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Hazardous infectious waste collection and government aid distribution during COVID-19: A robust mathematical leader-follower model approach

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ABSTRACT

The outbreak of COVID-19 has posed significant challenges to governments across the world. The increase in hazardous infectious waste (HIW) caused by the pandemic is associated with the risk of transmitting the virus. In this study, hazardous waste includes infectious waste generated both by individuals and by hospitals during the COVID-19 pandemic. To control the outbreak by maintaining social distance and home quarantine protocols, daily necessities and health supplies must be provided to the people affected. Governments play an essential role in the management of the crisis, creating an elaborate plan for collecting HIW and providing necessities and health supplies. This paper proposes a leader-follower approach for hazardous infectious waste collection and government aid distribution to control COVID-19. At the top level of the model, government policies are designed to support people by distributing daily necessities and health supplies, and to support contractors by waste collection. The lower level of the model is related to the operational decisions of contractors with limited capacities. Due to the potential risk of virus transmission via contaminated waste, the proposed model considers the complications imposed on contractors at the lower level. Applying a stochastic programming approach, four possible scenarios are examined, dependent of the severity of the outbreak. As a solution approach, the Benders decomposition method is combined with Karush-Kuhn-Tucker conditions. The results show that government support, in addition to much better management of citizen demand, can control the spread of the virus by implementing quarantine decisions.

1. Introduction

In mid-December 2019, a new virus was first detected in Wuhan, Hubei Province, China, and has since spread across 180 countries around the world. To curb COVID-19, many governments have taken significant steps to reduce human interaction, including tightening home quarantine protocols, banning large-scale private and public gatherings, restricting private and public transportation, and encouraging direct action (Sarkis, Cohen, Dewick, & Schroeder, 2020). During home quarantine, the government should provide daily necessities and health supplies, particularly for those who live in poverty or are victims of COVID-19. Although there is no doubt that the cost of these precautionary measures is enormous, these actions can have major social benefits, alongside health advantages. As an example of government support, the US government launched the COVID-19 Response Fund, a national food- and fund-raising effort to support people facing hunger. The UN World Food Program (WFP), as the world’s largest humanitarian agency, has revised its food distribution procedures to provide food assistance to millions of people across 83 countries in response to the urgent needs created by COVID-19. The virus has spread widely in Iran during recent months (Fig. 1) and the government has adopted various measures, such as maintaining home quarantine and social distancing, as well as providing daily necessities and health supplies to control the outbreak.

During the COVID-19 pandemic, the use of disposable supplies, and a large rise in online shopping, has increased the amount of municipal waste (MW) generation (Valizadeh & Mozafari, 2021). Meanwhile, food loss and waste has also been a major part of the waste generated during
the epidemic. In addition, medical waste collected from the recognized hospitals in Tehran ranged from 52–74 tons per day between March 2019 and January 2020, at an average of 68 tons per day; this figure increased to 80–110 tons per day during the COVID-19 pandemic (Daryabeigi Zand & Vaezi Heir, 2020). Additionally, the use of personal protective equipment (PPE) such as face masks has recently been recommended for all Iranians by executive agencies. As a result, a large amount of these PPEs are produced daily during the COVID-19 epidemic in Tehran which, if not separated at source, mix with MW and cause further spread of the virus. Meanwhile, the lack of effective waste separation programs has increased the generation rate of infectious waste and associated treatment costs, compared to many other developing countries (Daryabeigi Zand & Vaezi Heir, 2020).

A recent study Kampf et al. (2020) found that human coronaviruses can remain active on inanimate hard surfaces (such as metal, glass or plastic) for up to nine days. In particular, inadequate solid waste management may increase the spread of coronavirus, especially in developing countries (Mol and Caldas, 2020). In addition, many developing countries, including Cambodia, Philippines, Thailand, India, Malaysia, Indonesia, Bangladesh, Vietnam, and Palestine, have been widely observed as dumping solid waste into poorly managed and open landfills (Ferronato and Torretta, 2019). This provides another example where improper management of contaminated PPEs and healthcare waste may increase the spread of viral disease in an environment (Nzediegwu and Chang, 2020). Although no definite result has been proven so far, it can be concluded that if municipal waste is not separated from hazardous sanitary waste carrying the COVID-19 virus, the entire waste can become infected through surface transmission. As a result, efficient waste separation during the COVID-19 epidemic will not only be able to reduce costs, but also help prevent the spread of the virus through waste.

