objective in the model. Besides, the exposure of infectious wastes to population has a detrimental impact. To incorporate this dangerous impact to population, the second objective function, which is minimization of the exposure risk to contamination has been considered in the proposed model. We review the assumptions of the model in the following:

- The network presumed to have multiple levels and products.
- The locations of hospitals are known, but other centers will be located by the proposed formulation.
- Gathering infectious wastes between healthcare center and treatment centers is performed via the routing process.
- Gathering non-infectious waste between hospitals and recycling centers is carried out through routing decisions.
- Different technologies are used to neutralize infectious wastes.
- Vehicles and centers have limited capacities.
- The separation of recyclable and non-recyclable wastes is performed in recycling centers.
- The fleet of vehicles is heterogeneous.
- The length of time required to traverse between two hospitals varies per vehicle.
- It is possible to visit any hospital by any vehicle at most once, but may visit several vehicles of a hospital (Split-delivery).
- Any carrier for gathering infectious waste must be assigned to a treatment center.
- Any carrier for gathering non-infectious waste must be assigned to a recycling center.
- The multi-depot routing problem is considered.

Soft and hard time windows are considered, simultaneously. Table 1, Table 2, and Table 3 show the indices, parameters, and variables of the model, respectively.

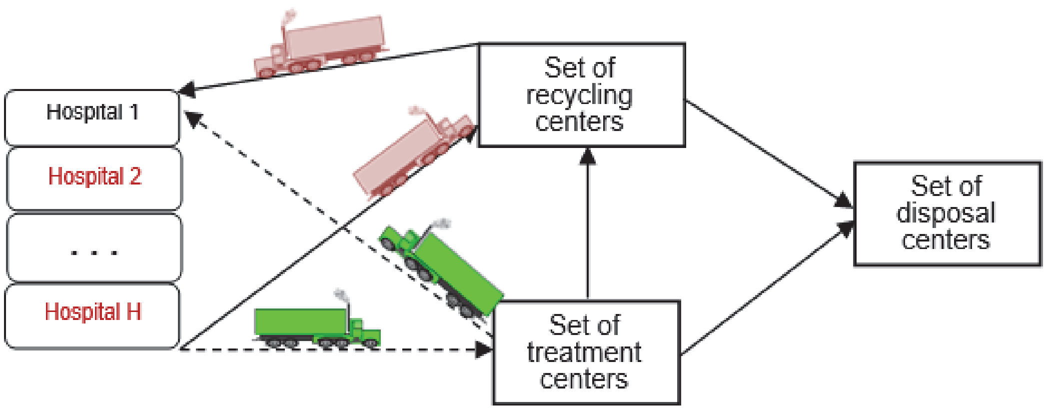

Fig. 1. The network's structure

Table 1. Indices used in the formulation

Indices	*Definition*	*Domain*
i	Infectious wastes	$(1 \le i \le I)$
n	Non-infectious wastes	$(1 \le n \le N)$
h, h'	Hospitals	$(1 \le h \le H)$
f	Treatment technology	$(1 \le f \le F)$
t	Treatment center	$(1 \le t \le T)$
r	Recycling center	$(1 \le r \le R)$
d	Disposal center	$(1 \le d \le D)$
k	Set of vehicles for gathering infectious wastes	$(1 \le k \le K)$
l	Set of vehicles for gathering non-infectious wastes	$(1 \le l \le L)$

Table 2. Parameters of the proposed mathematical model

Parameter	*Definition*
CF_{tf}^{treat}	Fixed cost of opening treatment center t with technology level f
CF_{r}^{recy}	Fixed cost of opening recovery center r
CF_{d}^{dis}	Fixed cost of opening disposal center d
$CF_{k}^{v-treat}$	Constant cost of employing vehicle type k for gathering infectious wastes
CF_{l}^{v-recy}	Constant cost of employing vehicle type l for gathering non-infectious wastes
PR_{itf}^{treat}	Cost of treating infectious waste type i in treatment center t with technology type f (each unit)
$PR_{ir}^{treat-recy}$	Cost of recycling infectious waste type i, in treatment center r (each unit)
PR_{nr}^{recy}	Cost of recycling non-infectious waste type n, in treatment center r (each unit)
$PR_{id}^{treat-dis}$	Cost of disposing infectious waste i in disposal center d (each unit)
$PR_{nd}^{recy-dis}$	Cost of disposing non-infectious waste n in disposal center d (each unit)
$TR_{itr}^{treat-recy}$	Transportation cost of infectious waste type i from treatment center t to recycling center r (each unit)
$TR_{itd}^{treat-dis}$	Transportation cost of infectious waste type i from treatment center t to disposal center d (each unit)
$TR_{nrd}^{recy-dis}$	Transportation cost of non-infectious waste type n from recycling center r to disposal center d (each unit)
$treat_{tf}^{cap}$	Capacity of treatment center t with technology level f
$recy_{r}^{cap}$	Capacity of recycling center r
dis_{d}^{cap}	Capacity of disposal center d
$v_{k}^{cap-treat}$	Capacity of vehicle type k for collecting infectious wastes
$v_{l}^{cap-recy}$	Capacity of vehicle type l for collecting non-infectious wastes
$\eta_{h'h}^{ds-hos}$	Distance between hospital h and hospital h’
$\eta_{ht}^{treat-hos}$	Distance that must be travelled between hospital h and treatment center t by a vehicle
$\eta_{hr}^{recy-hos}$	Distance that must be travelled between hospital h and recycling center r by a vehicle
$\eta_{kh'h}^{tm-hos}$	Amount of time elapse to travel between hospital h’ and hospital h by vehicle type k
$\eta_{kht}^{tm-treat}$	Amount of time elapse to travel between hospital h and treatment center t by vehicle type k
$\eta_{lrt}^{tm-recy}$	Amount of time elapse to travel between hospital h and recycling center r by vehicle type l
twl_{h}	Time window’s lower bound for gathering infectious materials from hospital h
twu_{h}	Time window’s upper bound for gathering infectious materials from hospital h without paying penalty
$twup_{h}$	Time window’s upper bound for gathering infectious materials from hospital h with paying penalty
w_{ih}^{infec}	Amount of material type i that is produced by hospital h (infectious material)
$w_{nh}^{non-infec}$	Amount of material type n that is produced by hospital h (non-infectious material)
$p_{itf}^{treat-recy}$	Recycling rate of infectious material i in treatment center t with technology type f
$p_{nr}^{recy-dis}$	Rate of non-recyclable waste type n obtained from recycling center r
$POP_{h'h}$	Amount of population located between hospitals h and h’
fvt_{k}	Amount of fuel consumed for each distance unit with vehicle type k

fvr_l	Amount of fuel consumed for each distance unit with vehicle type l
p^{fuel}	Unit price of fuel
pc	Penalty for violating the time window
M	A very big number

Table 3. Variables of the proposed mathematical model

Variable	*Type*	*Definition*
$\alpha_{tf}^{treat}\begin{cases}1\\0\end{cases}$	Binary	If treatment center t is opened with technology level f Otherwise
$\alpha_{r}^{recy}\begin{cases}1\\0\end{cases}$	Binary	If recycling center r is opened Otherwise
$\alpha_{d}^{dis}\begin{cases}1\\0\end{cases}$	Binary	If disposal center d is opened Otherwise
$veh_{k}^{treat}\begin{cases}1\\0\end{cases}$	Binary	If vehicle k is utilized for collecting infectious wastes Otherwise
$veh_{l}^{recy}\begin{cases}1\\0\end{cases}$	Binary	If vehicle l is utilized for collecting infectious wastes Otherwise
$\beta_{kt}^{treat}\begin{cases}1\\0\end{cases}$	Binary	If vehicle k is assigned to treatment center t Otherwise
$\beta_{lr}^{recy}\begin{cases}1\\0\end{cases}$	Binary	If vehicle l is assigned to recycling center r Otherwise
$tour_{kh'h}^{treat}\begin{cases}1\\0\end{cases}$	Binary	If vehicle k goes from hospital h' to hospital h Otherwise
$tour_{lh'h}^{recy}\begin{cases}1\\0\end{cases}$	Binary	If vehicle l goes from hospital h' to hospital h Otherwise
$atrm_{kh}$	Positive	The time that vehicle k enters hospital h
x_{kh}	Positive	Amount of time violated from the time window by vehicle k at hospital h
y_{ikth}^{treat}	Positive	Amount of infectious waste i collected from hospital h by treatment center t through vehicle k
y_{nlrh}^{recy}	Positive	Amount of infectious waste i collected from hospital h by recycling center r through vehicle l
y_{nlh}	Positive	Amount of material type n in vehicle l when entering hospital h (non-infectious material)
$z_{itr}^{treat-recy}$	Positive	Amount of infectious waste i treated and transported from treatment center t to recycling center r
$z_{nrd}^{recy-dis}$	Positive	Amount of non-infectious waste n transported to disposal center d from recycling center r
$z_{itd}^{treat-dis}$	Positive	Amount of material type i treated and transported to disposal center d from treatment center t (infectious material)

3.1. Mathematical formulation

Eq. (1) minimizes all costs of the network (first objective of the developed model). The second objective function (Eq. 2) is to minimize the risk of population exposed to the spread of harmful substances originated from infectious materials. Eq. (3) takes care of the limited capacity of treatment centers. Eqs. (4-7) present constraints on capacity of recycling facilities, fuel, and carriers. Eqs. (8-9) guarantee that a vehicle departs after gathering waste materials. Eq. (10) and Eq. (11) state that each vehicle can visit each hospital at most once. Eq. (12) assures that any vehicle carrying infectious material must be allocated to a treatment center, as well as Eq. (13) for vehicles carrying non-infectious wastes. A vehicle can be assigned to a center if the respective center has already been set up. For both types of wastes, this condition have been presented in Eqs. (14-15), respectively. Restrictions on the removal of the sub-tour, the sequencing of visiting hospitals, and the implementation of a time-window for gathering infectious wastes are presented in Eqs. (16-17). Eqs. (18-19) calculate the extent of violations of soft windows. Restrictions on the clearance of sub-tours and the sequence of visits to hospitals by vehicles carrying non-infectious wastes are shown in Eqs. (20-23) guarantee that all wastes are gathered from hospitals. Eqs. (24-25) state that a vehicle can gather wastes of a hospital if it visits the hospital. Another condition for collecting wastes from hospitals is that, firstly, the vehicle employed is allocated to a facility; these conditions for vehicles carrying infectious wastes are ensured in the Eqs. (26-28) respectively, and for vehicles transporting non-infectious wastes is mentioned in the Eqs. (27-29). Eqs. (30-31) compute the quantity of infectious materials from treatment to recycling facilities.

