Sustainable development-oriented location-transportation integrated optimization problem regarding multi-period multi-type disaster medical waste during COVID-19 pandemic

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Abstract
After the outbreak of COVID-19 pandemic, devising an effective reverse logistics supply chain to clean up disaster medical waste is conducive to controlling and containing novel coronavirus transmission. Thus, the focus of this paper concentrates on multi-period multi-type disaster medical waste location-transportation integrated optimization problem with the concern of sustainability, which is formulated as a tri-objective mixed-integer programming model with the goals of maximizing total economic benefits, minimizing total carbon emissions and total potential social risks. Then, a real-world case from Wuhan using CPLEX solver is used to validate the developed model. Results indicate that constructing DMWTTSs with flexible capacity in different periods is encouraged to handle the sharply increasing disaster medical waste. The multi-period decision model outperforms the single-period one in disaster medical waste supply chains because the former has the capability of handling the uncertainties in the future periods. Increasingly, since the increase of budget doesn’t always work well and social resources are limited, the estimation of minimum budget to obtain optimum overall performance is of great importance.
Keywords  Disaster medical waste · COVID-19 pandemic · Sustainable development · Multi-period multi-type location-transportation · Multi-objective mixed-integer programming model

Abbreviations

COVID-19  Coronavirus Disease 2019
DMWTTS(s)  Disaster medical waste temporary transfer stations
DMWGP(s)  Disaster medical waste generation points
DMWDC(s)  Disaster medical waste disposal centers

1 Introduction

The outbreak of COVID-19 pandemic as major sudden public health emergency challenges not only the supply of different types of medical goods, but the ability of the existing medical waste management system. It is reported that a daily maximum amount of disaster medical waste is 263 tons in Wuhan in 2020, which shows a dramatic increase relative to an average daily production mass of approximately 55 tons in 2019 (Chen et al., 2021). Kampf et al. (2020) and Valizadeh et al. (2021) further underlined novel coronavirus could be transmitted via various inanimate surfaces including disaster medical waste. In this sense, designing effective disaster medical waste supply chains is conducive to controlling and containing the spread of COVID-19 pandemic, which is the focus of this paper.

In the aftermath of COVID-19 pandemic, a sharp increasing medical waste production mass poses a demanding disposal capacity. In this regard, the location of temporary transfer stations as the linkage between generation points and disposal centers seems very critical to enhance the performance of disaster medical waste supply chains, which is supported by Onan et al. (2015), Kargar et al. (2020), Mahyari et al. (2022), and Zhao et al. (2021). Another fact is that the number of temporary transfer stations and the existing disposal centers, and their capacity to cope with disaster medical waste is very limited. How to design an effective transportation scheme to balance the workloads from a global standpoint and meet all needs for disaster medical waste disposal is urgent and challenging during COVID-19 pandemic (Tirkolaee et al., 2021; Valizadeh et al., 2021). Besides, logistics infrastructure construction such as temporary transfer stations is the prerequisite for successful transportation and clean-up of disaster medical waste. In this context, study on disaster medical waste location-transportation integrated optimization problem is pressing.

To effectively control COVID-19 pandemic, the location-transportation joint decisions on disaster medical waste need to be immediately made to ensure timely disposal within 24 h (Chen et al., 2021). It indicates that the best decision period for local authorities to make the corresponding decisions based on real-time information seems one day. In this sense, more attention should be attached to multi-period disaster medical waste location-transportation problem. Studies such as Yu et al. (2020a), Valizadeh et al. (2021), and Valizadeh and Mozafari (2022) indicated that it was a conventional classification method to regard disaster medical waste as infectious and non-infectious one. In terms of the former, it would cause secondary and cross infection if contaminated disaster medical waste is not handled in a timely and safe manner. Therefore, disaster medical waste type is also a significant factor that needs to be considered into the above incorporated issue.
As above mentioned, once contaminated disaster medical waste is improperly managed, it may increase the infection risks of novel coronavirus among residents, thus adverse influences on social sustainability (Kargar et al., 2020). Transportation activities on disaster medical waste clean-up would inherently produce carbon emissions, thus unfavourable impacts on environment (Fathollahi-Fard et al., 2022; Jalloul et al., 2022). Although most of studies addressed the costs spent in handling medical waste, it cannot turn a blind eye on the fact that disaster medical waste clean-up activities also can create economic benefits (Boonmee et al., 2018). Consequently, the focus of this paper is sustainable development-oriented location-transportation integrated optimization problem concerning multi-period multi-type disaster medical waste during COVID-19 pandemic. The goals here manifest the following points.

1. How to use a mathematical programming approach to capture economic, environmental, social sustainability performance?
2. How to formulate a multi-objective optimization model for multi-period multi-type disaster medical waste location-transportation joint decisions?
3. What is an optimal scheme concerning multi-period disaster medical waste location-transportation during COVID-19 pandemic?
4. What are the influences of waste type, decision method, and budget on the overall performance of disaster medical supply chains?

To address the above four challenges, economic sustainability is measured by economic benefits. Carbon discharge is used to characterize environmental dimension of sustainability, and this paper formulates social sustainability as potential social risks. A multi-objective mixed-integer programming model is applied to characterize multi-period decisions regarding multi-type disaster medical waste location-transportation. Then, the constructed model is solved by using a CPLEX solver. Furthermore, the impacts of waste type, decision method, and budget on disaster medical waste supply chains performance are observed by a real case from Wuhan, China.

This paper contributes to the following three points. Firstly, most of the existing studies focused on non-infectious disaster waste management in the aftermath of natural disasters such as earthquake, Hurricane (Boonmee et al., 2018; Cheng et al., 2021; Habib et al., 2019; Heydari et al., 2022; Onan et al., 2015). Nevertheless, this paper investigated disaster medical waste location-transportation integrated optimization problem in the presence of sustainability, infection risks, multi-period, multi-type, budget, workload level, multiple generation points, and multiple disposal centers, thus building a theoretical linkage of disaster medical waste clean-up with sustainable development, and furnishing the systematic guidelines of operations to control COVID-19 pandemic. Secondly, this paper formulated the above problem as a tri-objective mixed-integer programming model to maximize total economic benefits, minimize total carbon emissions, and minimize total potential social risks, which fills the gaps pointed out by Tirkolaee et al. (2021), Valizadeh et al. (2021), Eren and Tuzkaya (2021), and Govindan et al. (2021) in the field of COVID-19 medical waste management. Thirdly, establishing temporary transfer stations with flexible capacity in different periods is encouraged to handle the sharp increase of COVID-19 medical waste (Mahyari et al., 2022). The accurate prediction of infectious disaster medical waste by using advanced technologies, the use of energy-saving vehicles and smart portable equipment, and the application of the multi-period decision model is beneficial to decrease potential novel coronavirus infection risks, which enriches the studies of Kargar et al. (2020), and Chen et al. (2021). Once the increase of budget doesn’t lead to the reduction of infection risks, non-monetary incentive measures and precise estimation of minimum budget is necessary for further improvement in combating COVID-19 pandemic.
The reminder of this paper includes the following sections. Section 2 concludes the related works from different aspects. Problem description and disaster medical waste location-transportation model is shown in Sect. 3. The corresponding solution strategies for the multi-objective optimization model is devised in Sect. 4. In Sect. 5, a real-world case from Wuhan is used to validate the effectiveness of the proposed methodology. Finally, Sect. 6 concludes this paper and suggests the potential promising topics in the future.

2 Literature review

After the outbreak of COVID-19 pandemic, disaster medical waste management attracts an increasing awareness of researchers. Given the diversity of current achievements in the field of disaster medical waste management, this section concludes relevant literature from three streams. The first stream pays attention to sustainability measurement under disaster context. The second one concentrates on disaster medical waste management problem considering different characteristics. Last one concerns location and transportation optimization models in reverse logistics supply chains. The critical papers of each stream are summarized in Table 1 to present the gaps among different studies from the following aspects: the type of supply chain, sustainability, problem characteristics, model features, case study, and disaster type.

2.1 Sustainability formulation under disaster context

Sustainable development refers to the coordinated development of economy, environment, and society by using a triple-bottom-line approach. In the context of both commerce and disaster, there is no consensus on the definition and formulation of sustainability in the field of management science and operations management. Studies regarding sustainability in the context of disaster relative to commerce are still in its early stage (Dubey & Gunasekaran, 2016; Dubey et al., 2017, 2019; Haavisto & Kovacs, 2014; Kunz & Gold, 2017).

For instance, Cao et al. (2018) focused on post-disaster relief distribution problem in sustainable disaster supply chains, and used survivors’ perceived satisfaction to measure social aspect of sustainability. Habib et al. (2019) applied emergency costs, carbon emissions, and job opportunities to respectively characterize the economic, environmental, and social sustainability concerned in disaster waste location-transportation optimization problem. For multi-period post-disaster relief distribution issue, Cao et al. (2021) proposed unmet demand rate, environmental risks, and emergency costs to measure social, environmental, and economic concerns, respectively. Tirkolaee et al. (2021) designed three indicators including total traveling time, total violation, and total disposal sites risks to formulate social sustainability in a disaster medical waste location-routing problem.