Governmental support and regulation policies are crucial factors for reducing the risk of the virus spreading during the pandemic. One effective government policy can be providing health supplies to citizens in exchange for waste separation. In addition to encouraging citizens to separate infectious waste from MW, this action will enlist citizens in preventing the spread of COVID-19. As another supportive policy, the government can distribute daily necessities to citizens while maintaining home quarantine protocols and social distancing. Given the above, there are two pertinent concerns for waste management during the COVID-19 epidemic. First, the government’s concern is dealing with the spread of the virus by separating infectious and hazardous waste from MW and by supporting citizens through supplying daily necessities and health supplies. Second, the contractors’ concerns involve managing the costs associated with collecting the large volumes of waste generated during the COVID-19 epidemic. These two concerns have been optimized using a leader-follower game approach. This paper expects to address several goals including (1) Improving the HIW collecting system during the COVID-19 pandemic by a leader-follower approach, (2) Considering government policy in providing citizens with daily necessities and health supplies during the COVID-19 pandemic, and (3) Considering government spending and total contractor costs in waste collection in four probable scenarios. Moreover, to the best of the authors’ knowledge, no study has been performed on the distribution of aid and daily necessities during a pandemic situation. In this regard, the current study specifically tries to answer the several research questions including (1) Given the transmission of the virus via surfaces, how should HIW virus transmission be considered? (2) How can daily necessities and health supplies be optimally provided by the government to maintain effective home quarantine during the COVID-19 pandemic? (3) How can the interactions between contractors collecting HIW and government policies be formulated? (4) Given the COVID-19 outbreak, how can governments minimize the risk of transmitting the disease through HIW?

This research is focused on the city of Tehran, and all the restrictions are derived from real-world, current conditions. The remainder of this study is laid out as follows:

Section 2 provides a brief literature review. The research methodology is explained in Section 3. The developed mathematical model is introduced in Section 4. Section 5 presents the case study, which is analyzed using real data in Gams software; the results of solving the model are evaluated. Finally, in Section 6, a conclusion and future suggestions are presented.

2. Literature review

In this section, literature related to the research problem is classified into three subsections. In the first one, research related to hazardous waste is presented. The studies related to government support during the outbreak are reviewed in Subsection 2. The studies related to bi-level programming problems in waste management are reviewed in
Subsection 3. Finally, the research gap and contributions of this study are given in Subsection 4.

2.1. Survey on hazardous waste

Hazardous waste management includes the collection, transportation, recycling and disposal of hazardous waste that affects the environment and therefore includes a variety of criteria for decision-making. As Fig. 2 shows, three categories of hazardous waste are considered, including household hazardous waste, medical hazardous waste, and industrial hazardous waste. This study considers the first and second categories of hazardous waste. Much research has been done on hazardous waste management.

Many studies have considered the risks of hazardous waste (Das, Gupta, & Mazumder, 2012; Dourson, Gadagbui, Thompson, Pfau, & Lowe, 2016; Karademir, 2004; Rabbani, Heidari, Farrokhi-Asl, & Rahimi, 2018; Xu, Deng, & Manci, 2019; Zhao & Ke, 2019; Valizadeh, 2020; Zhao & Kaluarachchi, 2002). Given that this study focuses on infectious waste, research in the field of infectious and medical waste management was conducted. Yu, Razon, and Tan (2020) provided a stochastic network design problem for hazardous waste management. The proposed model and solution method were validated through numerical experiments, whose results show that uncertainty may not only affect the objective value, but also lead to different strategic decisions in numerical experiments, whose results show that uncertainty may not only affect the objective value, but also lead to different strategic decisions in the network design of a hazardous waste management system. Camacho, Ruiz-Penalver, and Rodríguez (2020) identified the leading hazardous waste industries with high recovery potential in Spain. They showed that the largest hazardous waste industries are also minimally efficient, and have a high potential for improvement. Table 1 provides an overview of studies related to hazardous waste collection under pandemic and non-pandemic conditions.

2.2. Survey of government support during the outbreak

Effective cooperation between the government and the people is a necessity in solving natural disasters or epidemics. The governments shoulder the serious responsibility of supporting people in these crises. By providing daily necessities and health supplies, the government can encourage people to maintain home quarantine and keep them safe from coronavirus exposure. For example, the Canadian government has provided people’s daily necessities and health supplies during the COVID-19 epidemic. Similarly, in the COVID-19 public health crisis in New York City, the city managers took steps to make sure every New Yorker had access to the food they need. In addition, the European Union parliament has adopted particular measures to address the immediate needs of vulnerable citizens.

There are a limited number of studies that have investigated the role of government support in healthcare problems or pandemic and epidemic conditions. Fatiu and Barsoum (2008) examined government policy among South African countries to combat the spread of chronic kidney disease. Youde (2012) looked at government support policies to combat AIDS in sub-Saharan Africa. The survey data showed that the implementation of comprehensive anti-HIV / AIDS policies by African governments has had positive consequences on public opinion. examined government support for preventing the aging of societies via a simulation method. According to the results, these efforts are especially important for older societies such as Japan, many European countries, and the United States. Fong, Law, & Ye, 2020 examined the role of the government in supporting tourism companies during the COVID-19 epidemic. Using an online survey in the early stages of the epidemic, they showed that Macau residents are predicting an improvement in the tourism industry, due to effective disease prevention and government efficiency in promoting tourism.

The studies conducted on waste collection under uncertain conditions are laid out in Table 2.

