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Two-phase COVID-19 medical waste transport optimisation considering sustainability and infection probability

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ABSTRACT

A safe and effective medical waste transport network is beneficial to control the COVID-19 pandemic and at least decelerate the spread of novel coronavirus. Seldom studies concentrated on a two-phase COVID-19 medical waste transport in the presence of multi-type vehicle selection, sustainability, and infection probability, which is the focus of this paper. This paper aims to identify the priority of sustainable objectives and observe the impacts of multi-phase and infection probability on the results. Thus, such a problem is formulated as a mixed-integer programming model to minimise total potential infection risks, minimise total environmental risks, and maximise total economic benefits. Then, a hybrid solution strategy is designed, incorporating a lexicographic optimisation approach and a linear weighted sum method. A real-world case study from Chongqing is used to illustrate this methodology. Results indicate that the solution strategy guides a good COVID-19 medical waste transport scheme within 1 min. The priority of sustainable objectives is society, economy, and environment in the first and second phases because the total *Gap* of case No.35 is 3.20%. A decentralised decision mode is preferred to design a COVID-19 medical waste transport network at the province level. Whatever the infection probability is, infection risk is the most critical concern in the COVID-19 medical waste clean-up activities. Environmental and economic sustainability performance also should be considered when infection probability is more than a certain threshold.

1. Introduction

It is well known that a large-scale public health incident caused by a novel coronavirus has affected more than 200 countries and areas worldwide. During the COVID-19 pandemic, a series of response activities, including prevention and treatment measures, have generated large quantities of medical waste. It is reported that 136 thousand tons of COVID-19 medical waste have been disposed of in China from January to March 2020 (Shan, 2020). In this regard, handling the overwhelming medical waste is challenging due to the limited disposal capacity. In addition, large quantities of COVID-19 medical waste make transport activities increasingly important. The main reason is that if the contaminated medical waste leaks due to negligence in transport management, it will restrain society from operating normally and give rise to irreparable losses to lives, the economy, and the environment (Kaur and Singh, 2019). In this context, a study on the medical waste transport optimisation problem is significant in the COVID-19 pandemic.

Studies demonstrate that the novel coronavirus is surprisingly hardy because it can survive on an inanimate surface for up to 9 days and transmit between animals for 28 days (Kampf et al., 2020). Yu et al. (2020a) and Cao et al. (2022) also emphasised that infection probability which should be considered in practical measures was a critical factor in managing COVID-19 medical waste. A real case from the Health Commission of Nanjing indicated the spread of novel coronavirus due to the improper clean-up activities for the contaminated COVID-19 medical

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waste at Nanjing Lukou International Airport (http://wjw.nanjing.gov.cn/), which further supports the above-mentioned viewpoint. In this regard, both theoretical and practical cases show that infection probability imposes significant influences on the decision-making of COVID-19 medical waste clearance. In other words, it underscores the necessity and urgency of incorporating infection probability into medical waste transport issues after the outbreak of the COVID-19 pandemic.

In COVID-19 medical waste treatment activities, generation areas, transfer, and disposal centres are usually considered to design an effective transport network (Kargar et al., 2020). Generally, a centralised decision mode is preferred for a small-scale transport network, while a decentralised mode is prevalent in a large-scale one (Cao et al., 2018). In the aftermath of the COVID-19 pandemic, it is challenging for decision entities to make all operational decisions regarding such a large-scale medical waste transport network. In terms of transport from generation areas to transfer centres (called the first phase), such activities usually occur inside cities with high population density. Relevant decisions are made by local governments or those entities who should be responsible for this task. Regarding transport activities from transfer centres to disposal centres (called the second phase), there is a consensus on the fact that they are always cross-regional, which requires those upper-level authorities to immediately make decisions on COVID-19 medical waste clean-up. To have a quick and effective response to the COVID-19 pandemic, devising a two-phase medical waste transport network seems more practical but challenging.

Practical cases indicate COVID-19 medical waste carries pathogenic microorganisms and inherently poses enormous threats to human health, thus detrimental to controlling novel coronavirus transmission and promoting social sustainability. Consequently, reducing infection risks seems conducive to alleviating public anxiety and mitigating social impacts, which is also a common concern for residents and public health authorities (Yu et al., 2020a; Valizadeh et al., 2021b). To clean up large quantities of medical waste generated from the COVID-19 pandemic, transport activities in the two-phase network would inevitably produce plenty of carbon emissions, thus unfavourable impacts on the environment. In addition, it cannot ignore the fact that the exposure risks of COVID-19 medical waste due to transport accidents caused by employees and vehicles also impose undesirable influences on the environment. In this regard, both carbon emissions and transport accidents would increase environmental pressure and risks (Boostani et al., 2021; Cao et al., 2021). It also must be acknowledged that COVID-19 medical waste clean-up activities are not only cost-intensive but benefit-creating for key stakeholders (e.g., logistics service providers) (Boonmee et al., 2018). Subsequently, combined with the insights of Mantzaras and Voudrias (2017), Tirkolaee et al. (2021), and Cao et al. (2022), the incorporation of social, environmental, and economic sustainability and a two-phase COVID-19 medical waste transport optimisation in the presence of infection probability needs to be further studied.