In summary, most of the studies focused on sustainability of commercial supply chains, but rarely incorporated sustainability into disaster supply chains, especially reverse logistics supply chains in the context of disaster, which is depicted in Table 1. In detail, the existing studies paid more attention to the combination of sustainability and relief distribution problem. How to integrate philosophies of sustainable development into disaster medical waste clean-up, and how to construct efficient and appropriate indicators to measure social, environmental, and economic concerns need to be investigated in depth.
| References             | Year | Stream | Type of SC | Sustain. | Problem characteristics | Model features | Case study | Disaster type |
|------------------------|------|--------|------------|----------|--------------------------|----------------|------------|--------------|
|                        |      | a      | b          | c        | d                        | e              | f          | g            |
|                        |      |        |            |          | WGP(s)                  | WDC(s)         | WT         | Context      | Period(s) | Obj. | Main obj. |         |              |
| Çelik et al.           | 2015 | 3      | Reverse    | None     | –                        | –              | –          | Disaster     | Multi     | Single | 2       | Numer | Earthquake |
| Onan et al.            | 2015 | 3      | Reverse    | None     | –                        | –              | –          | Disaster     | Single    | Multi  | 1, 4    | Real  | Earthquake |
| Cao et al.             | 2017 | 1      | Forward    | S, En, Ec | –                        | –              | –          | Disaster     | Single    | Multi  | 1, 3, 5 | Real  | Earthquake |
| Mantzaras and Voudrias | 2017 | 3      | Reverse    | None     | Multi                    | Multi          | Single     | Commerce     | Multi     | Single | 1       | Real  | –          |
| Cao et al.             | 2018 | 1      | Forward    | S         | –                        | –              | –          | Disaster     | Single    | Multi  | 4       | Real  | Earthquake |
| Boonmee et al.         | 2018 | 3      | Reverse    | En, Ec   | –                        | –              | –          | Disaster     | Single    | Multi  | 1       | Numer | –          |
| Laguna-Salvadó et al.  | 2019 | 1      | Forward    | S, En, Ec | –                        | –              | –          | Disaster     | Multi     | Multi  | 1, 3, 4 | Real  | –          |
| Habib et al.           | 2019 | 1,3    | Reverse    | S, En, Ec | –                        | –              | –          | Disaster     | Single    | Multi  | 1, 3, 4 | Numer | Hurricane |
| Kargar et al.          | 2020 | 2,3    | Reverse    | None     | Multi                    | Multi          | Single     | Disaster     | Multi     | Multi  | 1, 4    | Real  | COVID-19   |
| Yu et al.              | 2020a| 2,3    | Reverse    | None     | Multi                    | Multi          | Single     | Disaster     | Multi     | Multi  | 1, 4    | Real  | COVID-19   |
| Yu et al.              | 2020b| 3      | Reverse    | None     | Multi                    | Multi          | Single     | Commerce     | Single    | Multi  | 1, 4    | Real  | –          |
| Cao and Cao            | 2020 | 3      | Reverse    | S, En, Ec | –                        | –              | –          | Commerce     | Single    | Multi  | 2, 3, 4 | Numer | –          |
| Boostani et al.        | 2021 | 1      | Forward    | S, En, Ec | –                        | –              | –          | Disaster     | Single    | Multi  | 1, 3, 4 | Numer | Earthquake |
| Cao et al.             | 2021 | 1      | Forward    | S, En, Ec | –                        | –              | –          | Disaster     | Single    | Multi  | 1, 3, 4 | Real  | Earthquake |
| Eren and Tuzkaya       | 2021 | 2      | Reverse    | None     | Multi                    | Multi          | Single     | Disaster     | Single    | Single | 5       | Real  | COVID-19   |
| Valizadeh et al.       | 2021 | 2,3    | Reverse    | None     | Multi                    | Multi          | Multi      | Disaster     | Single    | Single | 1       | Real  | COVID-19   |
| Mojtabahi et al.       | 2021 | 3      | Reverse    | S, En, Ec | –                        | –              | –          | Commerce     | Single    | Multi  | 1, 3, 4 | Real  | –          |
| Cheng et al.           | 2021 | 3      | Reverse    | None     | –                        | –              | –          | Disaster     | Multi     | Multi  | 1, 5    | Real  | Bushfire  |
| References          | Year | Stream | Type of SC | Sustain. | Problem characteristics | Model features | Case study | Disaster type |
|---------------------|------|--------|------------|----------|-------------------------|----------------|------------|---------------|
|                     |      | a      | b          | c        |                         |                |            |               |
| Tirkolaee et al.    | 2021 | 1, 2, 3| Reverse    | S        | Multi                   | Multi          | 4, 5       | Real          |
|                     |      |        |            |          | WGP(s)                 |                 |            | COVID-19      |
|                     |      |        |            |          | WDC(s)                 |                 |            |               |
|                     |      |        |            |          | WT                      |                 |            |               |
|                     |      |        |            |          | Context                 |                 |            |               |
|                     |      |        |            |          | Period(s)               |                 |            |               |
|                     |      |        |            |          | Obj.                    |                 |            |               |
|                     |      |        |            |          | Main obj.               |                 |            |               |
| Valizadeh and      | 2022 | 2, 3   | Reverse    | None     | Multi                   | Single          | 1          | Real          |
| Mozafari            |      |        |            |          | WGP(s)                 |                 |            | COVID-19      |
|                     |      |        |            |          | WDC(s)                 |                 |            |               |
|                     |      |        |            |          | WT                      |                 |            |               |
|                     |      |        |            |          | Context                 |                 |            |               |
|                     |      |        |            |          | Period(s)               |                 |            |               |
| This paper          | 1, 2, 3| Reverse | S, En, Ec  | Multi    | Multi                   | Multi          | 2, 3, 4    | Real          |
|                     |      |        |            | WGP(s)   | WDC(s)                  | WGP(s)         |            | COVID-19      |
|                     |      |        |            | WDC(s)   | WT                      | WDC(s)         |            |               |
|                     |      |        |            | WT       | Context                 | WDC(s)         |            |               |
|                     |      |        |            | Context  | Period(s)               | WDC(s)         |            |               |
|                     |      |        |            | Period(s)| Obj.                    | WDC(s)         |            |               |
| aThree streams are 1. Sustainability formulation under disaster context; 2. Disaster medical waste management problems considering different characteristics; 3. Location or transportation or both optimization models in reverse logistics supply chains |
| bSupply chain (SC) is divided into forward and reverse one |
| cThis term shows that one or more aspect(s) of social (S), environmental (En), and economic (Ec) sustainability is (are) explicitly taken into account. Note that ‘None’ represents the philosophies of sustainability is not clearly incorporated into the optimization issues |
| dIt demonstrates the number of medical waste generation points (WGPs) is single or multiple. Note that ‘–’ represents it cannot be explicitly found in the text |
| eThis term indicates that there is single or multiple medical waste disposal centers (WDCs). Note that ‘–’ shows it cannot be explicitly found in the text |
| fWaste type (WT) denotes that either single- or multi-type medical waste is explicitly considered into supply chains. Note that ‘–’ indicates it is not clearly mentioned in the text |
| gThe optimization problem in supply chains is considered in the context of commerce or disaster |
| hThis column denotes that the issue involved in supply chains is single- or multi-period one |
| iThe developed mathematical programming model has single or multiple objective(s). Particularly, it just accounts for the objectives of the upper-level optimization problem if the model is a bi-level one |
| jIt demonstrates the main objectives of the proposed model can be related to 1. costs (e.g. minimization of transportation costs), 2. economic benefits (e.g. maximization of the expected benefits), 3. environment (e.g. minimization of carbon emissions), 4. social benefits (e.g. minimization of the population exposure risk, deviation of fair load allocation, unmet demand rate, maximization of the perceived satisfaction, job opportunities, local empowerment), 5. rapidity (e.g. minimization of total traveling time, weighted completion time, tour distance) |
| kIt indicates that the case using to validate the proposed model and solution strategy is numerical (numer.) or real |
| lThis term shows that which disaster type is considered to validate the proposed methodology. Note that ‘–’ indicates it is not explicitly mentioned in the text |
2.2 Disaster medical waste management problem considering different characteristics

Brown et al. (2011) and Zhang et al. (2019) claimed that there were a plenty of topics to be further studied in the field of disaster waste management. In particular, the popular issues are related to prediction of waste quantity (Chen et al., 2021), selection of treatment technologies and approaches (Chen et al., 2021; Dharmaraj et al., 2021), route planning (Eren & Tuzkaya, 2021; Tirkolaee et al., 2021), location (Kargar et al., 2020; Onan et al., 2015), transportation (Valizadeh et al., 2021), and others.

For instance, Habib et al. (2019) addressed a sustainable disaster waste supply chain spanning multiple temporary management points, and multiple disposal sites. They attached single-period to the problem concerning disaster waste transportation and selection of disposal methods in the aftermath of hurricane. Eren and Tuzkaya (2021) studied a vehicle routing issue regarding medical waste collection in the presence of safe distance, single-period, and single-objective during COVID-19 pandemic. Valizadeh et al. (2021) incorporated multiple WGP's and WDC's, multi-type, single-period, hierarchal relations, and single-objective characteristics into disaster medical waste collection and government aid distribution problem.

To sum up, Table 1 demonstrated that the existing studies concentrated on reverse logistics supply chains in the context of commerce, yet disaster waste management, especially disaster medical waste clean-up, was rarely considered in the literature. Most of them merely took into account the features of single period and single type, while seldom studies focused on multi-period multi-type disaster medical waste optimization problem with the concern of social, economic, and environmental sustainability. The overwhelming majority of researchers only highlighted one or more term(s) in Table 1, but this paper addressed all aspects.

2.3 Location and transportation optimization models in reverse logistics supply chains

Practical and theoretical cases demonstrated that location and transportation optimization problem was the critical and prevalent topic in reverse logistics supply chains. In recent years, there is a growing awareness of such issues, thus considerable achievements.

For example, Yu et al. (2020b) devoted to devising a stochastic network for hazardous waste management, and developed a bi-objective mixed-integer programming model to minimize overall costs and population exposure risk. Mojtahedi et al. (2021) attached attention to sustainable vehicle routing optimization problem in solid waste management, and proposed a corresponding multi-objective mixed-integer programming model to minimize total costs, carbon dioxide emissions, and total deviation of fair load allocation. Tirkolaee et al. (2021) formulated sustainable disaster medical waste location-routing problem as a mixed-integer linear programming model with the aims of minimizing total travelling time, total violation from time windows, and total infection risks imposed on the population around disposal points.

Overall, Table 1 shown that most of researches constructed single-period single-objective optimization models for location or transportation or integrated issue in commercial reverse logistics supply chains, yet a multi-period multi-objective mixed-integer programming model for multi-type disaster medical waste location-transportation problem was still limited. In addition, they usually attached more importance to optimize cost-related objectives, but the linkage of traditional objectives with sustainable development could only be found in rare studies, which is the focus of this paper.
3 Problem description and multi-period multi-type disaster medical waste location-transportation optimization model formulation

3.1 Problem description

The conception of medical waste is extended to all debris that has been in contact with patients, healthcare personnel, and related workers during COVID-19 pandemic (Chen et al., 2021). Once a major sudden public health emergency occurs, the exponentially increasing amount of disaster medical waste from hospitals will pose serious threats to both environment and residents, patients, and healthcare workers (Yu et al., 2020a). To contain the transmission of novel coronavirus and relieve the impacts, different regions and countries have developed the targeting regulations and policies to manage the medical waste in the context of pre- and under-COVID-19 pandemic in practice.

For instance, before the end of 2019, Chinese government requires the registration, prohibition of sale and purchase, attaching obvious warning sign to package of medical waste, and the use of specialized vehicle for only cleaning up medical waste. Safe management of wastes from health-care activities published by World Health Organization (WHO) pointed out the importance of detailing collection, storage, transportation, and final disposal for different types of medical waste. After the outbreak of COVID-19 pandemic, the capacity building implementation programme for centralized medical waste disposal facilities is proposed to improve the current regulation framework in China. In addition, the time duration for temporarily storing medical waste is updated as 24 from 48 h. The principle on handling medical waste generated in the designated hospitals and fever clinics is daily production and daily clearance. Household waste produced in centralized quarantine sites should be classified into medical one. For a global standpoint, WHO recommends residents to use personal protective equipment with environment-friendly package and transportation. National health sectors over the world are required to reduce carbon footprint for handling disaster medical waste. Moreover, the current medical waste management system can be enhanced by increasing the budget. According to the above statement, it is evident that collection, transportation, storage, and disposal are the main activities in disaster medical waste clean-up (Jalloul et al., 2022).

In terms of collection activities, disaster medical waste generated by hospitals usually can be divided into infectious and non-infectious one (Kargar et al., 2020). The former is collected in dedicated yellow containers, while the latter is packed in other containers. Regarding transportation and storage activities, one of the most critical tasks is to choose the location of temporary transfer stations to temporarily store the soaring disaster medical waste. Another one is to devise an effective transportation plan to satisfy all demands with simultaneously optimizing all objectives. When it comes to disposal activities, landfill, incineration, recycling are the most popular methods in disaster medical waste management (Habib et al., 2019). Chen et al. (2021) and Yang et al. (2021) supported that incineration was preferred disaster medical disposal method during COVID-19 pandemic. In this context, it can be inferred that disaster medical waste generation points (DMWGPs), disaster medical waste temporary transfer stations (DMWTTSs), and disaster medical waste disposal centers (DMWDCs), forming a disaster medical waste supply chain in Fig. 1, play an indispensable role in managing disaster medical waste. Figure 1 presents a framework of the integrated optimization problem for disaster medical waste location-transportation, which is the focus of this paper.

According to the bottom-layer of Fig. 1, the basic environment of disaster medical waste management system spans facilities, stakeholders, and equipment after the outbreak of
COVID-19 pandemic. In the middle layer, different types of disaster medical waste need to be immediately delivered from DMWGP s to DMWTTS s, then to DMWDC s from the perspective of disaster medical waste flow. To effectively combat COVID-19 pandemic, the maximum time length of disposing all kinds of waste is 24 h, which is highlighted by Chen et al. (2021). At the top layer, the framework of disaster medical waste supply chains is further formulated by a mathematical programming approach. In this paper, the decisions concerning disaster medical waste location-transportation include: whether to establish DMWTTS s at candidate locations, the amounts of different types of disaster medical waste transported to DMWTTS s, and those delivered to DMWDC s. The ultimate goals aim to achieve sustainable development of disaster medical waste supply chains, including maximum total economic benefits (economic sustainability), minimum total carbon emissions (environmental sustainability), and minimum total potential social risks (social sustainability).
3.2 Assumptions

**Assumption 1** Disaster medical waste generated by clinics and communities around a certain hospital is assumed to be disposed in a unified manner in this hospital.

**Assumption 2** Disaster medical waste is divided into two types based on its infection, namely infectious and non-infection one.

**Assumption 3** Disaster medical waste supply chains consisting of DMWGPs, DMWTTSs, and DMWDCs is the only focus of this paper. All types of disaster medical waste are first delivered from DMWGPs to DMWTTSs, and then to DMWDCs.

**Assumption 4** The location and amounts of DMWGPs referring to hospitals can be identified through advanced technologies in the aftermath of COVID-19 pandemic. The location and amounts of DMWTTSs and DMWDCs candidates can be pre-specified in advance according to strategic decisions of national emergency management.

**Assumption 5** Populations located in DMWTTSs and DMWDCs, on the routes from DMWGP $i$ to DMWTTS $j$, then to DMWDC $k$ are assumed to be constant in each period.

**Assumption 6** To simplify this problem, each DMWTTS retains identical capacity to temporarily store disaster medical waste. However, the benefits obtained and costs generated from DMWTTSs are different in each period.

**Assumption 7** Given the possibility of novel coronavirus transmission via contaminated disaster medical waste, this paper assumes that all types of medical waste are completely cleaned up in each period, thus beneficial to the control of COVID-19 pandemic.