Eq. (32) computes the quantity of non-infectious materials from treatment to recycling facilities. Eqs. (33-34) satisfy the conditions for receiving wastes by respective facilities. Besides, the condition for sending infectious materials from treatment to recycling centers is presented in the Eqs. (35-36). In addition, Eq. (37) indicates the condition for transferring infectious wastes from treatment centers to disposal centers. Eqs. (38-39) satisfy the condition for carrying non-infectious type of materials from recycling to nodes.

3.2. Linearization

In the Eq.(1), $tour_{kh'h}^{treat} \times \beta_{kt}^{treat}$ and $tour_{lh'h}^{recy} \times \beta_{lr}^{recy}$ terms are the causes of non-linearity. To linearize the model, two dummy variables,

$$t\beta_{lh'hr}^{recy} \text{ and } t\beta_{kh'ht}^{treat},$$

are defined and replaced with non-linear terms. Then, the non-linear objective function should be replaced with Eqs. (40-48) as follows:

$$\begin{aligned}
Min \ \ Z^{Cost} = & \sum_{t,f} CF_{tf}^{treat} \times \alpha_{tf}^{treat} + \sum_{r} CF_{r}^{recy} \times \alpha_{r}^{recy} + \sum_{d} CF_{d}^{dis} \times \alpha_{d}^{dis} + \\
& \sum_{k} CF_{k}^{v-treat} \times veh_{k}^{treat} + \sum_{l} CF_{l}^{v-recy} \times veh_{l}^{recy} + \sum_{i,k,t,f,h} PR_{itf}^{treat} \times y_{ikth}^{treat} + \\
& \sum_{i,t,r} PR_{ir}^{treat-recy} \times z_{itr}^{treat-recy} + \sum_{i,t,d} PR_{id}^{treat-dis} \times z_{itd}^{treat-dis} + \\
& \sum_{n,l,r,h} PR_{nr}^{recy} \times (1 - p_{nr}^{recy-dis}) \times y_{nlrh}^{recy} + \sum_{n,r,d} PR_{nd}^{recy-dis} \times z_{nrd}^{recy-dis} + \\
& \sum_{i,t,r} TR_{itr}^{treat-recy} \times z_{itr}^{treat-recy} + \sum_{i,t,d} TR_{itd}^{treat-dis} \times z_{itd}^{treat-dis} + \\
& \sum_{n,r,d} TR_{nrd}^{recy-dis} \times z_{nrd}^{recy-dis} + \sum_{k,h} x_{kh} \times pc + \\
& p^{fuel} \times \Big(\sum_{k,\hat{h}>1,h>1} fvt_{k} \times tour_{k\hat{h}h}^{treat} \times \eta_{\hat{h}h}^{ds-hos} + \\
& \sum_{k,h>1,t} fvt_{k} \times \eta_{ht}^{treat-hos} \times \beta_{kt}^{treat} \times (tour_{k1h}^{treat} + tour_{kh1}^{treat}) \Big) + \\
& p^{fuel} \times \Big(\sum_{l,\hat{h}>1,h>1} fvr_{l} \times tour_{l\hat{h}h}^{recy} \times \eta_{\hat{h}h}^{ds-hos} + \\
& \sum_{k,h>1,t} fvr_{l} \times \eta_{hr}^{recy-hos} \times \beta_{lr}^{recy} \times (tour_{l1h}^{recy} + tour_{lh1}^{recy}) \Big) +
\end{aligned} \tag{1}$$

$$Min \ Z^{Risk} = \sum_{k,h',h} POP_{h'h} \times tour_{kh'h}^{treat} \tag{2}$$

***Subject to*:**

$$\sum_{i,k,h} y_{ikth}^{treat} \le treat_{tf}^{cap} \times \alpha_{tf}^{treat} \qquad \forall t, f \tag{3}$$

$$\sum_{n,l,h} y_{nlrh}^{recy} + \sum_{i,t} z_{itr}^{treat-recy} \le recy_{r}^{cap} \times \alpha_{r}^{recy} \qquad \forall r \tag{4}$$

$$\sum_{n,r} z_{nrd}^{recy-dis} + \sum_{i,t} z_{itd}^{treat-dis} \le dis_{d}^{cap} \times \alpha_{d}^{cap} \qquad \forall d \tag{5}$$

$$\sum_{i,h} y_{ikth}^{treat} \le v_{k}^{cap-treat} \times veh_{k}^{traet} \qquad \forall k, t \tag{6}$$

$$\sum_{n,h} y_{nlrh}^{recy} \le v_{l}^{cap-recy} \times veh_{l}^{recy} \qquad \forall l, r \tag{7}$$

$$\sum_{h'} tour_{kh'h}^{treat} = \sum_{h'} tour_{khh'}^{treat} \qquad \forall k, h \tag{8}$$

$$\sum_{h'} tour_{lh'h}^{recy} = \sum_{h'} tour_{lhh'}^{recy} \qquad \forall l, h \tag{9}$$

$$\sum_{h'} tour_{kh'h}^{treat} \le 1 \qquad \forall k, h \tag{10}$$

$$\sum_{h'} tour_{lh'h}^{recy} \leq 1 \qquad \forall l,h \tag{11}$$

$$\sum_{t} \beta_{kt}^{treat} \leq 1 \qquad \forall k \tag{12}$$

$$\sum_{r} \beta_{lr}^{recy} \leq 1 \qquad \forall l \tag{13}$$

$$\sum_{t} \beta_{kt}^{treat} \leq M \times \alpha_{tf}^{treat} \qquad \forall t,f \tag{14}$$

$$\sum_{l} \beta_{lr}^{recy} \leq M \times \alpha_{r}^{recy} \qquad \forall r \tag{15}$$

$$artm_{kh} + (1 - tour_{kh'h}^{treat}) \times M \geq artm_{kh'} + \eta_{kh'h}^{tm-hos} \qquad \forall k,h',h>1 \tag{16}$$

$$twup_{h} + (1 - tour_{kh1}^{treat}) \times M \geq artm_{kh} + \eta_{kht}^{tm-treat} \times \beta_{kt}^{treat} \qquad \forall k,h,t \tag{17}$$

$$atrm_{kh} \geq twl_{h} \qquad \forall k,h \tag{18}$$

$$atrm_{kh} - twu_{h} \leq x_{kh} \qquad \forall p,r \tag{19}$$

$$y_{nlh} + (1 - tour_{lh'h}^{recy}) \times M \geq y_{nlh'} + y_{nlrh'}^{recy} \qquad \forall n,l,r,h',h \tag{20}$$

$$y_{nl1} \geq \sum_{h} y_{nlrh}^{recy} \qquad \forall n,l,r \tag{21}$$

$$\sum_{k,t} y_{ikth}^{treat} \geq w_{ih}^{infec} \qquad \forall i,h \tag{22}$$

$$\sum_{l,r} y_{nlrh}^{recy} \geq w_{ih}^{non-infec} \qquad \forall n,h \tag{23}$$

$$y_{ikth}^{treat} \leq M \times \sum_{h'} tour_{kh'h}^{treat} \qquad \forall i,k,t,h \tag{24}$$

$$y_{nlrh}^{recy} \leq M \times \sum_{h'} tour_{lh'h}^{recy} \qquad \forall n,l,r,h \tag{25}$$

$$y_{ikth}^{treat} \leq M \times veh_{k}^{treat} \qquad \forall i,k,t,h \tag{26}$$

$$y_{nlrh}^{recy} \leq M \times veh_{l}^{recy} \qquad \forall n,l,r,h \tag{27}$$

$$y_{ikth}^{treat} \leq M \times \beta_{kt}^{treat} \qquad \forall i,k,t,h \tag{28}$$

$$y_{nlrh}^{recy} \leq M \times \beta_{lr}^{recy} \qquad \forall n,l,r,h \tag{29}$$

$$\sum_{k,h} y_{ikth}^{treat} = \sum_{r} z_{itr}^{treat-recy} + \sum_{d} z_{itd}^{treat-dis} \qquad \forall i,t \tag{30}$$