Thus, this paper aims to answer the following questions.

1. How can a multi-objective programming approach be used to tackle a two-phase medical waste transport optimisation problem that includes sustainability, infection probability, and multiple objectives in the COVID-19 pandemic?
2. What is the social, environmental, and economic sustainability priority in the COVID-19 medical waste transport network for each phase?
3. What is the optimal two-phase COVID-19 medical waste transport scheme?
4. What are the influences of multi-phase and infection probability on the overall performance of the COVID-19 medical waste transport network?

To address the above-mentioned questions, infection risks, environmental risks, and benefit-creating are used to respectively measure social, environmental, and economic sustainability performance. A multi-objective programming model is further constructed to formulate the two-phase COVID-19 medical waste transport optimisation problem in the presence of sustainability, infection probability, and vehicle selection. A hybrid solution strategy consisting of a lexicographic optimisation approach and a linear weighted sum method is devised to tackle the model, thus prioritizing social, environmental, and economic sustainable objectives for each phase, and observing the influences of multiple phases and infection probability on the overall performance of the COVID-19 medical waste transport network.

This paper also contributes to the existing studies from the following aspects. Firstly, by comparing the existing studies on necessary household supplies, medical materials, vaccine distribution, and healthcare staff allocation issues after the outbreak of the COVID-19 pandemic (Kumar et al., 2021; Bertsimas et al., 2022; Gao et al., 2022; Yin et al., 2023), a two-phase COVID-19 medical waste transport optimisation problem with the consideration of vehicle selection, sustainability, infection probability, multiple generation areas and disposal centres is discussed here to enrich the achievements in humanitarian operations. Secondly, this paper proposed a two-phase multi-objective mixed-integer programming model for the COVID-19 medical waste transport problem, which extends the existing studies that focused on the single-period optimisation model (Valizadeh et al., 2021a; Eren and Tuzkaya, 2021) and the multi-period one (Tirkolaee et al., 2021; Govindan et al., 2021). In addition, the objectives of the proposed model are to minimise total potential infection risks and total environmental risks and maximise total economic benefits, which extends the studies of Valizadeh et al. (2021a), Valizadeh et al. (2021b), Valizadeh and Mozafari (2022) seeking to minimise total cost or total government expenditure. Thirdly, most recent studies resolved the multi-objective optimisation programming models by using Pareto optimisation, epsilon-constraint, and goal programming in humanitarian operations (Onan et al., 2015; Govindan et al., 2021; Aghababaei et al., 2022). Yet, only a fraction of researchers focused on applying the lexicographic optimisation method or linear weighted sum approach (Hu and Sheu, 2013; Yu et al., 2020a; Tirkolaee et al., 2021; Aghababaei et al., 2022; Cao et al., 2022). This paper leverages and extends the insights of the above studies to design a hybrid solution strategy that incorporates the above-mentioned two approaches, thus observing the priority of sustainable objectives and the influences of key factors on results, obtaining a feasible COVID-19 medical waste transport scheme.

The rest of this paper is arranged as follows. Section 2 presents a literature review on medical waste management. Section 3 describes a two-phase COVID-19 medical waste transport network and establishes a multi-objective mathematical programming model for such an issue. To solve the proposed model, different solution strategies are given in Section 4. In Section 5, a real-world case study regarding Chongqing during the COVID-19 pandemic is applied to illustrate the methodology. Remarks and future directions are given in Section 6.

2. Literature review

In this section, the related works are classified into three streams. The first one concerns humanitarian supply chain management under the COVID-19 pandemic. The second one concentrates on medical waste management problems and their characteristics. The last one focuses on the multi-objective optimisation models and relevant solution strategies. The key existing studies of each stream are summarised in Table 1 to present the similarities and differences in terms of context, sustainability, problem characteristics, model features, methods to handle multiple objectives, and case study.

2.1. *Humanitarian supply chain management in the context of the COVID-19 pandemic*

In recent years, to deal with natural and man-made disasters, humanitarian supply chain management receives growing awareness in

Table 1
Summary of medical waste management, context, sustainability, problem characteristics, model features, methods to handle multiple objectives, and case study supported by the existing models in the literature.