3.3 Notations of parameters and variables

| Indices and main sets | Parameters |
|-----------------------|------------|
| $I$                   | $A_i^s$    |
| $I$                   | $B_{ijm}^s$ |
| $J$                   | $B_{jkm}^s$ |
| $K$                   | $C_{ijm}^s$ |
| $M$                   | $C_{jkm}^s$ |
| $S$                   | $D_j^s$    |
| $T_s$                 | $a_{jm}$   |

- $I$: Set of $I$ disaster medical waste generation points (DMWGPs), indexed by $i \in I$
- $J$: Set of $J$ disaster medical waste temporary transfer stations (DMWTTSs), indexed by $j \in J$
- $K$: Set of $K$ disaster medical waste disposal centers (DMWDCs), indexed by $k \in K$
- $M$: Set of $M$ types of disaster medical waste, indexed by $m$, and $m \in M = \{1, 2\} = \{\text{infectious}, \text{non-infectious}\}$
- $S$: Set of $S$ different periods, indexed by $s \in S$

- $A_i^s$: Fixed benefits of DMWTTSs in period $s$
- $B_{ijm}^s$: Unit benefit obtained by transporting $m$ disaster medical waste per ton per kilometre from DMWGP $i$ to DMWTTS $j$ in period $s$
- $B_{jkm}^s$: Unit benefit obtained by transporting $m$ disaster medical waste per ton per kilometre from DMWTTS $j$ to DMWDC $k$ in period $s$
- $C_{ijm}^s$: Unit cost for delivering $m$ disaster medical waste per ton per kilometre from DMWGP $i$ to DMWTTS $j$ in period $s$
- $C_{jkm}^s$: Unit cost for delivering $m$ disaster medical waste per ton per kilometre from DMWTTS $j$ to DMWDC $k$ in period $s$
- $D_j^s$: Fixed costs for establishing DMWTTS $j$ in period $s$
- $T_s$: Total budget for disposing disaster medical waste in period $s$
- $a_{jm}^1$: Capacity of storing $m$ disaster medical waste at DMWTTS $j$
3.4 A tri-objective multi-period mixed-integer programming model formulation

According to the above mentioned, sustainable development-oriented multi-period multi-type disaster medical waste location-transportation integrated optimization problem during COVID-19 pandemic can be formulated as a tri-objective mixed-integer programming model \((M0)\), which is denoted by Eqs. (1)–(13).

\[
\begin{align*}
\max_{x_j^s, y_{ijm}^s, z_{jkm}^s} & \quad f_1 = \sum_{j \in J} \sum_{i \in I} A_j^s x_j^s + \sum_{i \in I} \sum_{j \in J} \sum_{m \in M} B_{ijm}^s d_{ij}^1 y_{ijm}^s \\
& \quad + \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} B_{jkm}^s d_{jk}^2 z_{jkm}^s \\
\min_{x_j^s, y_{ijm}^s, z_{jkm}^s} & \quad f_2 = \sum_{i \in I} \sum_{j \in J} \sum_{m \in M} E d_{ij}^1 y_{ijm}^s + \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} E d_{jk}^2 z_{jkm}^s \\
\min_{x_j^s, y_{ijm}^s, z_{jkm}^s} & \quad f_3 = \sum_{i \in I} \sum_{j \in J} \sum_{m \in M} \left( h_j^s R_m y_{ijm}^s + h_k^s R_m z_{jkm}^s \right) \\
& \quad + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} \left( p_{ij}^1 R_m y_{ijm}^s + p_{jk}^2 R_m z_{jkm}^s \right)
\end{align*}
\]
\[
\sum_{i \in I} y_{ijm}^s = \sum_{k \in K} z_{jkm}^s, \quad \forall j \in J, \quad \forall m \in M, \quad \forall s \in S \tag{6}
\]

\[
\sum_{i \in I} y_{ijm}^s \leq a_{jm}^1 x_j^s, \quad \forall j \in J, \quad \forall m \in M, \quad \forall s \in S \tag{7}
\]

\[
\sum_{j \in J} z_{jkm}^s \leq a_{km}^2, \quad \forall k \in K, \quad \forall m \in M, \quad \forall s \in S \tag{8}
\]

\[
\sum_{i \in I} \sum_{m \in M} y_{ijm}^s \geq \sum_{m \in M} \eta_{j} a_{jm}^1 x_j^s, \quad \forall j \in J, \quad \forall s \in S \tag{9}
\]

\[
\sum_{j \in J} \sum_{m \in M} z_{jkm}^s \geq \sum_{m \in M} \eta_{k} a_{km}^2, \quad \forall k \in K, \quad \forall s \in S \tag{10}
\]

\[
x_j^s \in \{0, 1\}, \quad \forall j \in J, \quad \forall s \in S \tag{11}
\]

\[
y_{ijm}^s \text{ are non-negative variables, } \forall i \in I, \forall j \in J, \forall m \in M, \forall s \in S \tag{12}
\]

\[
z_{jkm}^s \text{ are non-negative variables, } \forall j \in J, \forall k \in K, \forall m \in M, \forall s \in S \tag{13}
\]

In this model, Eqs. (1) to (3) represent the objective functions of the optimization problem. Specifically, Eq. (1) aims to maximize total economic benefits obtained from managing disaster medical waste, which is used to measure economic sustainability. Although most of the existing literature demonstrated that disaster waste clearance activities were cost-intensive (Onan et al., 2015; Valizadeh & Mozafari, 2022), it must be acknowledged that the collection, transportation, storage, and disposal of disaster waste also could create benefits for the whole supply chains (Boonmee et al., 2018; Jalloul et al., 2022). In this sense, this paper links the benefits as the indicator with economic concerns of sustainability. For Eq. (1), the first statement denotes the benefits that can be obtained at DMWTTSs. The second and third part defines the comprehensive benefits from disaster medical waste delivery activities from DMWGPs to DMWTTSs, then to DMWDCs, respectively.

Equation (2) expects to minimize total carbon emissions generated from transportation of disaster medical waste for each period. It is evident that a series of transportation activities would inherently produce a variety of hazardous substances, thus undesirable impacts on the environment (Cao et al., 2021). In addition, theoretical studies implied that it was very prevalent in using carbon emissions to formulate environmental sustainability performance in the context of both commerce and disaster (Cao et al., 2021; Habib et al., 2019; Laguna-Salvadó et al., 2019; Mojtahediet al., 2021). Thus, this paper leverages their viewpoints to measure environmental sustainability by a linear form of distance and the amounts of disaster medical waste. For Eq. (2), the first and second term defines total carbon emissions from DMWGPs to DMWTTSs, and then to DMWDCs, respectively.

Equation (3) is to minimize total potential social risks of contaminated disaster medical waste to residents’ health. After the outbreak of COVID-19 pandemic, everyone has to embrace the fact that the storage and disposal activities of disaster medical waste would pose residents at infection risks due to its inherent characteristics. Furthermore, some unexpected cases and improper operations, i.e., traffic accidents, irregular clearance activities during transportation would increase the exposure of residents to contaminated disaster medical waste, thus increasing novel coronavirus infection risks. Such action doing like this also can be found in Ahluwalia (2006), Onan et al. (2015), and Valizadeh et al. (2021). In this context, this paper uses a linear form of populations, the amounts of disaster medical waste, and potential risks for each person to manifest social sustainability. For Eq. (3), the first term demonstrates total potential infection risks of contaminated disaster medical waste to all residents located in DMWTTSs and DMWDCs. The second part describes total potential infection risks of
contaminated disaster medical waste delivered from DMWP$i$ to DMWTTS$j$, then to DMWD$k$.

Constraint (4) gives the limit of budget, and stipulates the upper bound of total costs for transportation and construction at DMWTTSs in each period. Constraint (5) ensures that the amounts of $m$ disaster medical waste collected in each DMWP are all transported to DMWTTSs in period $s$. Constraint (6) registers transportation balance of $m$ disaster medical waste between DMWTTSs and DMWD$s$ in each period. Constraints (7) and (8) indicate that the amounts of $m$ disaster medical waste delivered to each DMWTTS and DMWD can not exceed their corresponding maximum capacity in period $s$, respectively. Constraints (9) and (10) both require the workload or service level for all types of disaster medical waste of each DMWTTS and DMWD are no less than a certain threshold in each period. In fact, this constraint to some extent reflects the preference of decision entities to the utilization level of the infrastructure facilities. Constraints (7) and (9) also show that only when DMWTTS is established at location $j$, can $m$ disaster medical waste be delivered to DMWTTS $j$ from DMWP $i$ in period $s$. Constraints (11)–(13) present the decision variables of the optimization problem.

4 Solution strategies for a disaster medical waste location-transportation model

It is evident that the proposed mixed-integer programming model for multi-type disaster medical waste location-transportation integrated optimization problem has multiple periods and objectives. Regarding multiple periods, it is an effective way to capture dynamic features in disaster operations management in a discrete manner (Cao et al., 2018; Tirkolaee et al., 2021). In terms of multiple objectives, it is a critical and challenging thing to deal with them due to their conflict for cleaning up disaster medical waste in practice (Holguín-Veras et al., 2013). This section leverages and extends the insights of Chakraborty et al. (2014), Kargar et al. (2020), and Cao et al. (2021) to apply a linear weighted sum method to cope with multiple conflicting objectives, thus obtaining a reformulated single-objective optimization model. The specific procedure is given as follows.

Step 1 Tackle a single-objective optimization model considering economic sustainability
For each period, a branch-and-bound approach embedded in CPLEX solver is firstly applied to solve a single-objective mixed-integer programming model (M1) for multi-type disaster medical waste location-transportation integrated optimization problem with the goal of optimizing total economic benefits ($f_1$), which is denoted by Eqs. (14), and (4)–(13).

\[
\text{optimize } (\max \text{ or } \min) f_1 \\
\text{constraints (4)–(13)}
\]  

(14)

In this context, the maximum and minimum economic objective is denoted by $f_1^{\max}$ and $f_1^{\min}$, respectively.

Step 2 Solve a single-objective optimization model with environmental sustainability
A similar way is used to resolve a single-objective mixed-integer programming model with optimizing total carbon emissions ($f_2$) (M2), which is written by Eqs. (15), and (4)–(13).

\[
\text{optimize } (\max \text{ or } \min) f_2 \\
\text{constraints (4)–(13)}
\]  

(15)
Thus, the maximum and minimum environmental objective can be obtained and recorded as $f_{2}^{\text{max}}$ and $f_{2}^{\text{min}}$, respectively.

**Step 3** Resolve a single-objective optimization model considering social sustainability

Similarly, the maximum and minimum total potential social risks (namely, $f_{3}^{\text{max}}$, $f_{3}^{\text{min}}$) can be obtained in each period by tackling multi-type disaster medical waste location-transportation model with the aim of optimizing social objective of sustainability ($f_{3}$) (M3), which is denoted by Eqs. (16), and (4)–(13).

$$\text{optimize } (\text{max or min}) f_{3}$$

subject to constraints (4)–(13)

(16)

**Step 4** Convert model M0 into a single-objective mixed-integer programming model (M4)

As above highlighted, a linear weighted sum method is very prevalent in transforming a multi-objective optimization model into a single-objective one in the field of disaster operations management. In this regard, given the results depicted in **Steps 1–3**, model M0 is converted into a single-objective mixed-integer programming model (M4), which is denoted by Eqs. (17), and (4)–(13).

$$\min F = \omega_{1} \left( \frac{f_{1}^{\text{max}} - f_{1}^{\text{min}}}{f_{1}^{\text{max}} - f_{1}^{\text{min}}} \right) + \omega_{2} \left( \frac{f_{2}^{\text{max}} - f_{2}^{\text{min}}}{f_{2}^{\text{max}} - f_{2}^{\text{min}}} \right) + \omega_{3} \left( \frac{f_{3}^{\text{max}} - f_{3}^{\text{min}}}{f_{3}^{\text{max}} - f_{3}^{\text{min}}} \right)$$

subject to constraints (4)–(13)

(17)

In model M4, $F$ represents its objective function which aims to minimize total deviation between optimal and current value for each sustainable objective in each period. In addition, $\omega_{1}$, $\omega_{2}$ and $\omega_{3}$ respectively indicates the importance of total economic benefits, total carbon emissions, and total potential social risks for decision-makers in cleaning up disaster medical waste during COVID-19 pandemic. Notably, since the focus of decision entities varies from the evolution of COVID-19 pandemic, the weights of economic, environmental, and social goal may be different in different periods, which is in line with the practice. The following equation also should be always satisfied: $\omega_{1} + \omega_{2} + \omega_{3} = 1$.