$$\sum_{r} z_{itr}^{treat-recy} = \sum_{f,k,h} p_{itf}^{treat-recy} \times y_{ikth}^{treat} \qquad \forall i,t \tag{31}$$

$$\sum_{d} z_{nrd}^{recy-dis} = \sum_{l,h} p_{nrd}^{recy-dis} \times y_{nlrh}^{recy} \qquad \forall n,r \tag{32}$$

$$y_{ikth}^{treat} \leq M \times \alpha_{tf}^{treat} \qquad \forall i,k,t,f,h \tag{33}$$

$$y_{nlrh}^{recy} \leq M \times \alpha_{r}^{recy} \qquad \forall n,l,r,h \tag{34}$$

$$z_{itr}^{treat-recy} \leq M \times \alpha_{tf}^{treat} \qquad \forall i,t,f,r \tag{35}$$

$$z_{itr}^{treat-recy} \leq M \times \alpha_{r}^{recy} \qquad \forall i,t,r \tag{36}$$

$$z_{itd}^{treat-dis} \leq M \times \alpha_{d}^{dis} \qquad \forall i,t,d \tag{37}$$

$$z_{nrd}^{recy-dis} \leq M \times \alpha_{r}^{recy} \qquad \forall n,r,d \tag{38}$$

$$z_{nrd}^{recy-dis} \leq M \times \alpha_{d}^{dis} \qquad \forall n,r,d \tag{39}$$

$$\begin{aligned} Min \ \ Z^{Cost} = & \sum_{t,f} CF_{tf}^{treat} \times \alpha_{tf}^{treat} + \sum_{r} CF_{r}^{recy} \times \alpha_{r}^{recy} + \sum_{d} CF_{d}^{dis} \times \alpha_{d}^{dis} + \\ & \sum_{k} CF_{k}^{v-treat} \times veh_{k}^{treat} + \sum_{l} CF_{l}^{v-recy} \times veh_{l}^{recy} + \sum_{i,k,t,f,h} PR_{itf}^{treat} \times y_{ikth}^{treat} + \\ & \sum_{i,t,r} PR_{ir}^{treat-recy} \times z_{itr}^{treat-recy} + \sum_{i,t,d} PR_{id}^{treat-dis} \times z_{itd}^{treat-dis} + \\ & \sum_{n,l,r,h} PR_{nr}^{recy} \times (1 - p_{nr}^{recy-dis}) \times y_{nlrh}^{recy} + \sum_{n,r,d} PR_{nd}^{recy-dis} \times z_{nrd}^{recy-dis} + \\ & \sum_{i,t,r} TR_{itr}^{treat-recy} \times z_{itr}^{treat-recy} + \sum_{i,t,d} TR_{itd}^{treat-dis} \times z_{itd}^{treat-dis} + \\ & \sum_{n,r,d} TR_{nrd}^{recy-dis} \times z_{nrd}^{recy-dis} + \sum_{k,h} x_{kh} \times pc + \\ & p^{fuel} \times \Big(\sum_{k,\hat{h}>1,h>1} fvt_{k} \times tour_{k\hat{h}h}^{treat} \times \eta_{\hat{h}h}^{ds-hos} + \sum_{k,h>1,t} fvt_{k} \times \eta_{ht}^{dis-treat} \times (t\beta_{k1ht}^{treat} + t\beta_{kh1t}^{treat}) \Big) + \\ & p^{fuel} \times \Big(\sum_{l,\hat{h}>1,h>1} fvr_{l} \times tour_{l\hat{h}h}^{recy} \times \eta_{\hat{h}h}^{ds-hos} + \sum_{k,h>1,t} fvr_{l} \times \eta_{hr}^{dis-recy} \times (t\beta_{l1hr}^{recy} + t\beta_{lh1r}^{recy}) \Big) \end{aligned} \tag{40}$$

$$t\beta_{kh'ht}^{treat} \leq t\beta_{kt}^{treat} + (1 - tour_{kh'h}^{treat}) \times M \tag{41}$$

$$t\beta_{kh'ht}^{treat} \leq tour_{kh'h}^{treat} + (1 - \beta_{kt}^{treat}) \times M \tag{42}$$

$$t\beta_{kh'ht}^{treat} \geq 1 + (tour_{kh'h}^{treat} + \beta_{kt}^{treat} - 2) \times M \tag{43}$$

$$t\beta_{kh'ht}^{treat} \leq (tour_{kh'h}^{treat} + \beta_{kt}^{treat}) \times M \tag{44}$$

$$t\beta_{lh'hr}^{recy} \leq t\beta_{lr}^{recy} + (1 - tour_{lh'h}^{recy}) \times M \tag{45}$$

$$t\beta_{lh'hr}^{recy} \leq tour_{lh'h}^{recy} + (1 - \beta_{lr}^{recy}) \times M \tag{46}$$

$$t\beta_{lh'hr}^{recy} \geq 1 + (tour_{lh'h}^{recy} + \beta_{lr}^{recy} - 2) \times M \tag{47}$$

$$t\beta_{lh'hr}^{recy} \leq (tour_{lh'h}^{recy} + \beta_{lr}^{recy}) \times M \tag{48}$$

4. Solution approach

4.1. Benders decomposition algorithm

According to Mirchandani and Francis (1990), with so much complexity, the facility location problem has been proven to be an NP-hard problem. In this regard, the Benders Decomposition Algorithm is employed to cope with computational complexity of the mathematical model. This algorithm is developed by Benders (1962) to efficiently solve large-scale MIP models through decomposing the original problem into a master problem (MP) and a sub-problem (SP). The MP and dual of sub-problem (DSP) are solved iteratively and optimal solutions are used in the other one until the termination criterion is met.

4.1.1. Master problem

To implement the algorithm, the MP is developed based on Eqs. (49-58).

In the above model, if integer variables are fixed to feasible values, the sub-problem is apparently linear. Therefore, its dual feasible space is independent from integer variables.

4.1.2. Sub-problem

The sub-problem and its corresponding dual are presented as follows. Let $dv_{\circ}^{\circ}$ represent the dual variables of the constraints of the formulated SP (Eqs. 59-88).

4.1.3. Dual Sub-problem (DSP)

According to Benders (1962), if the SP is unbounded or infeasible, the solution space of the DSP is empty. This means that the model is developed wrongly. On the other hand, with the correct modeling, the DSP will have bounded or unbounded solution space. Accordingly, the solution space of the DSP has extreme points and extreme rays. As the DSP's being unbounded leads to infeasibility of the SP, to avoid the DSP from unbounded solutions, the following constraints as feasibility cuts are integrated into the dual sub-problem. Moreover, the upper bound acquired by the master problem is integrated into the dual sub-problem. In each iteration, only one of the feasibility or optimality cuts is added (Eqs. 89-101).

4.1.4. Optimality cut

According to the aforementioned explanations, the algorithm is explicated step by step:

Step 1. Set $LB = -\infty$ and $UB = +\infty$.

Step 2. Set binary variables equal to 1 as an initial feasible value.

Step 3. Solve the disaggregated dual sub-problems to detect the optimal quantity of dual variables ($dv_{\circ}^{\circ}$).

Step 4. Form the master problem by adding optimality and feasibility cuts.

Step 5. Solve the master problem and set $UB = MSP$.

Step 6. If $UB - LB < \varepsilon$, then stop the algorithm and report the obtained solution and relevant objective function value; otherwise, go to Step 3.

$$\begin{aligned} Min\ \ Z^{Cost} = &\sum_{t,f} CF_{tf}^{treat} \times \alpha_{tf}^{treat} + \sum_{r} CF_{r}^{recy} \times \alpha_{r}^{recy} + \sum_{d} CF_{d}^{dis} \times \alpha_{d}^{dis} + \\ &p^{fuel} \times (\sum_{k,\hat{h}>1,h>1} fvt_{k} \times tour_{k\hat{h}h}^{treat} \times \eta_{\hat{h}h}^{ds-hos} + \sum_{k,h>1,t} fvt_{k} \times \eta_{ht}^{dis-treat} \times \beta_{kt}^{treat} \times (tour_{k1h}^{treat} + tour_{kh1}^{treat})) + \\ &p^{fuel} \times (\sum_{l,\hat{h}>1,h>1} fvr_{l} \times tour_{l\hat{h}h}^{recy} \times \eta_{\hat{h}h}^{ds-hos} + \sum_{k,h>1,t} fvr_{l} \times \eta_{hr}^{dis-recy} \times \beta_{lr}^{recy} \times (tour_{l1h}^{recy} + tour_{lh1}^{recy})) \end{aligned} \quad (49)$$

$$Min\ Z^{Risk} = \sum_{k,h',h} POP_{h'h} \times tour_{kh'h}^{treat} \quad (50)$$

$$\sum_{h'} tour_{kh'h}^{treat} = \sum_{h'} tour_{khh'}^{treat} \qquad \forall k,h \quad (51)$$

$$\sum_{h'} tour_{lh'h}^{recy} = \sum_{h'} tour_{lhh'}^{recy} \qquad \forall l,h \quad (52)$$

$$\sum_{h'} tour_{kh'h}^{treat} \le 1 \qquad \forall k,h \quad (53)$$

$$\sum_{h'} tour_{lh'h}^{recy} \le 1 \qquad \forall l,h \quad (42)$$

$$\sum_{t} \beta_{kt}^{treat} \le 1 \qquad \forall k \quad (55)$$

$$\sum_{r} \beta_{lr}^{recy} \le 1 \qquad \forall l \quad (56)$$

$$\sum_{t} \beta_{kt}^{treat} \le M \times \alpha_{tf}^{treat} \qquad \forall t,f \quad (57)$$