2.3. Research gap and contributions

In most studies related to MWC, researchers tried to reduce the cost of collecting or recycling waste by implementing some simple assumptions, such as the specific capacity of recycling centers or the limited number of vehicles. For example, a recent study by Hannan, Begum, Al-Shetwi, Ker, and Mahlia (2020) only tried to minimize the total distance traveled by the MWC vehicles, accompanied by simple assumptions. According to previous research and the explanations provided in the previous sections, it can be seen that in existing studies, little attention has been paid to the collection and separation of infectious waste in relation to the distribution of aid.

To fill this gap, this study presents a bi-level planning model. The advantages of the proposed model include the simultaneous consideration of the bi-level concerns of executive bodies. In other words, the government, as the upper level of the model, intends to support citizens and contractors by setting up temporary stations for the collection of hazardous infectious waste, and warehouses related to support packages. Government support includes costs that must be minimized at the upper level of the model. The lower level of the model looks at contractors’ concerns related to managing municipal waste collection and infectious waste collection. The risk of virus transmission through waste was also considered in the proposed model. Furthermore, it was found that there is no study which that considers the government’s role in the distribution of daily necessities and health supplies to cover the immediate needs of vulnerable citizens during home quarantine. Therefore, the main contributions of this research are as follows:

i In the field of waste collection, waste is often collected from garbage bins located in alleys and streets. According to the government’s decisions on home quarantine, temporary stations are considered to collect the HIW. Meanwhile, daily necessities and health supplies are distributed via warehouses. In addition to preventing citizens from creating congestion at healthcare goods distribution stations, this will ensure that the home quarantine plan of the government is appropriately implemented.

ii A special shipping service (which only collects HIW) is also considered, which collects hazardous hospital waste separately and transports it to disposal centers. In other words, this category of waste is not collected by temporary stations. This was considered as a better HIW management solution. This also creates a system that does not mix hospital waste with MW, some of which is recyclable.

iii The risk of transmitting COVID-19 to waste collectors was also considered. Municipal waste may contain hazardous infectious waste, and the risk of this waste cannot be ignored. Therefore, the risk of virus transmission was considered in the proposed model, and according to the nature of the model, was minimized.

iv A mathematical model was formulated to consider the separation of the contaminated waste at the source, and to reduce the transmission of the virus by the waste at the source, by implementing government support policy in the waste collection process. This would not only prevent the transmission of the disease, but also prevent the waste of recyclable waste. As a novel bi-level planning approach, the decision variables are divided into two categories: first stage variables include government decisions, and second stage variables include the decisions of the MWC contractor.

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1. [https://www.canada.ca/en/department-finance/economic-response-plan.html](https://www.canada.ca/en/department-finance/economic-response-plan.html)
2. [https://www1.nyc.gov/assets/dsny/contact/services/COVID-19FoodAssistance.shtml](https://www1.nyc.gov/assets/dsny/contact/services/COVID-19FoodAssistance.shtml)
3. [https://www.europarl.europa.eu/news/en/agenda/briefing/2020-04-16/3/food-aid-and-assistance-to-people-in-need-during-covid-19-crisis](https://www.europarl.europa.eu/news/en/agenda/briefing/2020-04-16/3/food-aid-and-assistance-to-people-in-need-during-covid-19-crisis)
3. Research methodology

Since the field of this study is waste management during COVID-19, it seeks a solution to reduce the total cost and realization of government policies. Therefore, to reduce the costs related to municipal waste collection (and related waste collection planning), a leader-follower approach was proposed, supported by a mathematical planning model. To do this, the research methodology was divided into five steps:

① **First step:** In this step, the objective function at each level (upper and lower) is formulated according to the problem conditions and existing constraints by determining the parameters and decision variables.

② **Second step:** In the strategic planning problem considered in this study, the decision-maker must determine the strategic decisions for \( x \) before determining the values \( y \) of the uncertain parameters. After determining the stochastic variables, the decisions of the second level \( y \) are made. Therefore, the decisions of the first level are made in such a way that the costs of the first level and the expected costs of the second level are minimized. This step determines a parameter, which is related to scenarios by \( \mathscr{S} \). This parameter shows the probability of occurrence of scenario \( s \).

③ **Third step:** In this step, the robust optimization is used. Due to the uncertain nature of the data in the proposed model, it is necessary to reformulate the model based on a robust method, and to define stochastic variables based on possible scenarios (Tavanayi, Hafezalkotob, & Valizadeh, 2020). A robust optimization solution was used, first introduced by Mulvey, Vanderbei, and Zenios (1995). Robust optimization seeks a solution that makes the model remain feasible for most uncertain data (Valizadeh, Sadeh, Amini Sabegh, & Hafezalkotob, 2020).

④ **Fourth step:** In this step, to solve the bi-level problem, the problem can be transformed into a one-level problem by applying the KKT conditions (Yu & Qiu, 2017). This method is one of the most common ways to solve bi-level programming problems, by which the lower-level problem is placed in the upper-level problem using KKT conditions.