Reference	Year	Medical waste management		Context [a]		Sustainability [b]			Problem characteristics					
									MWGA(s) [c]		MWDC(s) [d]		Inf. prob. [e]	
		Yes	No	H	C	S	En	Ec	Single	Multiple	Single	Multiple	Yes	No
Hu and Sheu	2013		✓	✓		–	–	–	–	–	–	–		✓
Celik et al.	2015		✓	✓		–	–	–	–	–	–	–		✓
Onan et al.	2015		✓	✓		–	–	–	–	–	–	–		✓
Habib et al.	2017		✓	✓		–	–	–	–	–	–	–		✓
Lorca et al.	2017		✓	✓		–	–	–	–	–	–	–		✓
Mantzaras and Voudrias	2017	✓			✓	–	–	–		✓		✓		✓
Cheng et al.	2018		✓	✓		–	–	–	–	–	–	–		✓
Habib et al.	2019		✓	✓		✓	✓	✓	–	–	–	–		✓
Yu et al.	2020a	✓		✓		–	–	–		✓		✓	✓	
Yu et al.	2020b	✓			✓	–	–	–		✓		✓		✓
Kargar et al.	2020	✓		✓		–	–	–		✓		✓		✓
Cheng et al.	2021		✓	✓		–	–	–	–	–	–	–		✓
Tirkolaee et al.	2021	✓		✓		✓				✓		✓		✓
Eren and Tuzkaya	2021	✓		✓		–	–	–		✓	–	–		✓
Valizadeh et al.	2021a	✓		✓		–	–	–		✓		✓	✓	
Valizadeh et al.	2021b	✓		✓		–	–	–		✓		✓	✓	
Govindan et al.	2021	✓		✓		–	–	–		✓		✓	✓	
Cao et al.	2022	✓		✓		✓	✓	✓		✓		✓	✓	
Aghababaei et al.	2022		✓	✓		–	–	–	–	–	–	–		✓
Bertsimas	2022		✓	✓		–	–	–	–	–	–	–	✓	
Shahparvari	2022		✓	✓		–	–	–	–	–	–	–		✓
Valizadeh and Mozafari	2022	✓		✓		–	–	–	–	✓	–	–		✓
Yin et al.	2023		✓	✓		–	–	–	–	–	–	–	✓	
This paper		✓		✓		✓	✓	✓		✓		✓	✓	

Reference	Year	Model features							Methods to handle multiple objectives			Case study		
		Objectives		Main objectives			Inf. risk const.[h]					COVID-19		Country[l]
		Single	Multiple	Inf. risk[f]	Env. risk[g]	Benefit	Yes	No	LWSA[i]	LOM[j]	Others[k]	Yes	No	
Hu and Sheu	2013		✓	–	–	–		✓	✓				✓	China
Celik et al.	2015	✓				✓		✓	–	–	–		✓	–
Onan et al.	2015		✓	–	–	–		✓			✓		✓	Turkey
Habib et al.	2017	✓		–	–	–		✓	–	–	–		✓	Pakistan
Lorca et al.	2017	✓		–	–	–		✓	–	–	–		✓	USA
Mantzaras and Voudrias	2017	✓		–	–	–		✓	–	–	–		✓	Greece
Cheng et al.	2018	✓		–	–	–		✓	–	–	–		✓	Australia
Habib et al.	2019		✓	–	–	–		✓			✓		✓	Pakistan
Yu et al.	2020a		✓	✓				✓		✓		✓		China
Yu et al.	2020b		✓	–	–	–		✓			✓		✓	China
Kargar et al.	2020		✓	–	–	–		✓			✓	✓		Iran
Cheng et al.	2021		✓	–	–	–		✓			✓		✓	Australia
Tirkolaee et al.	2021		✓	–	–	–		✓	✓			✓		Iran
Eren and Tuzkaya	2021		✓	–	–	–		✓			✓	✓		Turkey
Valizadeh et al.	2021a	✓		–	–	–		✓	–	–	–	✓		Iran
Valizadeh et al.	2021b	✓		✓				✓	–	–	–	✓		Iran
Govindan et al.	2021		✓	–	–	–		✓			✓	✓		Iran
Cao et al.	2022		✓	✓		✓		✓	✓			✓		China
Aghababaei et al.	2022		✓			✓		✓			✓	✓		Iran
Bertsimas	2022		✓	–	–	–		✓	✓			✓		USA
Shahparvari	2022	✓		–	–	–		✓	–	–	–	✓		Australia
Valizadeh and Mozafari	2022	✓		–	–	–		✓	–	–	–	✓		Iran
Yin et al.	2023	✓		–	–	–	✓		–	–	–	✓		USA
This paper			✓	✓	✓	✓	✓		✓	✓		✓		China

Note that the term '-' for all columns represents that it cannot be clearly found in the text.

[a] The supply chain considered in the literature is either commercial or humanitarian.

[b] It indicates whether sustainability is clearly considered in the focused issue or not. If yes, which aspect(s) of social (S), environmental (En), and economic (Ec) sustainability is (are) considered in the proposed model.

[c] This term demonstrates the number of medical waste generation areas (MWGAs) is single or multiple.

[d] It shows that there is single or multiple medical waste disposal centre(s) (MWDCs).

[e] This column denotes whether infection probability (Inf. prob.) is explicitly considered in the text or not.

[f] Whether infection risk (Inf. risk) is regarded as one of the main objectives in the developed optimisation model.

[g] Whether environmental risk (Env. risk) is treated as one of the main objectives in the developed optimisation model.

[h] It indicates whether the infection risk constraint (Inf. risk const.) is added to the optimisation model.

[i] LWSA is short for the linear weighted sum approach.

[j] LOM is short for the lexicographic optimisation method.

[k] It indicates that other methods to handle multiple objectives include Pareto optimisation, goal programming, epsilon-constraint, and so on.