$$\sum_{l} \beta_{lr}^{recy} \le M \times \alpha_{r}^{recy} \qquad \forall r \quad (58)$$

$$\begin{aligned} Min\ \ Z^{Cost} = &\sum_{k} CF_{k}^{v-treat} \times veh_{k}^{treat} + \sum_{l} CF_{l}^{v-recy} \times veh_{l}^{recy} + \sum_{i,k,t,f,h} PR_{itf}^{treat} \times y_{ikth}^{treat} + \\ &\sum_{i,t,r} PR_{ir}^{treat-recy} \times z_{itr}^{treat-recy} + \sum_{i,t,d} PR_{id}^{treat-dis} \times z_{itd}^{treat-dis} + \sum_{n,l,r,h} PR_{nr}^{recy} \times (1 - p_{nr}^{recy-dis}) \times y_{nlrh}^{recy} + \\ &\sum_{n,r,d} PR_{nd}^{recy-dis} \times z_{nrd}^{recy-dis} + \sum_{i,t,r} TR_{itr}^{treat-recy} \times z_{itr}^{treat-recy} + \sum_{i,t,d} TR_{itd}^{treat-dis} \times z_{itd}^{treat-dis} + \\ &\sum_{n,r,d} TR_{nrd}^{recy-dis} \times z_{nrd}^{recy-dis} + \sum_{k,h} x_{kh} \times pc \end{aligned} \quad (59)$$

Constraints — **Dual Variable**

$$-\sum_{i,k,h} y_{ikth}^{treat} \ge -treat_{tf}^{cap} \times \overline{\alpha}_{tf}^{treat} \qquad \forall t,f \qquad dv_{tf}^{1} \quad (60)$$

$$-\sum_{n,l,h} y_{nlrh}^{recy} - \sum_{i,t} z_{itr}^{treat-recy} \ge -recy_{r}^{cap} \times \overline{\alpha}_{r}^{recy} \qquad \forall r \qquad dv_{r}^{2} \quad (61)$$

$$-\sum_{n,r} z_{nrd}^{recy-dis} - \sum_{i,t} z_{itd}^{treat-dis} \geq -dis_d^{cap} \times \overline{\alpha}_d^{cap} \quad \forall d \quad dv_d^3 \quad (62)$$

$$-\sum_{i,h} y_{ikth}^{treat} \geq -v_k^{cap-treat} \times \overline{veh}_k^{traet} \quad \forall k,t \quad dv_{k,t}^4 \quad (63)$$

$$-\sum_{n,h} y_{nlrh}^{recy} \geq -v_l^{cap-recy} \times \overline{veh}_l^{recy} \quad \forall l,r \quad dv_{l,r}^5 \quad (64)$$

$$artm_{kh} - artm_{kh'} \geq \eta_{kh'h}^{tm-hos} - (1 - \overline{tour}_{kh'h}^{treat}) \times M \quad \forall k,h',h>1 \quad dv_{khh'}^6 \quad (65)$$

$$twup_h - artm_{kh} \geq \eta_{kht}^{tm-treat} \times \overline{\beta}_{kt}^{treat} - (1 - \overline{tour}_{kh1}^{treat}) \times M \quad \forall k,h,t \quad dv_{kht}^7 \quad (66)$$

$$atrm_{kh} \geq twl_h \quad \forall k,h \quad dv_{kh}^8 \quad (67)$$

$$-atrm_{kh} + x_{kh} \geq -twu_h \quad \forall k,h \quad dv_{kh}^9 \quad (68)$$

$$y_{nlh} - y_{nlh'} - y_{nlrh'}^{recy} \geq -(1 - \overline{tour}_{lh'h}^{recy}) \times M \quad \forall n,l,r,h',h \quad dv_{nlrhh'}^{10} \quad (69)$$

$$y_{nl1} - \sum_{h} y_{nlrh}^{recy} \geq 0 \quad \forall n,l,r \quad dv_{nlr}^{11} \quad (70)$$

$$\sum_{k,t} y_{ikth}^{treat} \geq w_{ih}^{infec} \quad \forall i,h \quad dv_{ih}^{12} \quad (71)$$

$$\sum_{l,r} y_{nlrh}^{recy} \geq w_{ih}^{non-infec} \quad \forall n,h \quad dv_{nh}^{13} \quad (72)$$

$$-y_{ikth}^{treat} \geq -M \times \sum_{h'} \overline{tour}_{kh'h}^{treat} \quad \forall i,k,t,h \quad dv_{ikth}^{14} \quad (73)$$

$$-y_{nlrh}^{recy} \geq -M \times \sum_{h'} \overline{tour}_{lh'h}^{recy} \quad \forall n,l,r,h \quad dv_{nlrh}^{15} \quad (74)$$

$$-y_{ikth}^{treat} \geq -M \times \overline{\beta}_{kt}^{treat} \quad \forall i,k,t,h \quad dv_{ikth}^{16} \quad (75)$$

$$-y_{nlrh}^{recy} \geq -M \times \overline{\beta}_{lr}^{recy} \quad \forall n,l,r,h \quad dv_{nlrh}^{17} \quad (76)$$

$$-y_{ikth}^{treat} \geq -M \times \overline{veh}_k^{treat} \quad \forall i,k,t,h \quad dv_{ikth}^{18} \quad (77)$$

$$-y_{nlrh}^{recy} \geq -M \times \overline{veh}_l^{recy} \quad \forall n,l,r,h \quad dv_{nlrh}^{19} \quad (78)$$

$$\sum_{k,h} y_{ikth}^{treat} - \sum_{r} z_{itr}^{treat-recy} - \sum_{d} z_{itd}^{treat-dis} = 0 \quad \forall i,t \quad dv_{it}^{20} \quad (79)$$

$$\sum_{r} z_{itr}^{treat-recy} - \sum_{f,k,h} p_{itf}^{treat-recy} \times y_{ikth}^{treat} = 0 \quad \forall i,t \quad dv_{it}^{21} \quad (80)$$

$$\sum_{d} z_{nrd}^{recy-dis} - \sum_{l,h} p_{nrd}^{recy-dis} \times y_{nlrh}^{recy} = 0 \quad \forall n,r \quad dv_{nr}^{22} \quad (81)$$

$$-y_{ikth}^{treat} \geq -M \times \overline{\alpha}_{tf}^{treat} \qquad \forall i,k,t,f,h \qquad dv_{iktfh}^{23} \qquad (82)$$

$$-y_{nlrh}^{recy} \geq -M \times \overline{\alpha}_{r}^{recy} \qquad \forall n,l,r,h \qquad dv_{nlrh}^{24} \qquad (83)$$

$$-z_{itr}^{treat-recy} \geq -M \times \overline{\alpha}_{tf}^{treat} \qquad \forall i,t,f,r \qquad dv_{iftr}^{25} \qquad (84)$$

$$-z_{itr}^{treat-recy} \geq -M \times \overline{\alpha}_{r}^{recy} \qquad \forall i,t,r \qquad dv_{itr}^{26} \qquad (85)$$

$$-z_{itd}^{treat-dis} \geq -M \times \overline{\alpha}_{d}^{dis} \qquad \forall i,t,d \qquad dv_{itd}^{27} \qquad (86)$$

$$-z_{nrd}^{recy-dis} \geq -M \times \overline{\alpha}_{r}^{recy} \qquad \forall n,r,d \qquad dv_{nrd}^{28} \qquad (87)$$

$$-z_{nrd}^{recy-dis} \geq -M \times \overline{\alpha}_{d}^{dis} \qquad \forall n,r,d \qquad dv_{nrd}^{29} \qquad (88)$$