**Step 5** Tackle the reformulated model (M4)

The operations in solving the reformulated model (M4) are similar to those in **Steps 1–3**. Thus, the best location-transportation scheme regarding disaster medical waste and the corresponding value of sustainable objective functions can be ultimately obtained.

### 5 Computational studies

#### 5.1 A real case from Wuhan during COVID-19 pandemic

In this section, a real case using data from Wuhan, China is given to find the best location-transportation scheme concerning contaminated disaster medical waste during COVID-19 pandemic. The goals are also to test the influences of medical waste type, decision method, and the budget on the sustainable performance of disaster medical waste clean-up activities. After the outbreak of COVID-19 pandemic, Wuhan is one of the most severely affected cities in China with the largest number of confirmed cases, which calls for emergency materials, especially medical supplies support all the way. There is no doubt that the overwhelming disaster medical waste fill up the whole city from January 23rd, 2020 to April 8th, 2020, thus posing residents at infectious risks and dangerous situation.
A survey conducted by Chen et al. (2021) reported that the peak of disaster medical waste production mass occurred around March 1, 2020. The amounts of disaster medical waste were suddenly soaring on February 15, 2020, and those gradually declined from 22 March, 2020. In this sense, the lifecycle of disaster medical waste management from January 23, 2020 to April 8, 2020 in Wuhan can be subdivided into outbreak, peak, and mitigation period, which is the focus of this paper. In addition, according to daily production and daily clearance principle, this section only considers the daily decision-making regarding location-transportation of disaster medical waste for each period. Thus, February 15, March 1, and March 22, 2020 are treated as the representative of outbreak, peak, and mitigation period, respectively. In Fig. 2, it gives the location and other details concerning DMWGPs, DMWTTSs, and DMWDCs.

It is reported that when COVID-19 pandemic is under control in Wuhan, Health Commission of Hubei Province still designates fifteen hospitals as the DMWGPs to treat novel coronavirus patients and deal with other relevant activities (http://zwfw.hubei.gov.cn). Obviously, the number of designated and non-designated hospitals to receive confirmed and suspected cases are far more than fifteen during lockdown period. What should be clarified is that DMWTTSs are generally established near DMWGPs, which can be clearly seen in Fig. 2. For each DMWTTS, the containers with the same capacity are placed to temporarily store disaster medical waste, which is implemented in Wuhan during COVID-19 pandemic. Huoshenshan and Leishenshan hospital are not regarded as the DMWGPs because their disaster medical waste can be disposed by the configured mobile incineration equipment (http://www.mee.gov.cn), while two DMWTTSs near them are included. Thus, seventeen DMWTTSs in total are the focus of this paper. In addition, Fig. 2 demonstrates six

![Fig. 2 Location of DMWGPs, DMWTTSs, and DMWDCs in different districts of Wuhan](image-url)
DMWDCs spanning Hanyang, Qingshan, Caidian, Xiangyang, Xianning, and Huangshi are considered into the reverse logistics supply chains. Particularly, it is obvious that Xiangyang, Xianning, and Huangshi are outside Wuhan.

In terms of DMWGPs, this paper only takes into consideration fifteen hospitals which are operating from the outbreak of COVID-19 pandemic to date. The affected population and the amounts of disaster medical waste per day in each DMWGP can be found in Table A1. Relative to Chen et al. (2021), the amounts of disaster medical waste in this paper are relatively less due to only account for the designated medical hospitals excluding non-designated medical institution and others. However, for disaster medical waste production mass during outbreak, peak and mitigation period, there has a similar trend between of Chen et al. (2021) and this paper.

Regarding DMWTTSs, the maximum capacity of temporarily storing disaster medical waste for each type is assumed to be 30 tons for simplification. For each DMWTTS, minimum workload or service level which is located within [0,1] is set as 40 percent of its maximum storage capacity. The distance of hospitals and the corresponding DMWTTS is about 800 m (http://news.fdc.com.cn). In addition, the affected population by contaminated disaster medical waste at each DMWTTS is about 10,000. Those located on transportation routes equals half of the sum of the affected populations between two locations. The fixed benefits for each DMWTTS during outbreak, peak, and mitigation period are presented Table A2.

For DMWDCs, as depicted in Fig. 2, three DMWDCs are located inside Wuhan, and others are outside this city. The above mentioned six DMWDCs are chosen based on the reported news. The affected population and maximum capacity of disposing disaster medical waste for each type per day in each DMWDC are shown in Table A3. For each DMWDC, this paper lets the minimum workload or service level that belongs to the interval [0, 1] equal 10 percent of its maximum disposal capacity. It is noting that the first three DMWDCs in Wuhan marked as A, B, and C have specific name, while the name of the DMWDCs outside Wuhan cannot be explicitly found due to the incomplete information during COVID-19 pandemic. This section only uses the name of the corresponding district to attach a label to these DMWDCs.

In addition, the distance between any two locations involved in this paper is all measured by ‘Baidu map’. Thus, the distance in kilometre between DMWGPs and DMWTTSs, between DMWTTSs and DMWDCs are presented in Table A4 and Table A5, respectively. Unit benefit in yuan/ton·km obtained by delivering disaster medical waste during outbreak, peak, and mitigation period can be found in Tables A6, A7, A8, A9, A10, and A11. The above-mentioned Tables A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, and A11 are all included in “Appendix”. The value of other necessary parameters in the proposed model is as follows. The fixed costs for DMWTTSs construction in different periods are $D^1_j = 100,000$, $D^2_j = 250,000$, and $D^3_j = 150,000$. For each period, total budget on disaster medical waste clean-up is $T^1 = 300,000$, $T^2 = 1,200,000$, and $T^3 = 600,000$. Besides, unit transportation cost is assumed to be $C^1_{ij1} = 17$, $C^2_{ij1} = 15$, $C^3_{ij1} = 12$; $C^1_{ij2} = 14$, $C^2_{ij2} = 12$, $C^3_{ij2} = 10$; $C^1_{jk1} = 15$, $C^2_{jk1} = 13$, $C^3_{jk1} = 10$; $C^1_{jk2} = 12$, $C^2_{jk2} = 10$, $C^3_{jk2} = 8$. The potential risks of infectious and non-infectious disaster medical waste are set as 0.018 and 0.002, respectively. Finally, average carbon emissions from transporting disaster medical waste per ton per kilometre and the sufficiently large positive constant are respectively assumed to be 1 and 10,000. All experiments are conducted by a CPLEX solver and run on a computer with 1.8 GHz 64-bit Core (TM) i5-8265U CPU under Windows 10 Professional.
5.2 Optimal scheme regarding disaster medical waste location-transportation

In disaster operations management, practical cases and theoretical studies imply that it is of significance but difficult to determine the weights of multiple objectives. In terms of disaster medical waste location-transportation integrated optimization problem, how to assign the weights to different sustainable objective functions is also challenging. It is evident that the simultaneous consideration of economic, environmental, and social concerns into such a problem is conducive to controlling COVID-19 pandemic during lockdown period of Wuhan in a sustainable manner. Thus, this paper takes into account multi-dimension of sustainability with different priorities to make the decisions in outbreak, peak and mitigation period from a systematic standpoint.

As no one can turn a blind eye on the fact that one of the most typical characteristics of disaster medical waste is infection during COVID-19 pandemic, the most critical and urgent thing for decision entities is to reduce novel coronavirus transmission risks. In this sense, risk-related objectives manifesting social sustainability have the highest priority for the whole period, which is supported by Kargar et al. (2020), Yu et al. (2020a), and Valizadeh et al. (2021). In outbreak period, decision-makers aim to decrease environmental damage in a timely manner in addition to control and contain novel coronavirus spread, this paper thus regards environmental objective prior to economic one. During peak period, disaster medical waste generation mass almost reaches the maximum, one of the most challenging things for authorities is how to reduce the infection risks, thus hindering the spread of COVID-19 pandemic via contaminated medical waste. At this time, there is no obvious preference for both economic and environmental objective, the corresponding weights are assumed to be identical. When COVID-19 pandemic of Wuhan is under control (namely, mitigation period) by adopting some effective measures, i.e., social distance, home quarantine, border closure, and widespread testing, disaster medical waste generation mass shows a declining trend, disposal capacity of medical waste seems sufficient to guarantee a clean and safe environment. In addition, local authorities begin to pay attention to economic goal because of the limited financial support from senior governments and the need for boosting economy. In this regard, social and economic concerns of sustainability have the same superiority.

In addition to the above qualitative analysis, the weights can be quantitatively determined by Analytic Hierarchy Process, expert scoring method, and so on (Tirkolaee et al., 2021). This paper leverages the above-mentioned insights and the experience of the authors to give an example (see Table 2), illustrating the proposed model. In practice, the weights may still vary from different decision entities. The observations can be slightly modified based on their preferences. In this context, Table 2 presents the results regarding disaster medical waste location-transportation in combating COVID-19 pandemic.

According to Table 2, it is evident that only Huoshenshan Hospital is selected during outbreak period. In the period of peak, another three DMWTTSs, Hankou Hospital, Hospital of Red Cross Society, and Leishenshan Hospital are added to deal with the sharply increasing disaster medical waste. With the evolution of COVID-19 pandemic, only Xinzhou District People’s Hospital, Huoshenshan Hospital, and Leishenshan Hospital are retained in mitigation period. Tables 3, 4, 5 and 6 present the detailed scheme concerning disaster medical waste location-transportation in Wuhan.

In detail, Tables 3, 4, and 5 give disaster medical waste flow from DMWGPs to DMWTTSs in outbreak, peak, and mitigation period, respectively. Table 6 indicates medical waste flow from DMWTTSs to DMWDCs in different periods. The following main conclusions are yielded based on the results in Tables 2, 3, 4, 5 and 6.
Table 2 Computational results in different periods

| Period            | Weights of different objectives | $f_1$  | $f_2$  | $f_3$  | DMWTTSs |
|-------------------|---------------------------------|--------|--------|--------|---------|
| Outbreak period   | $\omega_1 = 0.2, \omega_2 = 0.3, \omega_3 = 0.5$ | 39,257 | 3687.9 | 26,274.569 | ⬜️ |
| Peak period       | $\omega_1 = 0.2, \omega_2 = 0.2, \omega_3 = 0.6$ | 166,937.5 | 13,106.5 | 81,686.474 | ⬜️⬜️⬜️ |
| Mitigation period | $\omega_1 = 0.4, \omega_2 = 0.2, \omega_3 = 0.4$ | 126,477.9 | 10,804.1 | 43,714.352 | ⬜️⬜️⬜️ |

Table 3 Medical waste flow from DMWGPs to DMWTTSs during outbreak period

| DMWGPs | DMWTTSs |
|---------|---------|
| Infectious | Non-infectious |
| 1 | 2.7 | 1.6 |
| 2 | 2.1 | 1.4 |
| 3 | 2.1 | 1.4 |
| 4 | 2.1 | 1.4 |
| 5 | 2.7 | 1.6 |
| 6 | 2.7 | 1.6 |
| 7 | 0.9 | 0.6 |
| 8 | 4.2 | 2.8 |
| 9 | 2.2 | 1.5 |
| 10 | 1.4 | 0.7 |
| 11 | 0.9 | 0.7 |
| 12 | 0.9 | 0.5 |
| 13 | 0.6 | 0.4 |
| 14 | 1.2 | 0.8 |
| 15 | 1.0 | 0.7 |
| Total | 27.7 | 17.7 |

Firstly, there is a common consensus on the fact that the amounts of DMWTTSs to be constructed depend on disaster medical waste generation mass. All of results embrace the conclusion that total number of available DMWTTSs is different during outbreak, peak, and mitigation period. In peak period, it needs establish the maximum number of DMWTTSs to temporarily store disaster medical waste. It is encouraged to use a dynamic approach to design and implement DMWTTSs deployment in cleaning up medical waste activities.