[l] This term shows which country the adopted case is from if the case study comes from the real world.

both academia and industry (Habib et al., 2016; Behl and Dutta, 2019; Wamba, 2022). In the last two and a half years, a global public health crisis caused by the COVID-19 pandemic has posed serious threats to all walks of life worldwide. Humanitarian supply chain management has been used to mitigate its impacts by optimising forward logistics activities (e.g., emergency resource allocation) and reverse ones (e.g., medical waste management).

Concerning the forward logistics supply chains in the context of the COVID-19 pandemic, Aghababaei et al. (2022) aimed to optimise scarce drug supply chains by using a multi-objective bi-level programming model, thus achieving equitable distribution and supply cost-saving. Yin et al. (2023) focused on medical supply rationing challenges and formulated a multi-stage stochastic ventilator allocation optimisation model to minimise the total expected number of infected and deceased people. Gao et al. (2022) addressed a healthcare staff rebalancing optimisation problem with the goal of maximizing expected total utility by applying a robust programming approach. In addition, Bertsimas et al. (2022) and Shahparvari et al. (2022) focused on the COVID-19 vaccine distribution problem concerning different characteristics in vaccine supply chain management.

Regarding reverse logistics supply chains, only a fraction of scholars intended to deal with such topics during the COVID-19 pandemic. For instance, Kargar et al. (2020) highlighted the importance of designing infectious medical waste supply chains to decelerate novel coronavirus spread and constructed a multi-objective linear programming model to minimise total costs and risks and maximise the amount of uncollected medical waste. Cao et al. (2022) proposed a multi-objective programming model for the multi-period multi-type COVID-19 medical waste location-transport integrated problem, and intended to maximise total economic benefits, minimise total carbon emissions, and minimise total potential social risks. Valizadeh and Mozafari (2022) formulated a multi-period infectious COVID-19 medical waste collection problem as a single-objective mixed-integer programming model to minimise total costs. Then, different cooperative game methods were applied to evaluate the results, thus achieving the goal of saving costs.

In summary, the existing studies paid more attention to optimisation issues of humanitarian operations in the aftermath of natural and man-made disasters relative to the COVID-19 pandemic. In addition, most of the studies were keen on emergency resource allocation, such as medical supplies and vaccine distribution, and medical or healthcare staff assignment after the outbreak of the COVID-19 pandemic. Table 1 indicated that although personal prevention, protection, and treatment activities produced large quantities of medical waste, which challenges quick and effective response to the COVID-19 pandemic, few studies dealt with this topic. In addition, by comparing with the existing literature that concerned single- or multi-period medical waste transport optimisation model in humanitarian operations, seldom studies were devoted to modelling a two-phase COVID-19 medical waste transport issue in the inclusion of social, economic, environmental sustainability, infection probability, vehicle selection, multiple generation areas, and disposal centres. More details on humanitarian supply chain management under the COVID-19 pandemic can refer to Kumar et al. (2022).

2.2. Medical waste management problems and their characteristics

Medical waste refers to a set of waste produced at health care facilities (e.g., hospitals, blood banks), medical research facilities and laboratories. It may be contaminated by blood or other potentially infectious materials. Thus, how to manage and regulate the medical waste generated is urgent and beneficial for the sustainable development of a city or even a country. Particularly, it seems more critical in a disaster or public health incident context because such an emergency would significantly increase the volume of medical waste. Naturally, after the outbreak of the COVID-19 pandemic, medical waste generated from a series of rescue activities challenged urban waste management systems (Yu et al., 2020a; Tirkolaee et al., 2021; Chen et al., 2021). To date, medical waste management issues in the context of both commercial and humanitarian operations are still prevalent in this field.

Under the context of the commercial operation, Mantzaras and Voudrias (2017) formulated a single-objective mathematical programming model to minimise total costs regarding the collection, haul, transfer, treatment, and disposal of infectious medical waste. To address the location and size plan for disposal facilities and transport strategies for medical waste management, Yu et al. (2020b) proposed a multi-objective mixed-integer programming model to reduce costs and exposure risks.

In response to the severe accumulation of medical waste produced by major public health incidents, Tirkolaee et al. (2021) developed a multi-objective mixed-integer programming model for the COVID-19 medical waste location-routing optimisation problem with the concern of multiple collection facilities and disposal sites, expecting to achieve social sustainability, i.e., the reduction of exposure risks. After the outbreak of the COVID-19 pandemic, Valizadeh et al. (2021a) used a bi-level optimisation approach to model medical waste collection and treatment problems with the aim of minimum expenditure of governments on the upper level and minimum total costs on the lower level.

According to Table 1, most researchers were keen on medical waste management problems in commercial operations. Yet, such topics could only be found in limited literature on humanitarian operations, especially in the aftermath of major public health incidents. Table 1 also indicated that non-medical waste optimisation issues relative to medical ones were more prevalent in the field of disaster waste management. According to the existing studies, the objectives of the developed mathematical programming models are mainly related to cost, and few works concentrated on the simultaneous incorporation of infection risks, environmental risks, and economic benefits in medical waste management. Besides, rare studies clearly considered an infection risk constraint in the mathematical programming models in this field.