⑤ **Fifth step:** In a bi-level model, the operational results obtained by solving the two levels of the model independently are not necessarily optimal; since the boundary constraints are not taken

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**Table 1**

Studies conducted on hazardous waste collection problem

| Authors | Household hazardous wastes | Medical hazardous wastes | Industrially hazardous wastes | Players | Risk | Pandemic | The country of the case study |
|---------|---------------------------|-------------------------|-------------------------------|---------|------|----------|--------------------------------|
| Birpinar, Bilgili, and Erdosan (2009) | * | * | | Contractors | Government | | Turkey |
| Komilis, Fouki, and Papadopoulos (2012) | | | | | | | Italy |
| Dotoli and Epicoco (2017) | * | | * | | | | Italy |
| Zhao and Ke (2017) | * | * | | | | | China |
| Herreroa, Roviraab, Marquesa, Nadala, and Domingoa (2019) | | | * | | | | Spain |
| Lim Wavde, Kauffman, Kam, and Dawson (2019) | * | | | | | | California |
| Sangkhram (2020) | | | | | | | Asia |
| Yu, Razon et al. (2020) | * | | * | | | | Canada |
| Ikiza, Mcharena, Alfredb, and Sivanesamb (2020) | * | | | | | | Iran |
| Saeidi-Mobarakeh, Reza, Navabakhsh, and Amoozad-Khalili (2020) | | | | | | | Brazil |
| Penteado and Castro (2020) | * | | | | | | Iran |
| Ghannadpour, Zandieh, and Esmaeili (2020) | | | * | | | | Iran |
| Madsen, Frederiksen, Jacobsen, and Tendal (2020) | * | | | | | | Romania |
| Mostafayi Darmian, Mouzzeni, and Magnus Hvattum (2020) | | | * | | | | Nepal |
| Taslimi, Batta, and Kwon (2020) | * | | | | | | China |
| Sapkota et al. (2020) | * | | | | | | Iran |
| Naï et al. (2021) | * | | | | | | Iran |
| Current research | * | * | | | | | Iran |
into account, the resulting solution may even be unfeasible. Therefore, a mathematical planning approach is needed to find all the feasible combined results. This approach considers the constraints of the relationship between the two levels of the proposed model. Therefore, the Benders decomposition algorithm was used. The general idea of the algorithm is to divide the problem into three parts: a linear sub-problem that contains only complex discrete variables, a constraint that includes continuous variables, as well as a principal related problem. The resulting linear problem can be easily solved by the linear programming method.

The structure of the proposed bi-level model is shown in Fig. 3.

![Fig. 3. The proposed bi-level model for the problem.](image-url)
4. Model formulation

As mentioned in Section 1, with the policy of separation at source, municipal waste is classified into two categories including HIW and MW (ordinary waste). To collect the waste generated by citizens, several temporary stations are set up by the government. The non-hazardous waste is transported to recycling centers and hazardous waste separated at source is transported to disposal locations. HIW generated by hospitals is transported directly to disposal locations and does not mix with municipal waste. Due to the risk of transmitting the virus through HIW, the transfer is carried out by a special shipping method. It is worth bearing in mind that, due to the special equipment involved in the special shipping, the cost of transporting HIW is different from the cost of transporting MW.

Meanwhile, in accordance with government requirements to stay at home and observe home quarantine, the provision of living necessities for citizens has posed new challenges during the COVID-19 epidemic. Obviously, if citizens do not have living necessities, they will be forced to go outside the house to supply these necessities, in which case home quarantine will not be applied properly. To solve this problem, the government intends to support citizens during the epidemic by providing support packages. Of course, another purpose of this task is to encourage citizens to separate waste into two categories: municipal waste and hazardous infectious waste. The government provides citizens with two support packages, including health supplies and daily necessities, by setting up government aid distribution warehouses.

Therefore, through the model formulation of the problem, two main research objectives are pursued: (i) providing an appropriate mathematical model for collecting HIW and distributing aid under government intervention, and (ii) establishing interactions between contractors collecting HIW and government support policies. The decisions of the government and contractor companies can be considered in two stages.

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Fig. 4. The proposed leader-follower model.
The decisions of the first stage include: the number and capacity of temporary stations; determining how to transfer separated waste from homes to temporary stations; the number of warehouses; and the number of facilities for the distribution of daily necessities and health supplies. In the second step, the contractor company determines: the number, location, and capacity of the recycling centers; how to transfer MW from temporary stations to the recycling centers; and how to transfer HIW to disposal locations. In addition, decisions about how to transfer the HIW from the hospitals to disposal locations are made by contractors. To illustrate the idea, Fig. 4 gives the schematic structure of the proposed bi-level programming model for the research problem.