Secondly, results indicate that although it needs more costs, most of infectious disaster medical waste is disposed in Xiangyang, Xianning, and Huangshi Disposal Plant, which are outside Wuhan. However, all non-infectious medical waste is transported to those DMWDCs.
| DMWPs | DMWTTSs | ① Infectious | Non-infectious | ② Infectious | Non-infectious | ③ Infectious | Non-infectious | ④ Infectious | Non-infectious |
|-------|---------|--------------|---------------|--------------|---------------|--------------|---------------|--------------|---------------|
|       |         | 0            | 0             | 0            | 0             | 0            | 0             | 9.0          | 6.0           |
| 2     | 0       | 0            | 0             | 0            | 0             | 4.8          | 7.5           |
| 3     | 2.2     | 5.0          | 0             | 0            | 5.3          | 0            | 0            |
| 4     | 0       | 0            | 0             | 0            | 0            | 0            | 7.5          | 5.0           |
| 5     | 0       | 0            | 0             | 2.6          | 8.4          | 3.0          | 0            | 0            |
| 6     | 8.4     | 5.6          | 0             | 0            | 0            | 0            | 0            |
| 7     | 0       | 0.4          | 0             | 0            | 0            | 0            | 2.7          | 1.2           |
| 8     | 0       | 0            | 0             | 0            | 10.0         | 0            | 0            | 7.0           |
| 9     | 0       | 0            | 0             | 0            | 6.3          | 0            | 0            | 4.2           |
| 10    | 0       | 0            | 4.2           | 0            | 0            | 0            | 0            | 1.8           |
| 11    | 0       | 0            | 3.6           | 2.4          | 0            | 0            | 0            | 0             |
| 12    | 0       | 0            | 1.5           | 1.6          | 0            | 0            | 1.2          | 0             |
| 13    | 0       | 0            | 0             | 1.4          | 0            | 0            | 2.1          |
| 14    | 0       | 2.4          | 3.6           | 0            | 0            | 0            | 0             |
| 15    | 0       | 0            | 3.1           | 0            | 0            | 0            | 0             | 2.2           |
| Total | 10.6    | 13.4         | 16.0          | 8.0          | 30.0         | 7.8          | 30.0         | 27.6          |
Table 5 Medical waste flow from DMWGs to DMWTSs during mitigation period

| DMWGs | DMWTSs | Infectious | Non-infectious | Infectious | Non-infectious | Infectious | Non-infectious |
|-------|--------|------------|----------------|------------|----------------|------------|----------------|
|       |        | 13         | 16             | 17         |                |            |                |
| 1     | 0.1    | 0.3        | 7.1            | 1.8        |                |            |                |
| 2     | 3.0    | 0.0        | 0.0            | 0.0        |                |            |                |
| 3     | 3.0    | 0.0        | 2.0            | 0.0        |                |            |                |
| 4     | 5.1    | 0.0        | 0.0            | 0.0        |                |            |                |
| 5     | 4.2    | 0.0        | 1.8            | 0.0        |                |            |                |
| 6     | 4.2    | 0.0        | 1.8            | 0.0        |                |            |                |
| 7     | 1.5    | 0.0        | 0.0            | 0.0        |                |            |                |
| 8     | 0.0    | 6.0        | 5.0            | 1.5        |                |            |                |
| 9     | 3.0    | 0.0        | 2.1            | 0.0        |                |            |                |
| 10    | 1.5    | 0.0        | 0.0            | 0.1        |                |            |                |
| 11    | 0.9    | 0.0        | 0.7            | 0.0        |                |            |                |
| 12    | 1.5    | 0.0        | 0.0            | 0.0        |                |            |                |
| 13    | 0.0    | 0.0        | 0.0            | 1.2        |                |            |                |
| 14    | 0.0    | 0.0        | 1.6            | 2.4        |                |            |                |
| 15    | 1.2    | 0.0        | 0.0            | 0.8        |                |            |                |
| Total | 29.2   | 6.0        | 18.0           | 12.2       |                | 11.8       |

located inside Wuhan during the whole decision periods. The main reason is to decrease novel coronavirus transmission risks as many as possible. In detail, although Guodingshan Medical Waste Incineration Plant and Wugangbeihu Disposal Plant are the best choice to handle infectious disaster medical waste based on travel distance, they are not the optimal options due to their high population density.

Thirdly, Table 6 shows that Guodingshan Medical Waste Incineration Plant is always considered to merely handle non-infectious disaster medical waste, while Xiangyang, Xianning, Huangshi Disposal Plant are used to manage only infectious disaster medical waste. Regarding Qianzishan Disposal Plant in Caidian District, it is always available for both infectious and non-infectious disaster medical waste clean-up activities.

Overall, the above results imply that constructing the DMWTSs with flexible capacity is of great importance to cover all service demands on disaster medical waste clean-up, which is supported by Valizadeh et al. (2021). In practice, decreasing the number of residents exposed to contaminated disaster medical waste is an effective measure to control novel coronavirus transmission, which is also clarified by Yu et al. (2020a). An emergency plan on jointly cleaning up infectious medical waste in neighbouring regions and cities needs to be developed to coordinate resources and share disposal capacity in the aftermath of major public health emergencies (Chen et al., 2021). In addition, it is not necessary for decision-makers to require all temporary DMWDCs established to have capability of simultaneously disposing both infectious and non-infectious disaster medical waste during COVID-19 pandemic.
| Period      | Outbreak period | Peak period | Mitigation period |
|------------|-----------------|-------------|------------------|
|            | DMWDCs          | DMWTTSs     |                  |
|            | Infectious      | Non-infectious | Infectious | Non-infectious | Infectious | Non-infectious | Infectious | Non-infectious |
| A          | 0               | 0           | 0                | 0               | 0           | 0               | 0           | 0               |
| B          | 0               | 0           | 0                | 0               | 0           | 0               | 0           | 0               |
| C          | 19.7            | 0           | 0                | 0               | 0           | 0               | 0           | 0               |
| D          | 0               | 0           | 0                | 0               | 0           | 0               | 0           | 0               |
| E          | 0               | 0           | 0                | 0               | 0           | 0               | 0           | 0               |
| F          | 2.0             | 0           | 0                | 0               | 0           | 0               | 0           | 0               |

**Table 6** Medical waste flow from DMWTTSs to DMWDCs in different periods
5.3 Impacts of disaster medical waste type on computational results

To observe how different types of disaster medical waste generation mass influence economic, environmental, and social objective during outbreak, peak, and mitigation period, relevant sensitive analyses are conducted in Fig. 3.

**Fig. 3** Impacts of different types of disaster medical waste generation mass on sustainable objectives in different periods
Figure 3a, b, and c represent the influences of infectious and non-infectious disaster medical waste generation mass on sustainable objectives during outbreak, peak, and mitigation period, respectively. From a global viewpoint, the amounts of infectious and non-infectious disaster medical waste dramatically affect the economic objective of sustainability, while have little impacts on environmental sustainability performance in the same period. In terms of social objective of sustainability, by comparing with non-infectious disaster medical waste, the number of infectious one exerts significantly greater influences on total potential social risks.

In detail, when the amounts of infectious disaster medical waste increase, both total economic benefits and total potential social risks show an ascending tendency, while total carbon emissions have no obvious change during outbreak, peak, and mitigation period. It can be inferred that although the increase of infectious disaster medical waste generation mass creates more economic benefits, it also increases potential social risks to residents. Given the non-profit nature of disaster operations management, more attention should be attached to reduce infection risks for the whole period. Regarding the non-infectious disaster medical waste, it only imposes favourable impacts on economic objectives, yet seems no influences on environmental and social sustainability performance.

To further analyse the impacts of waste type on the performance of reverse logistics supply chains, Fig. 4 indicates the influences of different types of unit disaster medical waste on sustainable objective function value in different periods.

It is noting that the purpose of obtaining the results in Fig. 4 is to exclude the influences of amounts of disaster medical waste on observations in different periods. For economic benefits in Fig. 4a, b and c, it to a large extent shows no obvious trend when the amounts of infectious and non-infectious disaster medical waste respectively increase for each period. The above observation also can be found in terms of carbon emissions, which is depicted in Fig. 4d, e and f. It can be concluded that although the total amounts of disaster medical waste present the significant impacts on economic objective with an increasing tendency, the influences of unit disaster medical waste on economic benefits are mixed during outbreak, peak, and mitigation period. In addition, total amounts of disaster medical waste seem no influences on environmental sustainability performance, while unit disaster medical waste would impose dramatical impacts on carbon emissions during the whole period.

According to Fig. 4a–f, it can be further summarized that with an increasing amount of both infectious and non-infectious disaster medical waste, economic benefits and carbon emissions have a respective soaring change in mitigation period relative to the previous two periods. In this sense, it can be inferred that although environmental objective of sustainability doesn’t retain the highest priority, more attention still should be paid to the reduction of carbon emissions in mitigation period.

Regarding potential social risks in Fig. 4g, h and i, with the increase of infectious disaster medical waste, potential social risks indicate a consistently ascending trend for each period. However, it presents a declining tendency with the increase of non-infectious disaster medical waste. From a systematic viewpoint, although there are different weights to social dimension of sustainability in different periods, the impacts of unit disaster medical waste on potential social risks are significant and extremely similar, which differs from those of total amounts of disaster medical waste on social sustainability performance.

In summary, it is necessary to precisely estimate and predict total number of infectious disaster medical waste based on real-time information regarding COVID-19 pandemic, which is supported by Kargar et al. (2020) and Chen et al. (2021). In practice, big data technology, blockchain, and digital twin could efficiently assist decision entities in dealing with such
jobs. For decision-makers, they can just stipulate the behaviours of contractors responsible for non-infectious or sanitary disaster medical waste clean-up via a long-term contract.

Furthermore, it is better to choose energy-saving and new-energy vehicles to deliver disaster medical waste in reverse logistics supply chains in mitigation period, thus reducing hazardous impacts on environment. There is a pressing need for reducing the number of both infectious and non-infectious disaster medical waste at the source, which is also addressed by WHO. A series of effective measures, i.e., daily necessity support to encourage residents to separate sanitary disaster medical waste from contaminated one are essential in decreasing the risks of novel coronavirus transmission (Valizadeh et al., 2021). Besides, smart portable devices and driverless vehicles can be used to collect and transport infectious disaster medical waste, thus decreasing potential social risks (Chen et al., 2021; Kargar et al., 2020). Overall, the most important task is to control and contain the spread of novel coronavirus whatever COVID-19 pandemic evolves within the whole period specified in this paper, which is in accordance with the real-world situation and the insights of the existing studies.
5.4 Computational results in the context of multi- and single-period decision method

Studies indicate that both multi- and single-period decision methods are commonly used to capture and formulate different characteristics of some optimization problems in disaster operations management. To show the superiority of the multi-period decision approach for disaster medical waste location-transportation integrated optimization problem, several experiments are implemented to obtain computational results, which is presented in Fig. 5.

For Fig. 5, the details regarding model M4 can be found in Sect. 3. In terms of single-period disaster medical waste location-transportation optimization problem, two methods are applied to estimate and define the fixed benefits of DMWTTSs, unit transportation cost, and unit benefit. The first one adopts average value of the parameters in different periods, which is denoted as model M5. Another one applies initial value in outbreak period to update these parameters, which is defined as model M6. The amounts of disaster medical waste in different DMWGPs and total budget are the sum of those during outbreak, peak, and mitigation period. Notably, summary of information on DMWGPs under the single-period decision method in Wuhan can be found in Table A.12. Construction costs of DMWTTSs are calculated based on the average value of those for the whole decision period. In addition, the preference of decision-makers to total economic benefits, total carbon emissions, and total potential social risks is identical for all models, namely, \( w_1 = w_2 = w_3 = 1/3 \).

Regarding Fig. 5a, it presents the value of different objective functions for disaster medical waste location-transportation integrated optimization model M4, M5, and M6 for combating COVID-19 pandemic. Figure 5b indicates the gaps of computational results obtained by model M5 and M6 relative to model M4.

According to Fig. 5a, it is evident that the multi-period model M4 is significantly superior to single-period model M5 and M6 in terms of total economic benefits and total potential social risks. The main reason is that the single-period decision method cannot cope with lots of uncertain factors in the future periods. Furthermore, such factors exert adverse impacts on the accurate estimation of disaster medical waste generation mass especially when it is always

![Fig. 5 Comparisons of different objectives under multi- and single-period decision method](image-url)
changing rapidly with the evolution of COVID-19 pandemic. Fortunately, the multi-period decision approach can reduce a variety of uncertainties in disaster medical waste location-transportation activities because of more available real information, thus achieving a better performance of economic and social sustainability.

On the contrary, both model M5 and M6 outperforms model M4 in terms of total carbon emissions based on Fig. 5a. It is evident that the split transportation phenomenon may frequently occur for a multi-period disaster medical waste location-transportation scheme relative to a single-period one, thus producing more carbon emissions and adverse influences on environment. Even so, it also cannot turn a blind eye on the fact that the multi-period decision model is better than the single-period one in disaster medical waste supply chains because the overall merits of economic and social sustainability performance could cover the disadvantages of environmental one from a holistic viewpoint.