$$\begin{aligned}
&-\sum_{t,f} treat_{tf}^{cap} \times \overline{\alpha}_{tf}^{treat} \times dv_{tf}^{1} - \sum_{r} recy_{r}^{cap} \times \overline{\alpha}_{r}^{recy} \times dv_{r}^{2} - \sum_{d} dis_{d}^{cap} \times \overline{\alpha}_{d}^{cap} \times dv_{d}^{3} - \\
&\sum_{k,t} v_{k}^{cap-treat} \times \overline{veh}_{k}^{traet} \times dv_{k,t}^{4} - \sum_{l,r} v_{l}^{cap-recy} \times \overline{veh}_{l}^{recy} \times dv_{l,r}^{5} + \\
&\sum_{k,h',h} (\eta_{kh'h}^{tm-hos} - (1-\overline{tour}_{kh'h}^{treat}) \times M) \times dv_{khh'}^{6} + \sum_{k,t,h} (\eta_{kht}^{tm-treat} \times \overline{\beta}_{kt}^{treat} - (1-\overline{tour}_{kh1}^{treat}) \times M) \times dv_{kht}^{7} + \\
&\sum_{k,h} twl_{h} \times dv_{kh}^{8} - \sum_{k,h} twu_{h} \times dv_{kh}^{9} - \sum_{nlrhh'} -(1-\overline{tour}_{lh'h}^{recy}) \times M \times dv_{nlrhh'}^{10} + \\
&\sum_{ih} w_{ih}^{infec} \times dv_{ih}^{12} + \sum_{inh} w_{ih}^{non-infec} \times dv_{nh}^{13} + \sum_{ikth} -M \times \sum_{h'} \overline{tour}_{kh'h}^{treat} \times dv_{ikth}^{14} + \\
&\sum_{nlrh} -M \times \sum_{h'} \overline{tour}_{lh'h}^{recy} \times dv_{nlrh}^{15} + \sum_{ikth} -M \times \overline{\beta}_{kt}^{treat} \times dv_{ikth}^{16} + \sum_{nlrh} -M \times \overline{\beta}_{lr}^{recy} \times dv_{nlrh}^{17} + \\
&\sum_{ikth} -M \times \overline{veh}_{k}^{treat} \times dv_{ikth}^{18} + \sum_{nlrh} -M \times \overline{veh}_{l}^{recy} \times dv_{nlrh}^{19} + \sum_{iktfh} -M \times \overline{\alpha}_{tf}^{treat} \times dv_{iktfh}^{23} + \\
&\sum_{nlrh} -M \times \overline{\alpha}_{r}^{recy} \times dv_{nlrh}^{24} + \sum_{iftr} -M \times \overline{\alpha}_{tf}^{treat} \times dv_{iftr}^{25} + \sum_{itr} -M \times \overline{\alpha}_{r}^{recy} \times dv_{itr}^{26} + \\
&\sum_{itd} -M \times \overline{\alpha}_{d}^{dis} \times dv_{itd}^{27} + \sum_{nrd} -M \times \overline{\alpha}_{r}^{recy} \times dv_{nrd}^{28} + \sum_{nrd} -M \times \overline{\alpha}_{d}^{dis} \times dv_{nrd}^{29}
\end{aligned} \qquad (89)$$

Constraints — Primal Variable

$$\sum_{h'} dv_{khh'}^{6} - \sum_{t} dv_{kht}^{7} + dv_{kh}^{8} - dv_{kh}^{9} \leq 0 \qquad \forall k, h > 1 \qquad atrm_{kh} \qquad (90)$$

$$-\sum_{h} dv_{khh'}^{6} \leq 0 \qquad \forall k, h' \qquad artm_{kh'} \qquad (91)$$

$$dv_{kh}^{9} \leq pc \qquad \forall k, h \qquad x_{kh} \qquad (92)$$

$$\begin{aligned}
&-\sum_{f} dv_{tf}^{1} - dv_{kt}^{4} + dv_{ih}^{12} - dv_{ikth}^{14} - dv_{ikth}^{18} + \\
&dv_{it}^{20} - \sum_{f} p_{itf}^{treat-recy} \times dv_{it}^{21} - \sum_{f} dv_{iktfh}^{23} \leq \sum_{f} PR_{itf}^{treat}
\end{aligned} \qquad \forall i,k,t,h \qquad y_{ikth}^{treat} \qquad (93)$$

$$\begin{aligned}
&-dv_{r}^{2} - dv_{l,r}^{5} - \sum_{h'} dv_{nlrhh'}^{10} - dv_{nlr}^{11} - dv_{nlrh}^{15} - dv_{nlrh}^{17} - \\
&dv_{nlrh}^{19} - \sum_{d} p_{nrd}^{recy-dis} \times dv_{nr}^{22} - dv_{nlrh}^{24} \leq PR_{nr}^{recy} \times (1 - p_{nr}^{recy-dis})
\end{aligned} \qquad \forall n,l,r,h \qquad y_{nlrh}^{recy} \qquad (94)$$

$$\sum_{r,h'} dv_{nlrhh'}^{10} + dv_{nlr}^{11} \leq 0 \qquad \forall n,l,h \mid h = 1 \qquad y_{nlh} \qquad (95)$$

$$\sum_{r,h'} dv_{nlrhh'}^{10} \leq 0 \qquad \forall n,l,r,h \mid h > 1 \qquad y_{nlh} \qquad (96)$$

$$-dv_{r}^{2}-dv_{it}^{20}+dv_{it}^{21}-\sum_{f}dv_{iftr}^{25}-dv_{itr}^{26}\le PR_{ir}^{treat-recy}+TR_{itr}^{treat-recy}\qquad \forall i,t,r\qquad z_{itr}^{treat-recy}\tag{97}$$

$$-dv_{d}^{3}+dv_{nr}^{22}-dv_{nrd}^{28}-dv_{nrd}^{29}\le PR_{nd}^{recy-dis}+TR_{nrd}^{recy-dis}\qquad \forall n,r,d\qquad z_{nrd}^{recy-dis}\tag{98}$$

$$-dv_{d}^{3}+dv_{it}^{20}-dv_{itd}^{27}\le PR_{id}^{treat-dis}+TR_{itd}^{treat-dis}\qquad \forall i,t,d\qquad z_{itd}^{treat-dis}\tag{99}$$

$$\begin{pmatrix}\sum_{k}CF_{k}^{v-treat}\times veh_{k}^{treat}+\sum_{l}CF_{l}^{v-recy}\times veh_{l}^{recy}+\sum_{i,k,t,f,h}PR_{itf}^{treat}\times y_{ikth}^{treat}+\\ \sum_{i,t,r}PR_{ir}^{treat-recy}\times z_{itr}^{treat-recy}+\sum_{i,t,d}PR_{id}^{treat-dis}\times z_{itd}^{treat-dis}+\\ \sum_{n,l,r,h}PR_{nr}^{recy}\times(1-p_{nr}^{recy-dis})\times y_{nlrh}^{recy}+\sum_{n,r,d}PR_{nd}^{recy-dis}\times z_{nrd}^{recy-dis}+\sum_{i,t,r}TR_{itr}^{treat-recy}\times z_{itr}^{treat-recy}+\\ \sum_{i,t,d}TR_{itd}^{treat-dis}\times z_{itd}^{treat-dis}+\sum_{n,r,d}TR_{nrd}^{recy-dis}\times z_{nrd}^{recy-dis}+\sum_{k,h}x_{kh}\times pc\end{pmatrix}+$$

$$\begin{pmatrix}-\sum_{t,f}treat_{tf}^{cap}\times\overline{\alpha}_{tf}^{treat}\times dv_{tf}^{1}-\sum_{r}recy_{r}^{cap}\times\overline{\alpha}_{r}^{recy}\times dv_{r}^{2}-\sum_{d}dis_{d}^{cap}\times\overline{\alpha}_{d}^{cap}\times dv_{d}^{3}-\sum_{k,t}v_{k}^{cap-treat}\times\overline{veh}_{k}^{traet}\times dv_{k,t}^{4}-\\ \sum_{l,r}v_{l}^{cap-recy}\times\overline{veh}_{l}^{recy}\times dv_{l,r}^{5}+\sum_{k,h',h}(\eta_{kh'h}^{tm-hos}-(1-\overline{tour}_{kh'h}^{treat})\times M)\times dv_{khh'}^{6}+\\ \sum_{k,t,h}(\eta_{kht}^{tm-treat}\times\overline{\beta}_{kt}^{treat}-(1-\overline{tour}_{kh1}^{treat})\times M)\times dv_{kht}^{7}+\sum_{k,h}twl_{h}\times dv_{kh}^{8}-\sum_{k,h}twu_{h}\times dv_{kh}^{9}-\\ \sum_{nlrhh'}-(1-\overline{tour}_{lh'h}^{recy})\times M\times dv_{nlrhh'}^{10}+\sum_{ih}w_{ih}^{infec}\times dv_{ih}^{12}+\sum_{inh}w_{ih}^{non-infec}\times dv_{nh}^{13}+\\ \sum_{ikth}-M\times\sum_{h'}\overline{tour}_{kh'h}^{treat}\times dv_{ikth}^{14}+\sum_{nlrh}-M\times\sum_{h'}\overline{tour}_{lh'h}^{recy}\times dv_{nlrh}^{15}+\sum_{ikth}-M\times\overline{\beta}_{kt}^{treat}\times dv_{ikth}^{16}+\\ \sum_{nlrh}-M\times\overline{\beta}_{lr}^{recy}\times dv_{nlrh}^{17}+\sum_{ikth}-M\times\overline{veh}_{k}^{treat}\times dv_{ikth}^{18}+\sum_{nlrh}-M\times\overline{veh}_{l}^{recy}\times dv_{nlrh}^{19}+\\ \sum_{iktfh}-M\times\overline{\alpha}_{tf}^{treat}\times dv_{iktfh}^{23}+\sum_{nlrh}-M\times\overline{\alpha}_{r}^{recy}\times dv_{nlrh}^{24}+\sum_{iftr}-M\times\overline{\alpha}_{tf}^{treat}\times dv_{iftr}^{25}+\sum_{itr}-M\times\overline{\alpha}_{r}^{recy}\times dv_{itr}^{26}+\\ \sum_{itd}-M\times\overline{\alpha}_{d}^{dis}\times dv_{itd}^{27}+\sum_{nrd}-M\times\overline{\alpha}_{r}^{recy}\times dv_{nrd}^{28}+\sum_{nrd}-M\times\overline{\alpha}_{d}^{dis}\times dv_{nrd}^{29}\end{pmatrix}\le lb\tag{100}$$