With the COVID-19 outbreak, the collector contractors often are not well-prepared to separate and collect viral waste from MW in a safe manner (from facilities and individuals). Thus, the government needs to take the appropriate steps to solve the problem. Two important beneficiaries in this problem (for example, a regulatory entity and a supervising entity) have different concerns and perspectives that can play different roles in the waste collection during the COVID-19 epidemic. With conflicting concerns, government officials should be aware of people’s necessities during home quarantine, as well as the concerns of contractors. This feedback should then be reflected in strategic decision-making, which leads to a bi-level structure. In other words, in an optimization problem, decision-making appears at both the upper-level (i.e. the leader) and the lower-level (i.e. the follower). The leader makes decisions and the followers react to those decisions, so the leader’s goal is optimized based on the followers’ behavior (Chang, 2006). Thus, a bi-level model can accurately articulate potentially contradictory decisions, by assuming the positions of leader and follower. Designing a bi-level programming model, this study considers the various concerns of the government, contractors, and ordinary people. In addition to meeting people’s health needs, the model considers the costs of HIW in the process of collecting HIW during an epidemic, as well as the distribution costs of daily necessities and health supplies. To accomplish this, the following five assumptions are made:

Assumption 1. Health supplies include face masks, gloves, and disinfectants. Daily necessities include meat, rice, oil, legumes, and vegetables. The aim of these activities is to satisfy the needs of citizens and to support them, which leads to the observance of home quarantine. In other words, if the needs of citizens are met, there is no need to go out and purchase these items.

Assumption 2. The costs of providing and distributing health supplies and daily necessities are quite different. In this study, by defining two different parameters, the costs related to government support packages are determined.

Assumption 3. Government support packages are given to citizens in exchange for separating hazardous infectious waste (face masks, gloves, and other infectious waste) from municipal waste (usual daily waste). In other words, the government intends to encourage people to separate the waste produced during the COVID-19 pandemic at source.

Assumption 4. Hazardous infectious waste, including face masks and gloves, which may carry the COVID-19 virus, can infect all waste if mixed with municipal waste. To prevent contamination of all waste sources, it is assumed that by separating the infectious waste, the contamination of all the waste is prevented, and subsequently the spread of the virus through waste.

Assumption 5. Government support packages are stored and distributed by separate warehouses. In other words, warehouses are set up in k places to distribute government support packages (health supplies and daily necessities). Meanwhile, waste is collected in other centers (temporary stations) and then transported.

| Parameter | Description |
|-----------|-------------|
| \( i \) | Index of the citizens; |
| \( j \) | Index of the hospitals; |
| \( w \) | Index of total collection of waste; |
| \( w' \) | Index of MW; |
| \( w'' \) | Index of HIW; |
| \( p \) | Index of the health supplies; |
| \( j' \) | Index of the potential locations for temporary stations for waste collection; |
| \( h \) | Index of potential locations for recycling centers; |
| \( i' \) | Index of potential locations for HIW disposal; |
| \( e \) | Index of daily necessities; |
| \( f \) | Index of the index of the contract capacity; |
| \( c \) | Index of different capacity levels for temporary stations; |
| \( k \) | Index of different capacity levels for recycling centers; |

The parameters and variables used for modeling are given below:

\begin{align*}
\rho^w_i & \quad \text{The amount of separated waste} \ w \text{ by the citizen} \ i \text{ which is collected by the temporary station} \ r; \\
\phi^w & \quad \text{The amount of MW unit} \ w' \text{ moved from temporary station} \ r \text{with the capacity level} \ l \text{ to recycling center} \ r; \\
\chi^w_j & \quad \text{The amount of HIW unit} \ w'' \text{ moved from temporary station} \ r \text{with the capacity level} \ e \text{ to disposal locations} \ h \text{ by special shipping} \ r; \\
\phi^w_j & \quad \text{The amount of HIW unit} \ w'' \text{ moved from hospital} \ j \text{ to disposal locations} \ h \text{ by special shipping} \ r; \\
\delta^w_p & \quad \text{The amount of daily necessities} \ p \text{ distributed from the warehouses} \ k \text{ to citizens} \ i; \\
\delta^w_i & \quad \text{A zero-one variable is equal to} \ 1 \text{ for setting up a temporary station} \ t \text{ with capacity level} \ e; \\
\beta^w & \quad \text{A zero-one variable is equal to} \ 1 \text{ for setting up a recycling center} \ r \text{ with a capacity of} \ l; \\
\eta^w_p & \quad \text{A zero-one variable is equal to} \ 1 \text{ for setting up a warehouse} \ k \text{ for daily necessities} \ p \text{ and health supplies} \ f; \\
\end{align*}
According to the issuance of government support policies in the COVID-19 outbreak aimed at reducing citizens’ exposure through contaminated waste collection and distribution support, the government model can be formulated by Eqs. (1)–(11).