Obviously, results in Fig. 5b further support the above observations. Regarding the two methods to determine the fixed benefits of DMWTTSs, unit transportation cost, and unit benefit, Fig. 5b indicates that model M5 and M6 seem no significant differences for total potential social risks. Nevertheless, in terms of total economic benefits and total carbon emissions, model M5 is superiority to model M6. In other words, for single-period disaster medical waste location-transportation optimization scheme, using respective average value of the fixed benefits of DMWTTSs, unit transportation cost, and unit benefit is beneficial to achieve a better sustainability performance during COVID-19 pandemic. If these parameters are attached to respective initial value defined at the beginning of COVID-19 pandemic, it would over-estimate various resources needed to handle uncertainties in the future periods.

To sum up, as addressed by Kargar et al. (2020), controlling novel coronavirus infection risks is the most important objective relative to economic one in response to COVID-19 pandemic, applying periodical decision method is conducive to decreasing novel coronavirus transmission risks through infectious disaster medical waste together with the increase of total economic benefits in practice. Similar viewpoints can be also found in Yu et al. (2020a), and Tirkolaee et al. (2021). Multi-period decision approach could provide a better resource distribution scheme, i.e., the allocation of smart portable equipment in transporting disaster medical waste, thus favourable impacts on social sustainability. Additionally, both over- and under-estimation of costs and benefits would be detrimental to develop the best disaster medical waste location-transportation scheme in combating COVID-19 pandemic.

5.5 Influences of total budget on computational results

In practice, there is no doubt that financial support plays a significant role in the successful implementation of a set of disaster medical waste clean-up activities. In response to COVID-19 pandemic, although the most important thing is to control and contain infection risks, it doesn’t mean it can be negligible for budget. Thus, Table 7 observes the influences of budget on the performance of disaster medical waste supply chains.

From the perspective of different periods, Table 7 indicates budget seems no obvious influences on the value of sustainable objective functions in outbreak and mitigation period, while it plays an indispensable role in that in peak period. In the aftermath of COVID-19 pandemic, there are relatively sufficient funds to support disaster medical waste clean-up activities in outbreak and mitigation period. In outbreak period, the funds mainly come from emergency plans on public health emergencies developed by local authorities under normal situation. In mitigation period, financial support is mainly from the donors, i.e., enterprises, individuals, charity institute, international humanitarian rescue organizations
around the world. However, results are sensitive to the presence of budget in peak period. The main reason is that financial support for the last period is exhausted and the funds for the current period from other entities are still on the way, for satisfying lots of service demands, i.e., cleaning up large quantities of disaster medical waste, providing considerable medical supplies.

Regarding sustainable objectives in peak period, Table 7 embraces the fact that budget exerts apparent influences on total economic benefits and total carbon emissions, yet imposes no significant impacts on total potential social risks. In other words, the limit of budget to some extent does not increase the social risks of novel coronavirus transmission through contaminated disaster medical waste, which manifests the potential superiority of the formulated multi-period optimization model here to the control of COVID-19 pandemic.

To further investigate the influences of budget on sustainable objectives, sensitivity analysis is performed with different budget levels in disaster medical waste supply chains, which is shown in Fig. 6.

In Fig. 6a and b, with the increase of the budget, the overall trend of total economic benefits and total carbon emissions is ascending during the whole decision rolling time. Nevertheless, total potential social risks first indicate a declining tendency, and then hold still when the budget reaches a certain threshold in Fig. 6c, which aligns with the practical cases during COVID-19 pandemic. This finding suggests that although the substantial increase of budget is beneficial to control the spread of novel coronavirus via contaminated disaster medical waste, it does not mean it always works well due to the inherent nature of disaster medical waste clean-up activities (Yu et al., 2020a).

In summary, the limited money should firstly support implementing the most important tasks of disaster medical waste supply chains, especially in peak period during COVID-19 pandemic. The measures i.e., making full use of the existing facilities and capacities to reduce unnecessary expenditures are encouraged in disaster medical waste management (Valizadeh

| Table 7 Computational results with and without considering budget |
| --- | --- | --- | --- |
| Scenario | Period | Weights of different objectives | $f_1$ | $f_2$ | $f_3$ |
| With total budget | Outbreak | $\omega_1 = 0.2$, $\omega_2 = 0.3$, $\omega_3 = 0.5$ | 39,257 | 3687.9 | 26,274.569 |
| | Peak | $\omega_1 = 0.2$, $\omega_2 = 0.2$, $\omega_3 = 0.6$ | 166,937.5 | 13,106.5 | 81,686.474 |
| | Mitigation | $\omega_1 = 0.4$, $\omega_2 = 0.2$, $\omega_3 = 0.4$ | 126,477.9 | 10,804.1 | 43,714.352 |
| | Objective function value in total | | 332,672.4 | 27,598.5 | 151,675.395 |
| Without total budget | Outbreak | $\omega_1 = 0.2$, $\omega_2 = 0.3$, $\omega_3 = 0.5$ | 39,257 | 3687.9 | 26,274.569 |
| | Peak | $\omega_1 = 0.2$, $\omega_2 = 0.2$, $\omega_3 = 0.6$ | 176,101.2 | 12,614.2 | 81,686.474 |
| | Mitigation | $\omega_1 = 0.4$, $\omega_2 = 0.2$, $\omega_3 = 0.4$ | 126,477.9 | 10,804.1 | 43,714.352 |
| | Objective function value in total | | 341,836.1 | 27,106.2 | 151,675.395 |
Fig. 6 Sensitivity analysis of sustainable objective functions against budget

et al., 2021). It is necessary to design other effective measures, i.e., reinforced separation of disaster medical waste to further reduce the potential social risks when monetary incentive does not work anymore. Furthermore, disaster medical waste location-transportation decisions, to some extent, are subject to the budget. Nevertheless, it will come to be ineffective once the budget is more than a certain threshold. Thus, it is of significance to accurately estimate minimum budget for achieving the optimal performance of disaster medical waste supply chains under different real-world situations, thus maximizing the utility of the limited social resources (Tirkolaee et al., 2021).
This paper uses the multi-objective optimization approach to make periodical decisions on multi-type disaster medical waste location-transportation in the inclusion of social, economic, and environmental sustainability, budget, and workload level, thus controlling COVID-19 pandemic. Several remarks are summarized as follows.

Firstly, the proposed model and solution strategy are suitable for solving multi-period multi-type disaster medical waste location-transportation optimization problem within a short computational time. Study results indicate the establishment of DMWTTSs with flexible capacity is encouraged during outbreak, peak, and mitigation period.

Secondly, different types of disaster medical waste have different impacts on economic and social objective for outbreak, peak, and mitigation period. It can be inferred that the accurate prediction of infectious disaster medical waste, the use of energy-saving vehicles, and the adoption of smart portable equipment are conducive to reducing potential risks of novel coronavirus transmission.

Thirdly, the multi-period decision approach outperforms the single-period one for disaster medical waste clean-up activities. The main reason is that the former relative to the latter has the capability of dealing with a variety of uncertainties in the future periods.

Fourthly, budget exerts significant impacts on sustainable objectives only in peak period. This may result from the flooding needs for handling disaster medical waste during COVID-19 pandemic. When budget overtrips a certain threshold, it doesn’t make a difference for reducing potential social risks anymore because money-related factors lost their dominant power at this moment. In this context, the estimation of minimum budget to obtain a better performance is of great importance in combating COVID-19 pandemic.

Fifthly, some promising digital technologies including blockchain, big data, digital twin, artificial intelligence have been proved to be effective to cope with uncertainties in the amounts of disaster medical waste and infection risks through the data-driven optimization models, thus accurately combating COVID-19 pandemic from a global standpoint (Ahmad et al., 2021; Hunt et al., 2022; Marić et al., 2021).

This paper theoretically builds the linkage of sustainable development, multi-objective optimization theory, and disaster medical waste location-transportation problem to reduce potential risks of novel coronavirus transmission, decrease the damage to environment, and improve economic benefits. It further fills the gap that the cost-related objective and transportation risks could be considered into the COVID-19 medical waste location-routing model highlighted by Tirkolaee et al. (2021).

In practice, this study could provide local authorities with critical guidelines on improving medical waste management system of Wuhan in China, i.e., the location of DMWTTSs, the adoption of smart portable equipment, the selection of periodical decision method, and the development of incentive and punishment measures. Secondly, the proposed tri-objective mixed-integer programming model and solution strategies for multi-period multi-type disaster medical waste location-transportation is beneficial to decrease infection risks and could be further embedded into the existing commercial software, which furnishes managers with the decision tool even though it cannot completely alternate human-beings. Thirdly, once relevant information updates, all period-related parameters in the developed model would be also renewed. The optimal decisions on disaster medical waste location-transportation will be naturally updated to make COVID-19 pandemic under control in a timely manner. In this paper, as the regulation that daily generation daily clean-up is given to handle disaster medical waste, the feature of multiple periods in the proposed model only reflects in the
value of parameters. Since the last update of information, the periodical influence of disaster medical waste generation mass as the new constraints will be added to the formulated model because the above protocol is out of consideration. Thus, the optimal multi-period decisions on disaster medical waste location-transportation can be made based on the new model.

Some valuable topics can be further studied in the future. Firstly, this paper focuses on disaster medical waste location-transportation optimization issue under certain environment, while how to use robust optimization method to model such problem in the presence of uncertainties in infection risks, delivery time, travel distance, production mass is promising. Secondly, this study applies a single-level mathematical programming approach to capture horizontal relations among stakeholders, how to use the bi-level or leader–follower optimization theory to formulate hierarchical decisions on disaster medical waste location-transportation needs to be studied in depth. Thirdly, most of studies independently concentrate on either COVID-19 medical supplies allocation or disaster waste clearance optimization problem, how to devise forward and reverse logistics supply chains simultaneously incorporating the above two issues is an interesting topic.

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**Appendix**
Table A1 Summary of information concerning DMWGs in Wuhan

| No | DMWGs or Hospitals                          | Affected population | The amounts of disaster medical waste (tons/per day) |
|----|-------------------------------------------|---------------------|------------------------------------------------------|
|    |                                           |                     | Outbreak period | Peak period | Mitigation period |
|    |                                           |                     | I    | NI  | I    | NI  | I    | NI  |I    | NI  |I    | NI  |
| 1  | Wuhan Hankou Hospital                     | 37,500              | 2.7  | 1.6 | 9.0  | 6.0 | 7.2  | 4.8 |
| 2  | Wuhan Hospital of Red Cross Society       | 32,500              | 2.1  | 1.4 | 7.5  | 5.0 | 3.0  | 2.0 |
| 3  | Wuhan Pulmonary Hospital                  | 30,100              | 2.1  | 1.4 | 7.5  | 5.0 | 3.0  | 2.0 |
| 4  | Fifth Hospital in Wuhan                   | 29,090              | 2.1  | 1.4 | 7.5  | 5.0 | 5.1  | 3.5 |
| 5  | Wuhan Wuchang Hospital                    | 28,890              | 2.7  | 1.6 | 8.4  | 5.6 | 4.2  | 1.8 |
| 6  | Wuhan Seventh Hospital                    | 27,900              | 2.7  | 1.6 | 8.4  | 5.6 | 4.2  | 1.8 |
| 7  | Jinyintan Hospital                        | 30,700              | 0.9  | 0.6 | 2.7  | 1.6 | 1.5  | 0.9 |
| 8  | Wuhan Fourth Hospital West Campus         | 25,700              | 4.2  | 2.8 | 10.0 | 7.0 | 7.5  | 5.0 |
| 9  | Wuhan Ninth Hospital                      | 26,980              | 2.2  | 1.5 | 6.3  | 4.2 | 3.0  | 2.1 |
| 10 | Caidian District People’s Hospital         | 24,590              | 1.4  | 0.7 | 4.2  | 1.8 | 1.5  | 1.1 |
| 11 | The first People’s Hospital of Jiangxia District | 21,000          | 0.9  | 0.7 | 3.6  | 2.4 | 0.9  | 0.7 |
| 12 | Dongxihu District People’s Hospital       | 15,550              | 0.9  | 0.5 | 2.7  | 1.6 | 1.5  | 0.9 |
| 13 | Xinzhou District People’s Hospital        | 9100                | 0.6  | 0.4 | 2.1  | 1.4 | 1.2  | 0.8 |
| 14 | Huangpi District People’s Hospital        | 8850                | 1.2  | 0.8 | 3.6  | 2.4 | 2.4  | 1.6 |
| 15 | Hannan District People’s Hospital         | 12,500              | 1.0  | 0.7 | 3.1  | 2.2 | 1.2  | 0.8 |