2.3. Multi-objective optimisation models and their solution strategies

At the early stage, a single-objective programming model is prevalent in optimising the relevant issues in humanitarian operations. For example, Celik et al. (2015), Habib and Sarkar (2017), and Lorca et al. (2017) contributed to the single-objective optimisation model for post-disaster debris clearance problems. Nevertheless, Altay and Green III (2006), Gutjahr and Nolz (2016), and Cao et al. (2021) highlighted multi-objective was the distinguishing characteristic of humanitarian operations, naturally including the reverse logistics under disaster context, such as post-disaster debris clearance. Furthermore, since there are always conflicting objectives from multiple decision entities or a decision entity may have different goals in different aspects in practice, it seems challenging to tackle the complex issues in the context of disaster by using the single-objective model. In this sense, the multi-objective optimisation model seems more reasonable and practical. For instance, Hu and Sheu (2013), Onan et al. (2015), Cheng et al. (2018), Moreno et al. (2018), and Cao et al. (2022) applied multi-objective optimisation method to address post-disaster relief distribution and waste clean-up problems, thus enriching the methodology in the field of humanitarian operations.

Another critical issue is how to solve the multi-objective mathematical programming model due to its complexity (Boostani et al., 2021). According to the related works, the methods to handle multiple objectives at least include linear weighted sum, lexicographic optimisation, and heuristic algorithm. In detail, Cao et al. (2017), Cao et al. (2018), and Cao et al. (2021) applied a linear weighted sum method to resolving multi-objective optimisation models for emergency organisation allocation, post-disaster relief distribution problems, and COVID-19 medical location-transport issues in sustainable humanitarian supply chains. However, the above studies indicated that determining the weights of different objectives was difficult in practice. For this, the lexicographic optimisation approach is used to tackle the optimisation problems in humanitarian operations, e.g, post-disaster relief distribution, thus overcoming the drawbacks of the linear weighted sum approach, which is studied by Moreno et al. (2018) and Laguna-Salvadó et al. (2019). In addition, Onan et al. (2015) and Cao et al. (2018) designed particle swarm optimisation and genetic algorithm to solve the multi-objective programming model for reverse and forward logistics supply chains in disaster operations management, respectively.

In summary, a multi-objective optimisation approach was more prevalent in the forward logistics supply chains compared with the reverse ones in humanitarian operations. Furthermore, Table 1 demonstrated that most of them applied Pareto optimisation, goal programming, and epsilon-constraint approach to tackle the multi-objective mathematical programming models in humanitarian operations. Only a handful of studies concerned the application of the linear weighted sum approach or lexicographic optimisation method in such issues, especially in disaster debris clean-up. An integrated approach incorporating the above two methods was scarce in humanitarian operations, especially in COVID-19 medical waste management. Nevertheless, this paper devises a hybrid solution strategy to incorporate such two methods. Particularly, the lexicographic optimisation method is first used to prioritise three objectives for each phase. Then, a linear weighted sum approach is applied to test the impacts of multiple phases and infection probability on sustainable objective function values and obtain the COVID-19 medical waste transport scheme.

3. Two-phase COVID-19 medical waste transport problem description and a multi-objective mathematical programming model formulation

3.1. *Problem description*

In the aftermath of the COVID-19 pandemic, one of the most important things is to deliver all medical waste from generation areas (e.g., hospitals) to disposal centres as soon as possible, thus reducing novel coronavirus transmission via the contaminated medical waste (Chen et al., 2021). For decision entities, since high infection and large-volume features of COVID-19 medical waste challenge practical activities, how to design a safe and effective transport network to handle medical waste seems critical to combat the COVID-19 pandemic.

In practice, it is reported that there are two types of COVID-19 medical waste transport networks (Yu et al., 2020a; Chen et al., 2021; Yoon et al., 2022). The first case is that the COVID-19 medical waste is transported from MWGAs to MWDCs directly. Chen et al. (2021) underlined that direct transport was preferred when the daily COVID-19 medical waste generation was less than the daily disposal capacity. Nevertheless, when the daily medical waste generation exceeds the daily disposal capacity, local storage and temporary transfer are necessary, especially during the peak period and in some provinces or counties with poor medical waste management systems, which is the second case and common in reality, and supported by Kargar et al. (2020), Tirkolaee et al. (2021), and Cao et al. (2022). In terms of the former (i.e., direct transport), COVID-19 medical waste is first stored in the designated areas of the generation points, and then directly transported to MWDCs. It is evident that there still exists temporary storage even for direct transport, which to some extent could be regarded as a kind of transfer activity within the MWGAs. In addition, Chongqing is selected as the case study of this paper. Practical activities demonstrate that medical waste temporary transfer centres (MWTTCs) are considered in the transport network in Chongqing, so it does not belong to the direct transport case. In this sense, the route of medical waste being directly transported to the MWDCs is not in the scope of this paper.