\[
\begin{align*}
\text{Min } & \quad Z_1 = \sum_{i \in N} \sum_{w \in W} c_{fi}^w r_i^w + \sum_{p \in P} \sum_{f \in F} c_{pf}^t r_p^t + \sum_{i \in N} \sum_{w \in W} c_{fi}^w d_i^w \mu_i^w \\
& \quad + \sum_{i \in N} \sum_{p \in P} \sum_{f \in F} c_{pf}^t d_p^t \theta_p^t \hspace{1cm} \text{s.t.} \\
& \quad \sum_{i \in N} \mu_i^w = 1 \quad \forall i \in N, w \in W \tag{2} \\
& \quad \gamma_i^f \leq 1 \quad \forall p \in M, f \in F \tag{3} \\
& \quad \varepsilon_{i}^f \leq \sum_{w \in W} c_{fi}^w \theta_i^w \quad \forall i \in T \tag{4} \\
& \quad \varepsilon_i^f \leq 1 \quad \forall t \in T \tag{5} \\
& \quad \sigma_{i}^f \leq 1 \quad \forall p \in M, k \in K \tag{6} \\
& \quad \delta_{i}^f \geq 1 \quad \forall f \in F, k \in K \tag{7} \\
& \quad \sum_{i \in i} \sigma_{i}^f + \sum_{i \in i} \delta_{i}^f \leq \sum_{i \in i} \varepsilon_i^f \quad \forall i \in N, p \in M, k \in K, f \in F \tag{8} \\
& \quad \sum_{i \in i} \varepsilon_i^f \leq \sum_{i \in i} \mu_i^w \quad \forall i \in N, w \in W, w \in W \tag{9} \\
& \quad \mu_i^w \geq 0, \varepsilon_i^f \geq 0, \sigma_{i}^f \geq 0, \delta_{i}^f \geq 0 \quad \forall i \in N, t \in T, v \in V, p \in M \text{ and } k \in K \tag{10} \\
& \quad \alpha^f, r^f \in (0, 1) \quad \forall i \in T, e \in E, p \in M \text{ and } f \in F \tag{11} \\
\end{align*}
\]

In this model, Eq. (1) represents the objective function of the upper-level problem, which aims at minimizing government expenditure. The first and second statements in this equation indicate the cost of setting up temporary stations and distribution warehouses. The third statement shows the cost of collecting the separated waste from citizen’s locations by temporary stations. The fourth and fifth statements show the cost of supplying and distributing the support packages (health supplies and daily necessities) between the citizens, respectively. Constraint (2) ensures that there is only one active temporary station for waste collection. Constraint (3) ensures that there is only one active warehouse for the distribution of packages. Constraint (4) guarantees that all requests received by a temporary station do not exceed the capacity of that station. Constraint (5) indicates that no more than one capacity level can be selected for each temporary station. Constraint (6) ensures that there is only one package that includes daily necessities for distribution. Constraint (7) ensures that there is at least one package that includes health supplies for distribution between the citizens. Constraint (8) determines the balance between packages and warehouses. Constraint (9) ensures that the volume of HIW does not exceed the total waste. Constraint (10) gives the constraints with regard to the non-negativity of continuous variables. Finally, constraint (11) shows the binary variable.

The waste collection model in an epidemic condition for the contractor company is designed as follows:

\[
\begin{align*}
\text{Min } & \quad Z_2 = \sum_{i \in i} \sum_{t \in T} c_{ft}^i \mu_i^w + \sum_{w \in W} \sum_{i \in i} \sum_{f \in F} c_{fi}^w \mu_i^w \\
& \quad + \sum_{w \in W} \sum_{i \in i} \sum_{f \in F} c_{pi}^w \mu_i^w \hspace{1cm} \text{s.t.} \\
& \quad \sum_{i \in i} \mu_i^w = 1 \quad \forall e \in E, w \in W \text{ and } r \in R \tag{13} \\
& \quad \sum_{w \in W} \sum_{i \in i} \sum_{f \in F} c_{pi}^w \mu_i^w \hspace{1cm} \text{subject to} \tag{14} \\
& \quad \sum_{w \in W} \sum_{i \in i} \sum_{f \in F} c_{pi}^w \mu_i^w \hspace{1cm} \text{subject to} \tag{15} \\
& \quad \mu_i^w \geq 0, \varepsilon_i^f \geq 0, \sigma_{i}^f \geq 0, \delta_{i}^f \geq 0 \quad \forall i \in N, t \in T, v \in V, p \in M \text{ and } k \in K \tag{10} \\
& \quad \alpha^f, r^f \in (0, 1) \quad \forall i \in T, e \in E, p \in M \text{ and } f \in F \tag{11} \\
& \quad \sum_{v \in V} c_{v}^w \mu_i^w \leq c_{v}^w \mu_i^w \quad \forall r \in R, l \in L \tag{16} \\
& \quad \sum_{i \in i} \sum_{f \in F} \mu_i^w \leq \sum_{i \in i} \mu_i^w \quad \forall i \in N, w \in W \tag{17} \\
& \quad \sum_{i \in i} \sum_{f \in F} \mu_i^w \leq \sum_{i \in i} \mu_i^w \quad \forall i \in N, w \in W \tag{18} \\
\end{align*}
\]
### Table 3
Amounts associated with waste (based on kg).