In this table, the term ‘I’ and ‘NI’ denotes infectious and non-infectious disaster medical waste, respectively
| No | Candidate DMWTTSs                              | Fixed benefits |                  |                  |                  |
|----|-----------------------------------------------|----------------|-----------------|-----------------|-----------------|
|    |                                               | Outbreak period | Peak period     | Mitigation period |
| ➀ | Wuhan Hankou Hospital                         | 12,500         | 13,500          | 14,500          |
| ➁ | Wuhan Hospital of Red Cross Society           | 11,000         | 12,000          | 13,000          |
| ➂ | Wuhan Pulmonary Hospital                      | 10,000         | 11,000          | 12,000          |
| ➃ | Fifth Hospital in Wuhan                       | 9500           | 10,500          | 11,500          |
| ➄ | Wuhan Wuchang Hospital                        | 9500           | 10,500          | 11,500          |
| ➅ | Wuhan Seventh Hospital                        | 9300           | 10,300          | 11,300          |
| ➆ | Jinyintan Hospital                            | 10,200         | 11,200          | 12,200          |
| ➇ | Wuhan Fourth Hospital West Campus             | 8500           | 9500            | 10,500          |
| ➈ | Wuhan Ninth Hospital                          | 9000           | 10,000          | 11,000          |
| ➉ | Caidian District People’s Hospital             | 8200           | 9200            | 10,200          |
| ⃣ | The First People’s Hospital of Jiangxia District | 7000         | 8000            | 9000            |
| ⃣ | Dongxihu District People’s Hospital           | 5200           | 6200            | 7200            |
| ⃣ | Xinzhou District People’s Hospital            | 3000           | 4000            | 5000            |
| ⃣ | Huangpi District People’s Hospital            | 3000           | 4000            | 5000            |
| ⃣ | Hannan District People’s Hospital              | 4200           | 5200            | 6200            |
| ⃣ | Wuhan Huoshenshan Hospital                    | 12,000         | 13,000          | 14,000          |
| ⃣ | Wuhan Leishenshan Hospital                    | 12,000         | 13,000          | 14,000          |
| No | DMWDCs                        | District     | Affected population | Maximum capacity (tons/per day) |
|----|-------------------------------|--------------|---------------------|---------------------------------|
|    |                               |              |                     | Infectious | Non-infectious |
| A  | Guodingshan Medical Waste Incineration Plant | Hanyang      | 30,000              | 40         | 50             |
| B  | Wugangbeihu Disposal Plant    | Qingshan     | 11,500              | 20         | 30             |
| C  | Qianzishan Disposal Plant     | Caidian      | 6500                | 30         | 40             |
| D  | Xiangyang Disposal Plant     | Xiangyang    | 28,500              | 30         | 0              |
| E  | Xianning Disposal Plant       | Xianning     | 14,600              | 30         | 0              |
| F  | Huangshi Disposal Plant       | Huangshi     | 8900                | 20         | 0              |
Table A4 Distance in kilometre between DMWGP and DMWTTs

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.8| 5 | 10| 12| 7 | 14| 10| 10| 33| 36| 20| 62| 34| 50| 34| 32|
| 2 | 5  | 0.8| 9 | 10| 12| 8 | 7 | 13| 26| 36| 18| 70| 40| 42| 25| 30|
| 3 | 10 | 5  | 0.8| 5 | 12| 12| 13| 3 | 16| 23| 30| 17| 67| 38| 36| 25| 22|
| 4 | 12 | 9  | 5  | 0.8| 15| 9 | 16| 19| 24| 26| 23| 69| 42| 37| 25| 19|
| 5 | 7  | 10 | 12 | 15| 0.8| 9 | 13| 11| 6 | 34| 29| 24| 64| 38| 48| 36| 23|
| 6 | 14 | 12 | 9  | 9 | 0.8| 18| 9 | 13| 31| 22| 28| 70| 43| 43| 32| 16|
| 7 | 10 | 8  | 13 | 16| 13| 18| 0.8| 13| 16| 32| 38| 18| 63| 31| 49| 30| 32|
| 8 | 10 | 7  | 4  | 11| 9 | 13| 0.8| 16| 24| 28| 19| 18| 38| 52| 36| 27|
| 9 | 10 | 13 | 16 | 19| 6 | 13| 16| 16| 0.8| 40| 32| 30| 61| 38| 52| 36| 27|
| 10| 33 | 26 | 23 | 24| 34| 31| 32| 40| 0.8| 44| 18| 90| 55| 33| 8 | 36|
| 11| 36 | 36 | 30 | 26| 29| 22| 38| 28| 32| 44| 0.8| 43| 83| 63| 34| 39| 9 |
| 12| 20 | 18 | 17 | 23| 24| 28| 18| 19| 30| 18| 43| 0.8| 79| 44| 47| 18| 36|
| 13| 62 | 70 | 67 | 69| 64| 70| 63| 18| 61| 90| 83| 79| 0.8| 45| 105|83 | 91|
| 14| 34 | 40 | 38 | 42| 38| 43| 31| 38| 38| 55| 63| 44| 45| 0.8| 76| 55 | 63|
| 15| 50 | 42 | 36 | 37| 48| 43| 49| 52| 52| 33| 34| 47| 105|76 | 0.8|30 | 38|
|    | A    | B    | C    | D    | E    | F    |
|----|------|------|------|------|------|------|
| 1  | 17   | 31   | 39   | 290  | 86   | 116  |
| 2  | 15   | 35   | 39   | 290  | 79   | 120  |
| 3  | 11   | 41   | 35   | 295  | 74   | 118  |
| 4  | 13   | 41   | 34   | 299  | 70   | 113  |
| 5  | 24   | 27   | 46   | 298  | 69   | 112  |
| 6  | 21   | 28   | 41   | 303  | 88   | 106  |
| 7  | 21   | 35   | 44   | 286  | 74   | 115  |
| 8  | 14   | 43   | 34   | 301  | 85   | 108  |
| 9  | 27   | 19   | 49   | 298  | 51   | 137  |
| 10 | 16   | 63   | 22   | 285  | 89   | 108  |
| 11 | 34   | 42   | 47   | 320  | 143  | 136  |
| 12 | 17   | 53   | 42   | 325  | 132  | 123  |
| 13 | 79   | 63   | 107  | 280  | 65   | 147  |
| 14 | 47   | 56   | 70   | 315  | 77   | 138  |
| 15 | 40   | 75   | 18   | 293  | 312  | 130  |
| 16 | 13   | 60   | 18   | 312  | 54   | 107  |
Table A6  Unit benefit in yuan/ton·km obtained by delivering disaster medical waste from DMWGs to DMWTTSs during outbreak period

|   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1 | 20  | 18  | 16  | 14  | 16  | 14  | 16  | 16  | 16  | 16  | 9   | 9   | 10  | 6   | 9   | 7   |
| 2 | 18  | 16  | 14  | 12  | 14  | 12  | 14  | 14  | 14  | 14  | 7   | 7   | 8   | 4   | 7   | 5   |
| 3 | 16  | 18  | 16  | 14  | 12  | 14  | 14  | 12  | 8   | 7   | 10  | 4   | 6   | 6   | 8   | 7   |
| 4 | 14  | 16  | 18  | 20  | 14  | 16  | 12  | 12  | 12  | 12  | 10  | 8   | 7   | 10  | 4   | 7   | 8   |
| 5 | 16  | 14  | 16  | 14  | 14  | 20  | 16  | 14  | 14  | 16  | 9   | 10  | 10  | 6   | 9   | 8   | 9   |
| 6 | 14  | 14  | 14  | 16  | 18  | 14  | 12  | 14  | 12  | 14  | 7   | 8   | 8   | 4   | 7   | 6   | 7   |

11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30
|   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 7 | 16  | 16  | 14  | 12  | 14  | 12  | 20  | 14  | 12  | 9   | 9   | 12  | 6   | 9   | 8   | 9   | 9   |
| 8 | 16  | 16  | 18  | 18  | 14  | 16  | 14  | 20  | 12  | 10  | 10  | 12  | 9   | 7   | 9   | 9   | 10  |
| 9 | 16  | 14  | 12  | 12  | 16  | 14  | 12  | 12  | 20  | 8   | 9   | 9   | 6   | 9   | 7   | 9   | 10  |
| 10| 16  | 14  | 12  | 10  | 10  | 14  | 12  | 10  | 18  | 6   | 7   | 7   | 4   | 7   | 5   | 7   | 8   |
| 11| 16  | 10  | 12  | 10  | 10  | 10  | 10  | 9   | 8   | 20  | 8   | 6   | 6   | 9   | 9   | 10  |
| 12| 10  | 12  | 12  | 10  | 10  | 12  | 12  | 9   | 12  | 8   | 20  | 6   | 8   | 8   | 12  |
| 13| 6   | 8   | 9   | 8   | 9   | 8   | 9   | 12  | 6   | 6   | 6   | 20  | 6   | 8   | 6   | 6   |
| 14| 6   | 4   | 4   | 4   | 4   | 4   | 4   | 10  | 4   | 4   | 4   | 4   | 18  | 6   | 2   | 4   | 4   |
| 15| 7   | 8   | 9   | 9   | 8   | 8   | 8   | 7   | 7   | 7   | 9   | 9   | 8   | 5   | 6   | 20  |

In each cell, the value on the top indicates unit benefit obtained by transporting infectious disaster medical waste per ton per kilometer, and that at the bottom shows unit benefit from transportation of non-infectious one.
Table A7 Unit benefit in yuan/ton·km obtained by delivering disaster medical waste from DMWTTSs to DMWDCs during outbreak period

|   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|
| A | 12| 12| 12| 12| 10| 10| 10| 10| 10| 12| 10| 12| 12| 9 | 12| 8 | 9 | 9 | 12| 12 |
|   | 10| 10| 10| 10| 8 | 8 | 8 | 8 | 10| 10| 7 | 10| 6 | 7 | 7 | 6 | 7 | 6 | 7 | 10| 8 |
| B | 9 | 9 | 9 | 9 | 10| 10| 9 | 9 | 12| 8 | 9 | 9 | 8 | 9 | 8 | 9 | 8 | 9 | 8 | 9 |
|   | 7 | 7 | 7 | 7 | 8 | 8 | 7 | 7 | 10| 6 | 7 | 7 | 6 | 7 | 6 | 7 | 6 | 7 | 7 | 7 |
| C | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 10| 9 | 9 | 7 | 8 | 12| 12| 9 | 12| 12| 9 |
|   | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 8 | 7 | 7 | 5 | 6 | 10| 10| 7 | 10| 10| 7 |
| D | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 |
|   | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 |
| E | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 5 | 6 | 8 | 8 | 7 | 8 | 8 | 7 |
|   | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3 | 4 | 6 | 6 | 5 | 6 | 6 |
| F | 7 | 7 | 7 | 7 | 7 | 7 | 6 | 7 | 7 | 6 | 7 | 6 | 6 | 5 | 6 | 6 | 6 | 7 | 6 | 6 |
|   | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 5 | 4 | 5 | 4 | 4 | 3 | 4 | 4 | 5 | 4 | 4 | 5 |