In terms of the latter (i.e., a transport network including MWGAs, MWTTCs, and MWDCs), it can to some extent alleviate the insufficient disposal capacity of COVID-19 medical waste. Secondly, establishing the MWTTCs is beneficial for timely cleaning up COVID-19 medical waste and reducing the exposure risks of the debris, thus decreasing transmission risks of novel coronavirus. Thirdly, Kargar et al. (2020), Tirkolaee et al. (2021), and Cao et al. (2022) highlighted the importance of MWTTCs construction from a theoretical perspective. Fourthly, the 'Public Assistance Debris Management Guide (Federal Emergency Management Agency, 2007)' and 'Disaster Waste Management Guidelines (UNEP/OCHA, 2011)' underscored the necessity of establishing MWTTCs from a practical or industrial standpoint. In this context, a medical waste transport network consisting of MWGAs, MWTTCs, and MWDCs is considered in this paper, which is depicted in Fig. 1.

From Fig. 1, the bottom layer clearly presents a two-phase COVID-19 medical waste transport network. It is evident that local authorities first make decisions regarding vehicle selection and the amount of COVID-19 medical waste transported from MWGAs to MWTTCs based on relevant information. They usually seek to optimise social, environmental, and economic sustainability performance. And then, the corresponding operational decisions are implemented into practical transport activities. According to the amount of COVID-19 medical waste in MWTTCs in the first phase, the upper-level entities would determine the type of vehicles and the amount of medical waste delivered from MWTTCs to MWDCs. Their focus is to minimise total potential infection risks, total environmental risks, and maximise total economic benefits in the second phase. Thus, these operational decisions guide COVID-19 medical waste clean-up activities in the real world.

For simplicity, several necessary assumptions are made. Firstly, the location and amount of MWGAs, MWTTCs, and MWDCs are prespecified. Secondly, it is assumed that the maximum capacity of each MWTTC and MWDC is different. All MWTTCs and MWDCs are required to meet a minimum service level, respectively, which reflects the preferences of decision entities. Thirdly, the number and type of trucks available for selection are known in COVID-19 medical waste transport activities. Fourthly, infection probability as the typical and important factor is assumed to be known, but it is different for transporting COVID-19 medical waste in the first and second phases. Fifthly, since the COVID-19 pandemic as a major public health incident significantly challenges the medical waste management system, this paper considers a two-phase transport network to handle these challenges. Sixthly, a discrete approach is usually applied to break down the whole decision period in practice. Such action expects to capture the rapidly changing features (e.g., the amount of medical waste generated) of the COVID-19 pandemic. Regarding discretisation, if it is too coarse, it would reduce the applicability of operational decisions. If it is too granular, it would need long computational times, thus detrimental to combating the COVID-19 pandemic (Bertsimas et al., 2022). In this sense, the length of each period depends on the disposal capacity of the existing and constructing facilities, infection risks, and regulation policies of COVID-19 medical waste. Following the global guidelines on handling COVID-19 medical waste, one day is regarded as a decisive period. In addition, this problem can be easily expanded to a multi-period transport issue by inputting different parameters and adding the correlation constraints of COVID-19 medical waste generation mass in two successive periods.

3.2. *Notations*

Indices and main sets.

I Set of medical waste generation areas (MWGAs), indexed by $i \in I$

J Set of medical waste temporary transfer centres (MWTTCs), indexed by $j \in J$

K Set of medical waste disposal centres (MWDCs), indexed by $k \in K$

M Set of medical waste collection vehicles, indexed by $m \in M$

Parameters.

α_{ij}^{1} Infection probability of novel coronavirus when transporting unit COVID-19 medical waste per kilometre from MWGA i to MWTTC j

α_{jk}^{2} Infection probability of novel coronavirus when delivering unit COVID-19 medical waste per kilometre from MWTTC j to MWDC k