| Districts of Region 5 | Volume of wastes | Infectious wastes are separated | Infectious wastes of hospitals | Municipal wastes |
|-----------------------|------------------|---------------------------------|-------------------------------|-----------------|
| 1                     | 885              | 628                             | 3560                          |
| 2                     | 489              | 131                             | 2931                          |
| 3                     | 800              | 450                             | 3435                          |
| 4                     | 613              | 653                             | 2895                          |
| 5                     | 257              | 125                             | 2659                          |
| 6                     | 361              | 387                             | 2948                          |
| 7                     | 381              | 223                             | 2915                          |
| 8                     | 921              | 608                             | 3571                          |
| 9                     | 419              | 484                             | 2757                          |
| 10                    | 251              | 200                             | 2805                          |
| 11                    | 748              | 436                             | 2931                          |
| 12                    | 597              | 375                             | 3152                          |
| 13                    | 388              | 326                             | 3411                          |
| 14                    | 941              | 653                             | 3187                          |
| 15                    | 740              | 414                             | 3332                          |
| 16                    | 427              | 613                             | 3429                          |
| 17                    | 527              | 486                             | 3764                          |
| 18                    | 263              | 386                             | 2787                          |
| 19                    | 579              | 545                             | 3303                          |
of occurrence, due to the severity of the virus outbreak, the use of sanitary ware and disposable utensils, etc. increases, which increases the volume of waste.

The problem formulation involves a large number of parameters. Changes to some of the important parameters are shown in Fig. 7. Cost parameter changes can be divided into three parts. The first part of the costs is related to the collection and transportation of segregated waste. In Table 6, the results for government spending as the leader during the COVID-19 epidemic are displayed, based on different scenarios. During the COVID-19 epidemic, the government is required to provide health supplies and daily necessities for citizens, which affects government expenditure. On the other hand, the cost of contractors, as follows, is affected by government policies. Although decisions about setting up new locations as temporary stations and distribution warehouses are strategic decisions, the outbreak of the virus will ultimately be a determining factor. Therefore, it is highly likely that the government’s previous decisions will not be optimal across different scenarios, and as a result, the government will incur exorbitant costs involved in setting up new locations.

Fig. 8(a) shows the control of the cost of government policies for supporting the people and supporting the contractors during COVID-19 outbreak.
outbreaks. It can be seen that the government cost increases with the severity of the virus outbreak. The reason for this is that with a larger outbreak of the virus, the government’s requirements for more health supplies (masks and gloves) has increased, along with the use of these supplies. Consequently, the government must supply and distribute more health supplies to meet the demands of the people. However, people also need more daily necessities in order to successfully maintain social distancing. Upon closer inspection, it can be seen that in the 37th day, the slope of the chart begins to decline. The reason for this change of direction could be the optimal allocation of health supplies and daily necessities. Moreover, Fig. 8 (b) shows the cost of contractors during COVID-19 outbreaks. It can be seen that when the demand for waste collection reaches 6600 units, costs are controlled, and the slope of the contractor’s cost chart changes downward. Fig. 8(b) demonstrates that the total costs are sensitive to the amount of waste.

Fig. 9 shows the changes related to the complications that have been imposed on the contractor. As previously stated in the parameter definition section, these complications are related to the virus being transmitted to the waste collectors by the contaminated waste. As can be seen in Fig. 9(a), the slope of the graph has been reduced in all scenarios, which indicates a reduction in the risk of virus transmission. More specifically, it can be seen that despite the significant increase in waste, complications have been reduced by about 52%. The reasons for this are the separation of waste at source, and the use of special shipping to transport hazardous infectious waste. Fig. 9 (b) shows the process of reducing the complications of virus transmission in more detail across the four scenarios. According to Fig. 9(b), the slope of the diagram in Scenario 1 is lower than in other scenarios. Obviously, in the first scenario, the prevalence of the virus is low, so the risk of transmitting the virus is also lower. The highest rate of complications is related to Scenario 2, which shows a significant growth of virus transmission by hazardous waste.

As indicated in Fig. 10, in Scenario 1, temporary station 2 shows the highest percentage response to the demand of citizens in region 5.
Moreover, all the demand of districts 4, 5, 6, 16 and a major part of the demand of district 18 is covered by this temporary station in scenario 1, while the rest of the demand is covered by temporary station 3. By increasing the demand in the second scenario, the capacity of the temporary station 3 can fulfill a lower percentage of demand. It is clear that in the second scenario, temporary station 3 could not fully cover the demand of district 7. Thus, this reduction in demand coverage must be covered by temporary station 4. In general, it was observed that temporary station 4 played an alternative role for temporary station 3, because in the fourth scenario, temporary station 3 is able to meet the demand of district 7 by reducing its workload. Using the heat map diagrams, Fig. 11 illustrates how the demand of the 19 districts from region 5 of Tehran are covered in different scenarios. The figure clearly shows that with the start of the epidemic, the demand of northeastern districts of region 5 went uncovered, because of its insufficient capacity to collect waste. As the prevalence of the virus increases and the epidemic intensifies, the production of MW and HIW will increase significantly. However, it can be seen that the demand for waste collection is well covered, and the high demand for waste collection has decreased from 40 % to 17 %, with only two districts in crisis situations. In the second and third scenarios, the coverage of the demand seems more appropriate, as the high demand has decreased from 17 % to 5 %. This indicates better coverage for waste collection. This trend continues to the point where, in the fourth scenario, at the peak of the epidemic, there is no high demand, and all districts are in better condition.