In each cell, the value on the top indicates unit benefit obtained by transporting infectious disaster medical waste per ton per kilometer, and that at the bottom shows unit benefit from transportation of non-infectious one
|   | ① | ② | ③ | ④ | ⑤ | ⑥ | ⑦ | ⑧ | ⑨ | ⑩ | ⑪ | ⑫ | ⑬ | ⑭ | ⑮ | ⑯ | ⑰ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 |  1 |  9 | 17 | 15 | 17 | 15 | 17 | 17 | 10 | 10 | 11 |  7 | 10 |  8 | 10 | 10 |
| 2 |  9 | 17 | 15 | 17 | 15 | 17 | 17 | 15 | 11 | 10 | 13 |  7 |  9 |  9 | 11 | 10 |
| 3 | 17 | 19 | 17 | 15 | 17 | 15 | 17 | 13 |  9 |  8 | 11 |  5 |  7 |  7 |  9 |  8 |
| 4 | 15 | 17 | 19 | 17 | 13 | 17 | 13 | 11 |  9 |  9 | 11 |  5 |  8 |  8 |  9 |  9 |
| 5 | 13 | 15 | 17 | 19 | 13 | 17 | 11 | 11 |  9 |  9 |  9 |  5 |  7 |  8 |  9 | 11 |
| 6 | 17 | 17 | 15 | 17 | 15 | 17 | 13 | 11 |  7 |  7 |  9 |  9 | 10 | 10 | 11 |
| 7 | 15 | 17 | 17 | 17 | 17 | 17 | 17 | 15 | 10 | 11 | 11 |  7 |  9 |  9 | 10 | 13 |
| 8 | 13 | 13 | 15 | 15 | 17 | 13 | 15 | 13 |  8 |  9 |  9 |  5 |  7 |  7 |  8 | 11 |
|   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|
| 7 | 17 | 17 | 15 | 13 | 15 | 13 | 21 | 15 | 13 | 10 | 10 | 13 | 7 | 10 | 9 | 10 | 10 | 10 | 10 |
| 15 | 17 | 15 | 13 | 11 | 13 | 11 | 19 | 13 | 11 | 8 | 8 | 8 | 11 | 5 | 8 | 7 | 8 | 8 |
| 8 | 17 | 17 | 15 | 17 | 15 | 21 | 13 | 11 | 11 | 13 | 13 | 10 | 8 | 10 | 10 | 11 | 9 | 9 |
| 15 | 17 | 15 | 17 | 13 | 15 | 13 | 19 | 11 | 9 | 9 | 11 | 11 | 8 | 6 | 8 | 9 | 11 |
| 9 | 17 | 15 | 13 | 13 | 17 | 15 | 13 | 13 | 21 | 9 | 10 | 10 | 7 | 10 | 8 | 10 | 11 | 11 |
| 15 | 13 | 11 | 11 | 15 | 13 | 11 | 11 | 19 | 7 | 8 | 8 | 5 | 8 | 6 | 8 | 9 | 10 |
| 10 | 10 | 11 | 11 | 10 | 10 | 10 | 10 | 11 | 9 | 21 | 9 | 13 | 7 | 8 | 10 | 17 | 10 | 10 |
| 8 | 9 | 9 | 9 | 8 | 8 | 9 | 7 | 19 | 7 | 11 | 5 | 6 | 8 | 15 | 8 | 10 |
| 11 | 10 | 10 | 10 | 11 | 11 | 11 | 10 | 10 | 9 | 21 | 9 | 7 | 7 | 10 | 10 | 17 | 8 |
| 8 | 8 | 8 | 9 | 9 | 9 | 8 | 9 | 8 | 7 | 19 | 3 | 3 | 8 | 8 | 15 | 10 |
| 12 | 11 | 13 | 13 | 11 | 11 | 11 | 13 | 13 | 10 | 13 | 9 | 21 | 7 | 9 | 9 | 13 | 10 |
| 9 | 9 | 11 | 11 | 9 | 9 | 9 | 11 | 11 | 11 | 8 | 11 | 11 | 7 | 5 | 7 | 7 | 11 |
| 13 | 7 | 7 | 7 | 7 | 7 | 7 | 13 | 7 | 7 | 7 | 21 | 9 | 6 | 7 | 7 | 10 |
| 5 | 5 | 5 | 5 | 5 | 5 | 5 | 11 | 5 | 5 | 5 | 5 | 19 | 7 | 3 | 5 | 5 |
| 14 | 10 | 9 | 10 | 10 | 9 | 10 | 10 | 10 | 10 | 8 | 7 | 9 | 9 | 21 | 7 | 8 |
| 8 | 8 | 8 | 9 | 9 | 8 | 7 | 8 | 8 | 8 | 6 | 5 | 7 | 7 | 19 | 5 | 6 | 5 |
| 15 | 8 | 9 | 10 | 10 | 9 | 9 | 9 | 8 | 8 | 10 | 10 | 9 | 6 | 7 | 21 | 10 | 10 |
| 6 | 7 | 8 | 8 | 7 | 7 | 7 | 6 | 6 | 8 | 8 | 7 | 3 | 5 | 19 | 8 | 8 |

In each cell, the value on the top indicates unit benefit obtained by transporting infectious disaster medical waste per ton per kilometer, and that at the bottom shows unit benefit from transportation of non-infectious one.
Table A9 Unit benefit in yuan/ton·km obtained by delivering disaster medical waste from DMWTTSs to DMWDCs during peak period

|    | ① | ② | ③ | ④ | ⑤ | ⑥ | ⑦ | ⑧ | ⑨ | ⑩ |
|----|----|----|----|----|----|----|----|----|----|----|
| A  | 13 | 13 | 13 | 13 | 13 | 11 | 11 | 11 | 11 | 11 |
|    | 11 | 11 | 11 | 11 | 9  | 9  | 9  | 9  | 9  | 9  |
| B  | 10 | 10 | 10 | 10 | 10 | 11 | 11 | 10 | 10 | 10 |
|    | 8  | 8  | 8  | 8  | 9  | 9  | 9  | 8  | 8  | 7  |
| C  | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 8  |
|    | 8  | 8  | 8  | 8  | 8  | 8  | 8  | 8  | 9  | 8  |
| D  | 5  | 5  | 5  | 5  | 5  | 4  | 5  | 4  | 5  | 4  |
|    | 3  | 3  | 3  | 3  | 3  | 2  | 3  | 2  | 3  | 2  |
| E  | 8  | 8  | 8  | 8  | 8  | 8  | 8  | 8  | 8  | 6  |
|    | 6  | 6  | 6  | 6  | 6  | 6  | 6  | 6  | 6  | 4  |
| F  | 8  | 8  | 8  | 8  | 8  | 7  | 8  | 7  | 8  | 5  |
|    | 6  | 6  | 6  | 6  | 6  | 5  | 6  | 5  | 5  | 4  |

In each cell, the value on the top indicates unit benefit obtained by transporting infectious disaster medical waste per ton per kilometer, and that at the bottom shows unit benefit from transportation of non-infectious one.
|          | ① | ② | ③ | ④ | ⑤ | ⑥ | ⑦ | ⑧ | ⑨ | ⑩ |
|----------|----|----|----|----|----|----|----|----|----|----|
| 1        | 22 | 20 | 18 | 16 | 16 | 18 | 18 | 18 | 18 | 18 |
| 2        | 20 | 18 | 16 | 14 | 16 | 16 | 16 | 16 | 16 | 16 |
| 3        | 3  | 2  | 2  | 2  | 2  | 2  | 2  | 2  | 2  | 2  |
| 4        | 4  | 4  | 4  | 4  | 4  | 4  | 4  | 4  | 4  | 4  |
| 5        | 5  | 5  | 5  | 5  | 5  | 5  | 5  | 5  | 5  | 5  |
| 6        | 6  | 6  | 6  | 6  | 6  | 6  | 6  | 6  | 6  | 6  |

Table A10: Unit benefit in yuan/ton·km obtained by delivering disaster medical waste from DMWGFs to DMWITTSs during mitigation period.
In each cell, the value on the top indicates unit benefit obtained by transporting infectious disaster medical waste per ton per kilometer, and that at the bottom shows unit benefit from transportation of non-infectious one.

|    | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1  | 18  | 18  | 16  | 14  | 14  | 12  | 14  | 22  | 16  | 14  | 11  | 11  | 14  | 8   | 11  | 10  | 11  | 11  | 11  |
| 2  | 16  | 16  | 14  | 12  | 14  | 12  | 20  | 14  | 12  | 9   | 9   | 9   | 12  | 6   | 9   | 8   | 9   | 9   | 9   |
| 3  | 11  | 11  | 11  | 11  | 11  | 11  | 11  | 11  | 11  | 10  | 14  | 8   | 11  | 10  | 10  | 12  | 12  | 12  | 9   |
| 4  | 9   | 10  | 10  | 9   | 9   | 9   | 9   | 10  | 8   | 20  | 8   | 12  | 6   | 7   | 9   | 9   | 16  | 9   | 9   |
| 5  | 9   | 9   | 10  | 10  | 10  | 9   | 9   | 10  | 9   | 8   | 20  | 8   | 6   | 6   | 9   | 9   | 16  | 9   | 9   |
| 6  | 12  | 12  | 12  | 12  | 12  | 12  | 14  | 14  | 14  | 14  | 10  | 22  | 8   | 10  | 10  | 14  | 11  | 11  | 11  |
| 7  | 10  | 12  | 12  | 10  | 10  | 10  | 12  | 12  | 12  | 12  | 12  | 20  | 8   | 8   | 8   | 12  | 9   | 9   | 9   |
| 8  | 13  | 8   | 8   | 8   | 8   | 8   | 8   | 8   | 14  | 8   | 8   | 8   | 8   | 22  | 10  | 7   | 8   | 8   | 8   |
| 9  | 6   | 6   | 6   | 6   | 6   | 6   | 6   | 12  | 6   | 6   | 6   | 6   | 20  | 8   | 4   | 6   | 6   | 6   | 6   |
| 10 | 14  | 11  | 10  | 11  | 11  | 11  | 11  | 11  | 9   | 8   | 10  | 10  | 22  | 8   | 9   | 8   | 9   | 8   | 9   |
| 11 | 9   | 9   | 8   | 9   | 9   | 9   | 9   | 7   | 6   | 8   | 8   | 20  | 6   | 7   | 6   | 6   | 6   | 6   | 6   |
| 12 | 9   | 10  | 11  | 11  | 10  | 10  | 10  | 9   | 9   | 11  | 11  | 10  | 7   | 8   | 22  | 11  | 11  | 11  | 11  |
| 13 | 7   | 8   | 9   | 9   | 8   | 8   | 8   | 7   | 7   | 9   | 9   | 8   | 4   | 6   | 20  | 9   | 9   | 9   | 9   |
Table A11 Unit benefit in yuan/ton·km obtained by delivering disaster medical waste from DMWTTSs to DMWDCs during mitigation period

|   | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| vA| 14| 14| 14| 14| 12| 12| 12| 14| 12| 14| 11| 14| 10| 11| 11| 14| 12|
|   | 12| 12| 12| 12| 10| 10| 10| 12| 10| 12| 9 | 12| 8 | 9 | 9 | 12| 10|
| B | 11| 11| 11| 11| 12| 12| 11| 11| 14| 10| 11| 11| 10| 11| 11| 10| 11|
|   | 9 | 9 | 9 | 9 | 10| 10| 9 | 9 | 12| 8 | 9 | 9 | 8 | 9 | 8 | 9 | 9 |
| C | 11| 11| 11| 11| 11| 11| 11| 11| 12| 11| 11| 9 | 10| 14| 14| 11|   |
|   | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 10| 9 | 9 | 7 | 8 | 12| 12| 9 |   |
| D | 6 | 6 | 6 | 6 | 6 | 5 | 6 | 5 | 6 | 6 | 5 | 6 | 5 | 6 | 5 | 6 |   |
|   | 4 | 4 | 4 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 |   |
| E | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 7 | 8 | 10| 10| 9 |   |
|   | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 5 | 6 | 8 | 8 | 7 |   |   |
| F | 9 | 9 | 9 | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 8 | 7 | 8 | 8 | 9 |   |   |
|   | 7 | 7 | 7 | 7 | 7 | 6 | 7 | 7 | 6 | 7 | 6 | 5 | 6 | 6 | 6 | 7 |   |

In each cell, the value on the top indicates unit benefit obtained by transporting infectious disaster medical waste per ton per kilometer, and that at the bottom shows unit benefit from transportation of non-infectious one.
### Table A12 Summary of information on DMWGPs in the context of single-period in Wuhan

| No | DMWGPs or hospitals                          | Affected population | The amounts of disaster medical waste (tons) |
|----|---------------------------------------------|---------------------|---------------------------------------------|
|    |                                             |                     | Infectious | Non-infectious |
| 1  | Wuhan Hankou Hospital                       | 37,500              | 18.9       | 12.4           |
| 2  | Wuhan Hospital of Red Cross Society         | 32,500              | 12.6       | 8.4            |
| 3  | Wuhan Pulmonary Hospital                    | 30,100              | 12.6       | 8.4            |
| 4  | Fifth Hospital in Wuhan                     | 29,090              | 14.7       | 9.9            |
| 5  | Wuhan Wuchang Hospital                      | 28,890              | 15.3       | 9.0            |
| 6  | Wuhan Seventh Hospital                      | 27,900              | 15.3       | 9.0            |
| 7  | Jinyintan Hospital                          | 30,700              | 5.1        | 3.1            |
| 8  | Wuhan Fourth Hospital West Campus           | 25,700              | 21.7       | 14.8           |
| 9  | Wuhan Ninth Hospital                        | 26,980              | 11.5       | 7.8            |
| 10 | Caidian District People’s Hospital          | 24,590              | 7.1        | 3.6            |
| 11 | The first People’s Hospital of Jiangxia District | 21,000      | 5.4        | 3.8            |
| 12 | Dongxihu District People’s Hospital         | 15,550              | 5.1        | 3.0            |
| 13 | Xinzhou District People’s Hospital          | 9100                | 3.9        | 2.6            |
| 14 | Huangpi District People’s Hospital          | 8850                | 7.2        | 4.8            |
| 15 | Hannan District People’s Hospital           | 12,500              | 5.3        | 3.7            |

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