$$\begin{pmatrix}-\sum_{t,f}treat_{tf}^{cap}\times\overline{\alpha}_{tf}^{treat}\times dv_{tf}^{1}-\sum_{r}recy_{r}^{cap}\times\overline{\alpha}_{r}^{recy}\times dv_{r}^{2}-\sum_{d}dis_{d}^{cap}\times\overline{\alpha}_{d}^{cap}\times dv_{d}^{3}-\\ \sum_{k,t}v_{k}^{cap-treat}\times\overline{veh}_{k}^{traet}\times dv_{k,t}^{4}-\sum_{l,r}v_{l}^{cap-recy}\times\overline{veh}_{l}^{recy}\times dv_{l,r}^{5}+\\ \sum_{k,h',h}(\eta_{kh'h}^{tm-hos}-(1-\overline{tour}_{kh'h}^{treat})\times M)\times dv_{khh'}^{6}+\sum_{k,t,h}(\eta_{kht}^{tm-treat}\times\overline{\beta}_{kt}^{treat}-(1-\overline{tour}_{kh1}^{treat})\times M)\times dv_{kht}^{7}+\\ \sum_{k,h}twl_{h}\times dv_{kh}^{8}-\sum_{k,h}twu_{h}\times dv_{kh}^{9}-\sum_{nlrhh'}-(1-\overline{tour}_{lh'h}^{recy})\times M\times dv_{nlrhh'}^{10}+\\ \sum_{ih}w_{ih}^{infec}\times dv_{ih}^{12}+\sum_{inh}w_{ih}^{non-infec}\times dv_{nh}^{13}+\sum_{ikth}-M\times\sum_{h'}\overline{tour}_{kh'h}^{treat}\times dv_{ikth}^{14}+\\ \sum_{nlrh}-M\times\sum_{h'}\overline{tour}_{lh'h}^{recy}\times dv_{nlrh}^{15}+\sum_{ikth}-M\times\overline{\beta}_{kt}^{treat}\times dv_{ikth}^{16}+\\ \sum_{nlrh}-M\times\overline{\beta}_{lr}^{recy}\times dv_{nlrh}^{17}+\sum_{ikth}-M\times\overline{veh}_{k}^{treat}\times dv_{ikth}^{18}+\\ \sum_{nlrh}-M\times\overline{veh}_{l}^{recy}\times dv_{nlrh}^{19}+\sum_{iktfh}-M\times\overline{\alpha}_{tf}^{treat}\times dv_{iktfh}^{23}+\sum_{nlrh}-M\times\overline{\alpha}_{r}^{recy}\times dv_{nlrh}^{24}+\\ \sum_{iftr}-M\times\overline{\alpha}_{tf}^{treat}\times dv_{iftr}^{25}+\sum_{itr}-M\times\overline{\alpha}_{r}^{recy}\times dv_{itr}^{26}+\\ \sum_{itd}-M\times\overline{\alpha}_{d}^{dis}\times dv_{itd}^{27}+\sum_{nrd}-M\times\overline{\alpha}_{r}^{recy}\times dv_{nrd}^{28}+\sum_{nrd}-M\times\overline{\alpha}_{d}^{dis}\times dv_{nrd}^{29}\end{pmatrix}\le 0\tag{101}$$

4.2. LP-Metric method

The LP-metric is one of the finest methods which is used for solving multi-objective models. This method has been used in this research to find solutions of the developed model.

This method separately finds optimal values of each objective. Thus, the bi-objective model is converted to a single-objective model using Eq. (102) (Deb and Miettinen, 2008; Mardan et al., 2019):

$$Min\ z^{LP} = (w \times (\frac{Z_1 - Z_1^*}{Z_1^*})^p + (1-w) \times (\frac{Z_2 - Z_2^*}{Z_2^*})^p)^{\frac{1}{p}} \quad (102)$$

In the above equation, Z_1^* and Z_2^* are optimal quantities of the first and the second objective functions, respectively. Z_1 and Z_2 denote the values of objective functions acquired by the method. w and $(1-w)$ are the weights of objectives. The weights of objectives are determined by experiments owing to the policies of the network. In Eq. (102), the value of p is set to 1, since greater values of this parameter will lead to non-linear terms.

5. Experimental results

This section dedicates to a comprehensive set of numerical experimentations to examine the efficiency of the proposed formulation and solution approach. Therefore, eleven number of test instances with different attributes have been produced. The parameters of test problems are scaled and simulated based on real-world cases. These test problems have different sizes including small, medium, and large instances. Table 4 details the bounds of parameters. The dimensions of these eleven problems have been demonstrated in Table 5. As reported in Table 5, the problem instances become larger from the first one to the eleventh one. The proposed model of this research has been implemented in the CPLEX software.

To validate the outputs of the BDA, its results have been compared with the optimal solutions obtained by the CPLEX software. Table 6 evaluates the BDA in comparison with the CPLEX. Regarding the test problems 8 to 11, the CPLEX has not reached any better solution after 7200 seconds of running. Hence, the best found solution until 7200 seconds has been reported. Running time of 7200 seconds has been used in other similar studies such as Mardan et al. (2019). Since the BDA is an exact algorithm (Rahmaniani et al., 2017), it is expected that this method obtains the optimal values for all test instances.

As reported in Table 6, it is obvious that the BDA has acquired the optimal values for all test instances in far less computation times. The results of Table 6 show that computation times of the CPLEX increases exponentially, while the running times of the BDA increases according to the size of instances. The computation times of the BDA imply that this method can be utilized for large-scale problems to achieve optimal solutions within a reasonable time. For having a better understanding, Fig. 2 offers a visual comparison between the CPLEX and BDA regarding objective function values and running times.

Table 4. Bounds of input parameters for generating test problems

Parameter	***Distribution function***	***Parameter***	***Distribution function***
CF_{tf}^{treat}	$Round(U \sim [1.7\times10^8, 1.9\times10^8])$	$PR_{itf}^{treat}, PR_{nr}^{recy}$	$Round(U \sim [1.2\times10^2, 1.4\times10^2])$
CF_{r}^{recy}	$Round(U \sim [1\times10^8, 1.2\times10^8])$	$PR_{ir}^{treat-recy}, PR_{id}^{treat-dis}, PR_{nd}^{recy-dis}$	$Round(U \sim [2.3\times10^2, 2.4\times10^2])$
CF_{d}^{dis}	$Round(U \sim [6\times10^7, 8\times10^7])$	$TR_{itr}^{treat-recy}, TR_{itd}^{treat-dis}, TR_{nrd}^{recy-dis}$	$Round(U \sim [1.2\times10^2, 1.5\times10^2])$
$CF_{k}^{v-treat}$	$Round(U \sim [4.5\times10^7, 5.5\times10^7])$	$w_{ih}^{infec}, w_{nh}^{non-infec}$	$Round(U \sim [1.2\times10^2, 1.6\times10^2])$
CF_{l}^{v-recy}	$Round(U \sim [3.5\times10^7, 4.5\times10^7])$	$v_{k}^{cap-treat}$	$Round(U \sim [1.8, 2.3]\times\sum_{i,h} w_{ih}^{infec} / k)$
$treat_{tf}^{cap}$	$Round(U \sim [2.5, 3]\times\sum_{i,h} w_{ih}^{infec} / t)$	$v_{l}^{cap-recy}$	$Round(U \sim [1.8, 2.3]\times\sum_{n,h} w_{nh}^{non-infec} / l)$
$\eta_{kh'h}^{tm-hos}$	$Round(U \sim (3,5)\times\eta_{h'h}^{ds-hos})$	dis_{d}^{cap}	$Round(U \sim [4\times10^{-1}, 6\times10^{-1}]\times\sum_{r} recy_{r}^{cap} / d)$
$\eta_{kht}^{tm-treat}$	$Round(U \sim (3,5)\times\eta_{ht}^{treat-hos})$	$p_{itf}^{treat-recy}$	$U \sim [4\times10^{-1}, 6\times10^{-1}]$
$\eta_{lrt}^{tm-recy}$	$Round(U \sim (3,5)\times\eta_{hr}^{recy-hos})$	$p_{nr}^{recy-dis}$	$U \sim [1.5\times10^{-1}, 2.5\times10^{-1}]$
$population_{h'h}$	$Round(U \sim [3\times10^3, 4\times10^3])$	fvt_k, fvr_l	$Round(U \sim [1.8\times10^{-1}, 2.2\times10^{-1}])$
p^{fuel}	1000	$\eta_{h'h}^{ds-hos}$	$\sqrt{(x_h - x_{h'})^2 + (y_h - y_{h'})^2}$
$\eta_{ht}^{treat-hos}$	$\sqrt{(x_h - x_t)^2 + (y_h - y_t)^2}$	$\eta_{hr}^{recy-hos}$	$\sqrt{(x_h - x_r)^2 + (y_h - y_r)^2}$
$x_h, x_{h'}$	$Round(U \sim (0,1)\times50)$	x_t	$Round(U \sim (0,1)\times50)$
$y_h, y_{h'}$	$Round(U \sim (0,1)\times50)$	y_t	$Round(U \sim (0,1)\times50)$

x_r	$Round\,(U\ \sim(0,1)\times 50)$	$recy_r^{cap}$	$Round\,(U\ \sim[2,2.5]\times (U\ \sim[0.4,0.6]\times\sum_{i,h} w_{ih}^{infec} + \sum_{n,h} w_{nh}^{non-infec})/r)$
y_r	$Round\,(U\ \sim(0,1)\times 50)$		