β_{ij}^{1} Potential damage risks to the environment caused by accidents

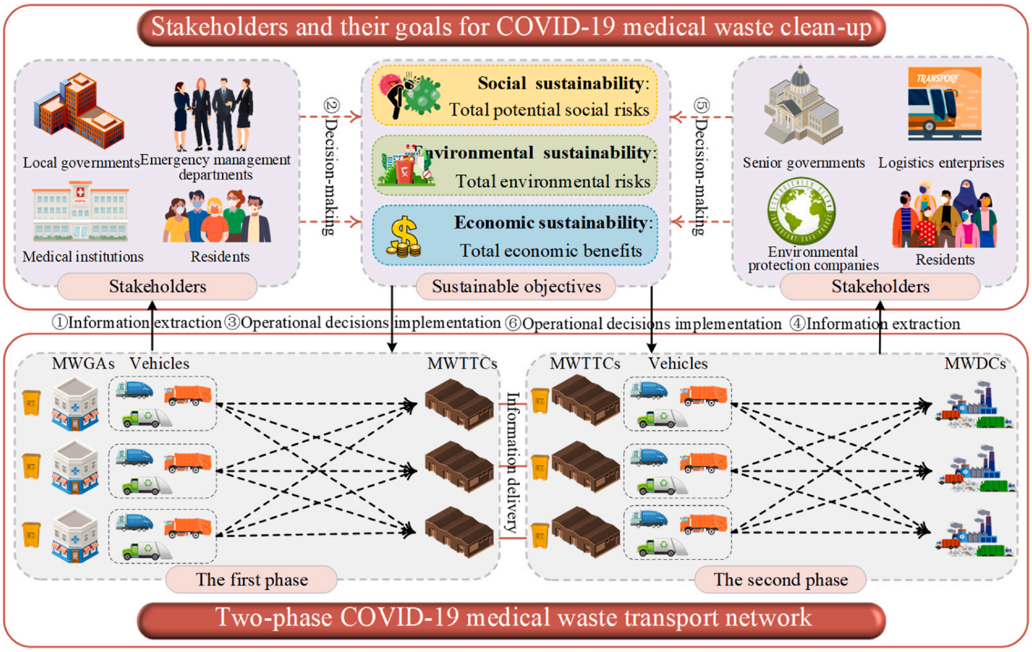


Fig. 1. Conceptual framework regarding two-phase COVID-19 medical waste transport.

when transporting unit COVID-19 medical waste per kilometre from MWGA i to MWTTC j

β^2_{jk} Potential damage risks to the environment caused by accidents when delivering unit COVID-19 medical waste per kilometre from MWTTC j to MWDC k

γ^1_{ijm} Carbon emissions of transporting unit COVID-19 medical waste per kilometre by vehicle m from MWGA i to MWTTC j

γ^2_{jkm} Carbon emissions of delivering unit COVID-19 medical waste per kilometre by vehicle m from MWTTC j to MWDC k

ε^1 Risk coefficient of carbon emissions produced by transporting unit COVID-19 medical waste from MWGA i to MWTTC j on the environment

ε^2 Risk coefficient of carbon emissions produced by delivering unit COVID-19 medical waste from MWTTC j to MWDC k on the environment

θ^1_{ij} Unit benefit obtained from COVID-19 medical waste transport per ton per kilometre from MWGA i to MWTTC j

θ^2_{jk} Unit benefit obtained from COVID-19 medical waste transport per ton per kilometre from MWTTC j to MWDC k

Q_i Amount of COVID-19 medical waste at MWGA i

C^1_j Maximum capacity of MWTTC j to temporarily store COVID-19 medical waste

C^2_k Maximum capacity of MWDC k to dispose of COVID-19 medical waste

φ^1_j Minimum service level provided by MWTTC j

φ^2_k Minimum service level provided by MWDC k

D^1_{ij} Distance from MWGA i to MWTTC j

D^2_{jk} Distance from MWTTC j to MWDC k

VC^1_m Maximum capacity of vehicle m to load COVID-19 medical waste in the first phase

VC^2_m Maximum capacity of vehicle m to load COVID-19 medical waste in the second phase

η^1_{ij} Potential infection risk level for each person can be accepted by the local authorities when COVID-19 medical waste is transported from MWGA i to MWTTC j

η^2_{jk} Potential infection risk level for each person can be accepted by the upper-level authorities when COVID-19 medical waste is delivered from MWTTC j to MWDC k

P^1_{ij} Number of residents around the transport routes between MWGA i to MWTTC j

P^2_{jk} Number of residents around the transport routes between MWTTC j to MWDC k

μ^1_{ijm} Unit cost of transporting COVID-19 medical waste per ton per kilometre by vehicle m from MWGA i to MWTTC j

μ^2_{jkm} Unit cost of delivering COVID-19 medical waste per ton per kilometre by vehicle m from MWTTC j to MWDC k

F^1 Total budget for transporting COVID-19 medical waste in the first phase

F^2 Total budget for delivering COVID-19 medical waste in the second phase

N A sufficiently large positive constant

Decision variables.

x^1_{ijm} Amount of COVID-19 medical waste transported by vehicle m from MWGA i to MWTTC j

x^2_{jkm} Amount of COVID-19 medical waste transported by vehicle m from MWTTC j to MWDC k

y^1_{ijm} Binary variable is equal to 1 if COVID-19 medical waste is transported by vehicle m from MWGA i to MWTTC j; otherwise, it is 0

y^2_{jkm} Binary variable is equal to 1 if COVID-19 medical waste is transported by vehicle m from MWTTC j to MWDC k; otherwise, it is 0

3.3. A tri-objective mixed-integer programming model for the first phase

As mentioned above, the COVID-19 medical waste transport optimisation issue in the first phase can be formulated as a tri-objective mixed-integer programming model, denoted by Equations (1)–(12).

$$\min_{x^1_{ijm},\, y^1_{ijm}} f^1_1 = \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\alpha^1_{ij} D^1_{ij} x^1_{ijm} \tag{1}$$

$$\min_{x^1_{ijm},\, y^1_{ijm}} f^1_2 = \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\beta^1_{ij} D^1_{ij} x^1_{ijm} + \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\varepsilon^1 \gamma^1_{ijm} D^1_{ij} x^1_{ijm} \tag{2}$$

$$\max_{x^1_{ijm},\, y^1_{ijm}} f^1_3 = \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\theta^1_{ij} D^1_{ij} x^1_{ijm} \tag{3}$$