The government’s policy in the COVID-19 epidemic has helped to separate infectious waste at source, such that the safe collection of HIW has been significantly facilitated. The proposed model also helps
managers address the demand of citizens in all areas of Tehran, which is due to the increase in the volume of waste caused by the COVID-19 outbreak. For a more detailed review, the costs allocated to the supply and distribution of health supplies and daily necessities are measured in Fig. 12.

Fig. 12 shows that government spending has not decreased during the 8 weeks review. Given the fixed cost of setting up a temporary station and recycling centers, this indicates that the reduction in total costs was exclusively related to more efficient waste collection and transportation. The main reason for reducing costs in the collection and transportation process is the accurate choice of the temporary stations for each area. This numerical example provides the following managerial insights:

- Due to the sudden increase in municipal waste due to the COVID-19 epidemic, the proposed bi-level model helps managers to better manage waste generated during COVID-19 by a leader-follower approach. In other words, as depicted in Fig. 10, despite the large increase in the volume of municipal waste and hazardous infectious waste during the COVID-19 pandemic (in different scenarios), the generated waste was collected appropriately and almost all demand was covered.
- The proposed model showed a cost-based approach that can help managers reduce the risk of virus transmission via waste. In other words, managers can optimize the number of people exposed to waste by considering the risk of contaminated waste to people’s health.

![Fig. 11. How to cover the demand of 19 districts in Tehran.](image1)

![Fig. 12. Costs of supply and distribution of health supplies and daily necessities over 8 weeks.](image2)
The inclusion of uncertain scenarios in WM planning and the use of a stochastic approach to deal with these uncertainties will lead to the acquisition of useful managerial and operational strategies. In a model based on certainty, dealing with systems with limited resources reduces overall efficiency. In other words, in the stochastic programming model, the unanswered part of the demand for HIW collection services in certain probable scenarios is due to lack of capacity. Therefore, the ability to change the capacities of the temporary stations for collecting HIW from citizens can be of great assistance in solving this problem.

Finally, according to Table 6 and Fig. 8, the proposed the bi-level model helped both government and contractors minimize total costs during a COVID-19 pandemic by making good use of existing capacities and facilities. These costs included setting up temporary stations, warehouses, and recycling centers as fixed costs; costs related to the supply and distribution of support packages and waste collection, as well as complications due to virus transmission were considered as running costs.

6. Conclusion and further research

The government should implement various measures to support citizens and relevant contractors during the COVID-19 pandemic. By distributing health equipment and daily necessities, the government can appropriately implement home quarantine decisions and traffic restrictions. The government may also encourage citizens to separate urban waste from HIW at source with an elaborate incentive policy. In the proposed model, the government’s supportive policy is considered through a bi-level programming model. The model included the government’s support policy as leader, and the activities of the waste collection contractor as follower. A scenario-based mathematical model was developed to solve the problem of HIW collection and daily necessity distribution among citizens during a COVID-19 epidemic. In order to evaluate the effect of the uncertain conditions of the COVID-19 pandemic, four scenarios were considered to model the varying severity of the outbreak. In addition, the proposed model showed that, despite the production of hazardous infectious waste during various scenarios, the complications of virus transmission imposed on contractors can be reduced.

Regarding the complexity of the stochastic bi-level programming problem developed, the KKT condition and Benders decomposition were used in the solution approach. The results of the problem in the case study show the efficiency of the proposed method. By stochastically generating different rates of demand for the waste generated under epidemic conditions, several computational analyses were performed, and significant managerial insights were obtained. The results showed that despite the high production of HIW and MW due to the outbreak of COVID-19 and its rapid spread in the four defined scenarios, the government would be able to manage the bulk of the generated waste.

For future work, only the uncertainty of the demand for the collection was investigated in this study; therefore, uncertainty related to other parameters could be considered (such as the capacity of facilities and reliability of equipment). The process of recycling and disposing of HIW during a COVID-19 outbreak can also be evaluated in future studies. Formulating other government policies, such as financial incentives or penalties for violating imposed regulations, may also provide useful research avenues.

CRediT authorship contribution statement

Jaber Valizadeh: Conceptualization, Methodology, Investigation, Resources, Software, Validation, Formal analysis, Writing - Original Draft preparation, Writing - Review & Editing. Ashkan Hafezalkotob: Conceptualization, Methodology, Investigation, Supervision, Validation, Formal analysis, Writing - Original Draft preparation, Writing - Review & Editing. Seyed Mehdi Seyed Alizadeh: Model formulation, Software, and Solution Method. Peyman Mozafari: Formal analysis, Editing and literature survey.

Declaration of Competing Interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. The authors confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. The authors would like to appreciate the referees for their insightful comments.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.scs.2021.102814.

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