Table 5. Dimensions of problem instances

Problem No	i	n	h	f	t	r	d	k	l
1	1	1	3	2	2	2	2	2	2
2	2	2	4	3	2	3	2	2	3
3	3	3	5	3	3	3	3	3	3
4	4	3	6	3	4	3	3	3	4
5	5	3	6	4	4	4	3	4	4
6	5	4	7	4	5	4	4	5	5
7	5	5	8	4	5	5	4	6	5
8	6	5	8	5	6	5	5	7	6
9	6	6	9	5	6	6	5	7	6
10	7	7	10	5	7	6	6	8	7
11	8	7	10	6	7	7	6	8	7

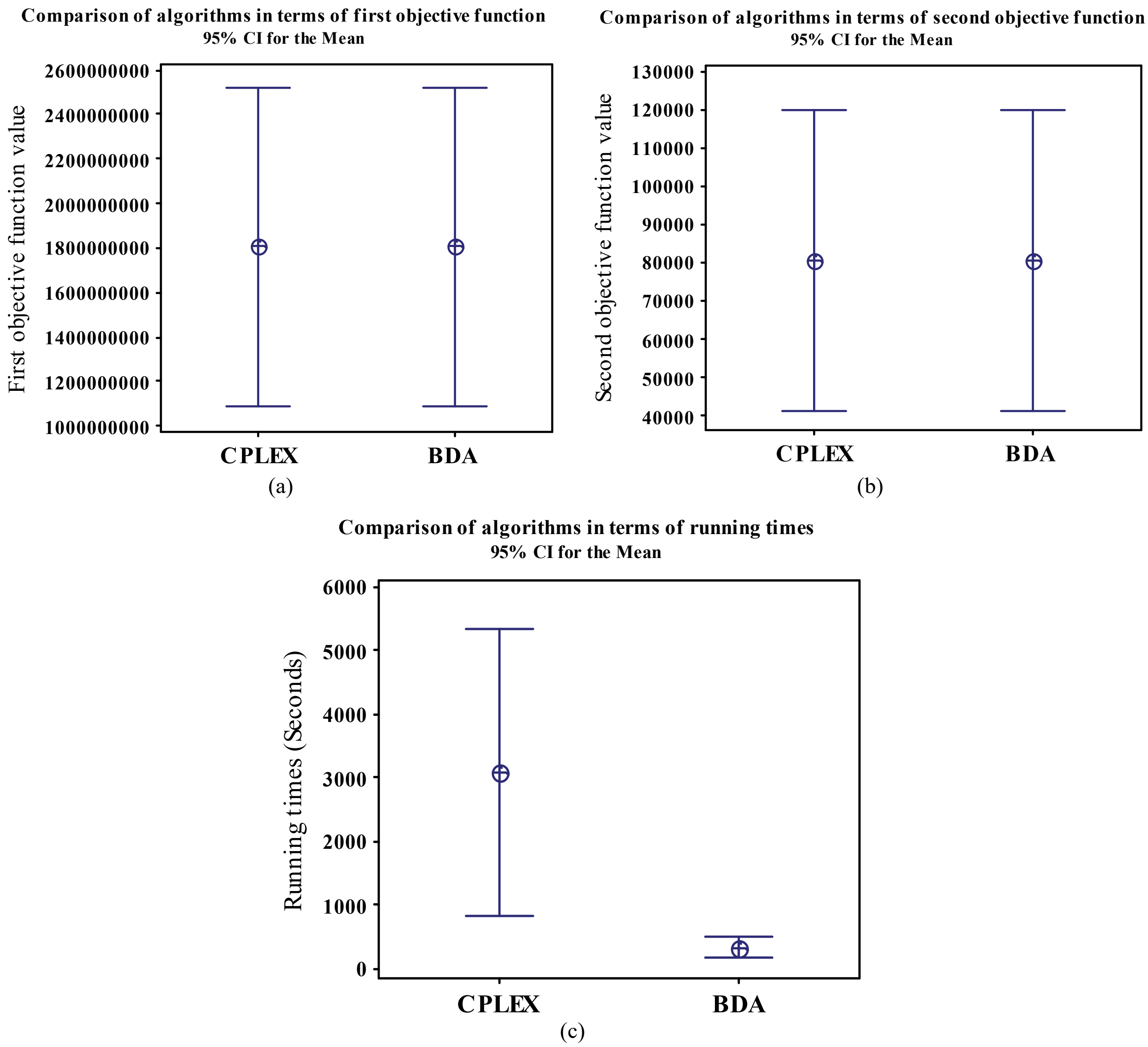

Fig. 2. Interval plots on the first and second objectives and running times of algorithms

To demonstrate that the computation times of the BDA in finding optimal solutions is significantly less than CPLEX, a statistical test is conducted via the Friedman test which is a non-parametric statistical test. Null hypothesis of this test assumes that there is no significant difference between the performances of the employed methods, while the alternative hypothesis assumes the opposite. This statistical test has been performed at 95% of confidence interval. Therefore, if $P - Value < 0.05$, we reject the null hypothesis. If the null hypothesis is rejected, we conclude that a significant difference exists between the running times of CPLEX and BDA.

The outputs of the statistical test has been shown in Table 7. Due to the fact that the running times of the BDA is far less than the CPLEX, results of Table 7 indicate significant statistical difference between the BDA and CPLEX (P-Value =0.00 < 0.05). Statistical comparison implies the supremacy of the Benders algorithm over CPLEX. As an example, the convergence behavior of the BDA has been shown for the second test problem in Fig. 3. Based on this Figure, the BDA has a fast convergence since it has converged in less than 40 iterations.

6. Case study

The model of this research has been used to design a part of the real logistic network of hospital waste management in Alborz Province, Iran. A private transportation enterprise gathers the wastes at nine selected hospitals (h, h'= 9) in this province. These hospitals are Alborz, Kosar, Shahid Rajaei, Sarallah, Madani, Bahonar, Hazrat Ali, Imam Khomeini, and Kamali.

The hospitals produce two kinds of non-infectious materials (dry and wet) and two kinds of infectious materials (n=2, i=2).

Table 6. Comparisons between the BDA and CPLEX

Problem No.	CPLEX			BDA		
	Objective function 1	*Objective function 2*	*Run time (Seconds)*	*Objective function 1*	*Objective function 2*	*Run time (Seconds)*
1	672389822	16962	3.18	672389822	16962	2.74
2	703792564	17657	12.45	703792564	17657	3.18
3	894738400	26706	54.01	894738400	26706	12.55
4	1009510964	37411	211.74	1009510964	37411	101.84
5	1374850193	48463	751.99	1374850193	48463	239.22
6	1460091621	68523	1127.27	1460091621	68523	327.31
7	1689203724	92805	2867.92	1689203724	92805	404.03
8	2178656781	101741	7200<	2178656781	101741	534.38
9	2916557733	124455	7200<	2916557733	124455	582.17
10	3318782211	162003	7200<	3318782211	162003	643.51
11	3671203473	188652	7200<	3671203473	188652	669.48

Table 7. Statistical tests between algorithms in terms of running times

Source	*SS*	*df*	*MS*	*Chi-sq*	*P-Value*
Columns	5.5	1	5.5	11	0.00
Error	0	10	0		
Total	5.5	21			

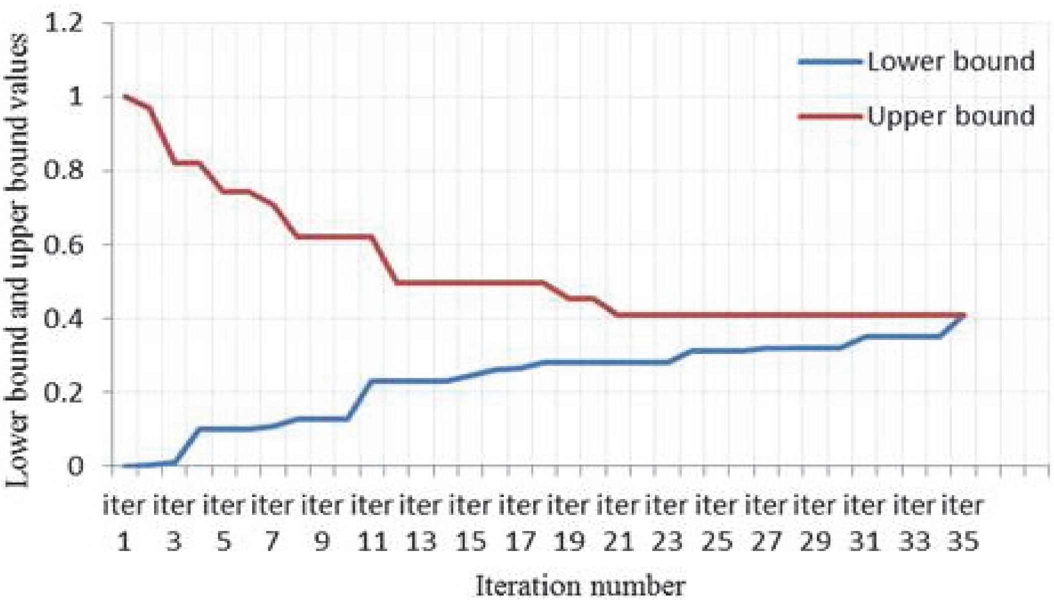

Fig. 3. Convergence of the proposed BDA

The daily quantity of produced wastes (w_{ih}^{infec} and $w_{nh}^{non-infec}$) in each hospital are estimated based on historical data. The company has selected three potential treatment centers (*t*=3) with different treatment technologies including Khoramdasht, Kamalshahr, and Malekabad. Nazarabad, Hashtgerd and Baharestan are three potential recycling centers (*r*=3) and Saifabad, Arababad and Yaubabad are three potential disposal centers (*d*=3).

The location of hospitals and potential facilities in the network are shown in Fig. 4. The shortest path between the hospitals and potential locations has been determined using Google Map. Moreover, the distances and time distances between each pair of locations in Fig. 4 ($\eta_{kh'h}^{tm-hos}$, $\eta_{kht}^{tm-treat}$, $\eta_{lrt}^{tm-recy}$, $\eta_{ht}^{treat-hos}$, $\eta_{hr}^{recy-hos}$ and $\eta_{hr}^{recy-hos}$) are estimated by using Distance Matrix Google API.

Three heterogeneous vehicles are considered for each infectious (*k*=3) and non-infectious (*l*=3) wastes with equal and restricted capacity. Table 8 shows the quantity of waste materials. The other model parameters such as cost units which are predicted. The hospital waste management problem in this case study with mentioned network structure and parameters have been solved by both CPLEX and BDA.

The model of this problem has been converted into single-objective model and solved to optimality by the CPLEX. The first and the second objectives have the values of 2167400088 and 106639, respectively. The BDA has detected the optimal solutions of the case study. However, the computation times of the CPLEX and BDA are remarkably different. The CPLEX has solved the problem in 3015.57 seconds, while the BDA has solved the problem to optimality in 421.68 seconds. Implementing the model on the illustrated logistics network, vehicle types 1 and 3 are chosen to collect infectious wastes. On the other hand, vehicle types 1 and 2 are selected for gathering non-infectious materials. The three potential locations Kamalshahr, Baharestan and Saifabad are opened as treatment, recycling, and disposal centers, respectively. The network of case study has been depicted in (Fig. 4). Vehicle routes can be observed in (Figs. 5-6).

The routes depicted in (Figs. 5-6) have been acquired by the Benders algorithm. Table 9 delivers the optimal order of visiting hospitals by the CPLEX and BDA. These outputs have been confirmed by the experts.

7. Conclusions

In this paper, healthcare waste management problem was investigated focusing on characteristics of logistic network. This paper proposed a new formulation to design a network consisting of different facilities. This proposed model is bi-objective that aims to optimize some important criteria in the field of waste management problem.

The proposed model minimizes total costs and risk of exposure to contamination. In the proposed network, location of facilities should be specified as well. The proposed model also determines the routes of carries for gathering wastes.

Table 8. Amount of wastes produced in hospitals

Infectious wastes		***Non-infectious wastes***	
Hospital	***Amount of waste in kilograms (x10^2)***	***Hospital***	***Amount of waste in kilograms (x10^2)***
Alborz	4.46	Alborz	0.81
Kosar	1.09	Kosar	0.57
Shahid Rajaei	3.76	Shahid Rajaei	0.75
Sarallah	2.64	Sarallah	1.08
Madani	4.39	Madani	0.96
Bahonar	2.15	Bahonar	0.77
Hazrat Ali	1.17	Hazrat Ali	0.24
Imam Khomeini	5.16	Imam Khomeini	1.28
Kamali	3.89	Kamali	1.04

Table 9. Order of visited hospitals by each vehicle

Waste type	*Vehicle*	*Order of hospitals in waste collection routes*
Infectious	**1**	**Kamalshahr→ Sarallah→ Shahid Rajaei→ Kosar→ Alborz→ Kamalshahr**
	3	**Kamalshar→ Madani→ Kamali→ Imam Khomeini→ Hazrat Ali→ Bahonar→ Kamalshahr**
Non-infectious	**1**	**Baharestan→ Bahonar→ Hazrat Ali→ Imam Khomeini→ Kamali→ Madani→ Baharestan**
	2	**Baharestan→ Kosar→ Alborz→ Shahid Rajaei→ Sarallah→ Baharestan**

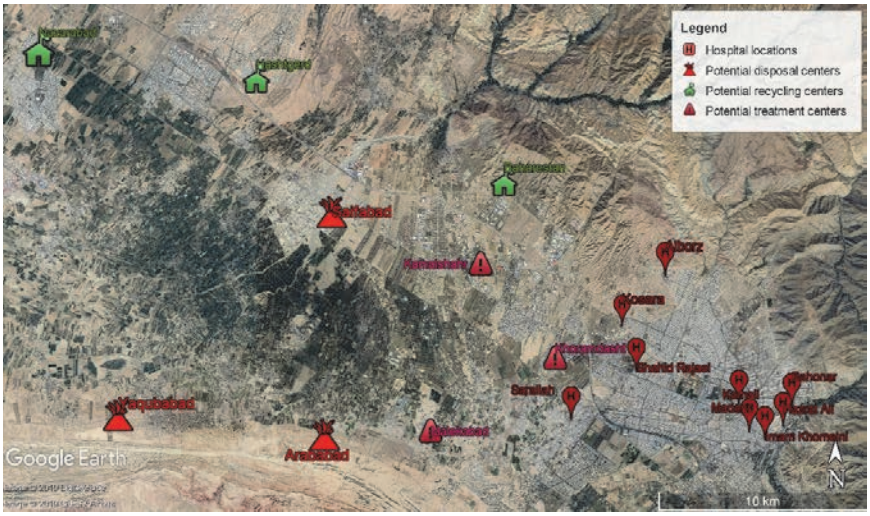

Fig. 4. Geographical locations of hospitals and potential centers

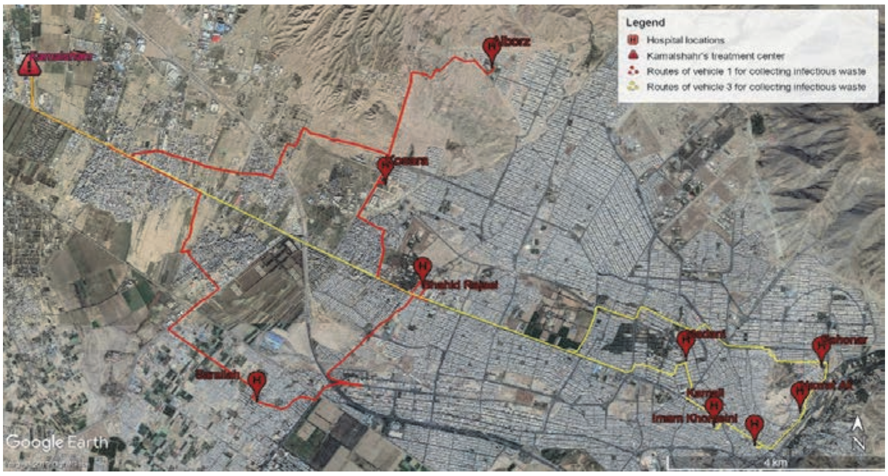

Fig. 5. Routes of vehicles for gathering infectious wastes

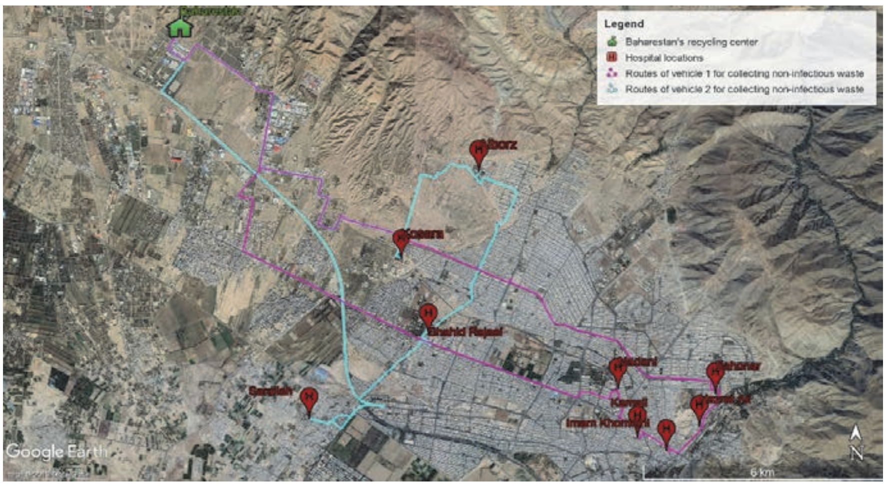

Fig. 6. Routes of vehicles for gathering non-infectious wastes

The problem is NP-hard and therefore a powerful algorithm is required to solve it. In this respect, a Benders decomposition algorithm was developed to cope with computational complexities of the problem. Several test problems have been generated with different sizes and characteristics. The optimal solutions of these test problems have been found by the CPLEX software. To test the credibility of the Benders algorithm, the outcome of this method has been compared with the outputs of the CPLEX. Results of comparisons indicate that the BDA has achieved optimal solutions for all test problems in far less running times. To show practical aspect of the developed formulation and BDA, a real case study for collection of wastes in Alborz Province of Iran is investigated.

The case study has been solved by both the CPLEX and BDA and the outputs were compared. The numerical results indicate that the BDA could reach optimal solution for the case study as well. The outputs of this real-world problem has been proven by experts. As for future research directions, extension of the model to incorporate social and environmental challenges beside the economic issues could be attractive both for academicians and practitioners. Furthermore, since today's business environment is exposed to different potential disruptions, robust and resilient strategies could provide a deep insight of the problem.

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