$$s.t. \sum_{j\in J}\sum_{m\in M} x^1_{ijm} = Q_i / \forall i \in I / \tag{4}$$

$$\sum_{i\in I}\sum_{m\in M} x^1_{ijm} \leq C^1_j / \forall j \in J / \tag{5}$$

$$\sum_{i\in I}\sum_{m\in M} x^1_{ijm} \geq \varphi^1_j C^1_j / \forall j \in J / \tag{6}$$

$$\sum_{i\in I}\sum_{j\in J} x^1_{ijm} \leq VC^1_m / \forall m \in M / \tag{7}$$

$$x^1_{ijm} \leq N y^1_{ijm} / \forall i \in I, j \in J, m \in M / \tag{8}$$

$$\frac{\sum_{m\in M} \alpha^1_{ij} D^1_{ij} x^1_{ijm}}{P^1_{ij}} \leq \eta^1_{ij} / \forall i \in I, j \in J / \tag{9}$$

$$\sum_{i\in I}\sum_{j\in J}\sum_{m\in M} \mu^1_{ijm} D^1_{ij} x^1_{ijm} \leq F^1 \tag{10}$$

$$x^1_{ijm} \geq 0 / \forall i \in I, j \in J, m \in M / \tag{11}$$

$$y^1_{ijm} = \{0, 1\} / \forall i \in I, j \in J, m \in M / \tag{12}$$

In this model, all objective functions in the first phase are given by Equations (1)–(3), which reflect social, environmental, and economic sustainability performance, respectively. Equation (1) aims to minimise total potential infection risks for residents when COVID-19 medical waste is delivered from MWGAs to MWTTCs, which is regarded as an indicator to quantify social sustainability performance. Such an idea is inspired by Yu et al. (2020a), Tirkolaee et al. (2021), Valizadeh et al. (2021b), and Cao et al. (2022). The main reason is that the improper transport of infectious COVID-19 medical waste is likely to pose threats to human health and increases the risks of novel coronavirus transmission, thus unfavourable impacts on social stability and social sustainability.

Equation (2) represents the minimum total environmental risks caused by accidents and carbon emissions when transporting COVID-19 medical waste from MWTTCs to MWDCs, which is supported by Fabiano et al. (2002), Cao et al. (2017), Cao et al. (2021), and Cao et al. (2022). The first one highlighted that environmental risks could be reflected by the accident rate of COVID-19 medical waste transport. The last three papers claimed that COVID-19 medical waste transport activities inevitably led to carbon emissions that impose potential environmental risks.

Equation (3) expects to achieve economic sustainability performance by maximizing total economic benefits. Boonmee et al. (2018) underscored that disaster debris clean-up activities also could create benefits except for spending costs. A similar insight is presented for COVID-19 medical waste clearance by Cao et al. (2022). Thus, this paper leverages their insight to regard economic benefits as an indicator to measure economic sustainability performance.

Constraint (4) ensures that COVID-19 medical waste from MWGAs is completely delivered to MWTTCs by the provided transport vehicles. Constraint (5) indicates that the amount of COVID-19 medical waste transported to MWTTC *j* cannot exceed its maximum capacity. Constraint (6) shows the preference of local authorities for a minimum service level of MWTTCs. Constraint (7) limits the amount of COVID-19 medical waste delivered to the maximum capacity of transport vehicles. Constraint (8) states COVID-19 medical waste can be delivered from MWGAs to MWTTCs only when the vehicle *m* is selected for transport between MWGA *i* and MWTTC *j*. Constraint (9) reflects the preference of decision entities regarding infection risks. Constraint (10) denotes that total transport costs are no more than the budget for delivering COVID-19 medical waste in the first phase. Constraints (11)–(12) register non-negativity and binary decision variables, respectively.

3.4. A tri-objective mixed-integer programming model for the second phase

Similarly, a tri-objective mixed-integer programming model for COVID-19 medical waste transport from MWTTCs to MWDCs in the second phase is constructed by Equations (13)–(24).

$$\min_{x^2_{jkm}, y^2_{jkm}} f^2_1 = \sum_{j\in J}\sum_{k\in K}\sum_{m\in M} \alpha^2_{jk} D^2_{jk} x^2_{jkm} \tag{13}$$

$$\min_{x^2_{jkm}, y^2_{jkm}} f^2_2 = \sum_{j\in J}\sum_{k\in K}\sum_{m\in M} \beta^2_{jk} D^2_{jk} x^2_{jkm} + \sum_{j\in J}\sum_{k\in K}\sum_{m\in M} \varepsilon^2 \gamma^2_{jkm} D^2_{jk} x^2_{jkm} \tag{14}$$

$$\max_{x^2_{jkm}, y^2_{jkm}} f^2_3 = \sum_{j\in J}\sum_{k\in K}\sum_{m\in M} \theta^2_{jk} D^2_{jk} x^2_{jkm} \tag{15}$$

$$s.t. \sum_{k\in K}\sum_{m\in M} x^2_{jkm} = \sum_{i\in I}\sum_{m\in M} x^1_{ijm} / \forall j \in J / \tag{16}$$

$$\sum_{j\in J}\sum_{m\in M} x^2_{jkm} \leq C^2_k / \forall k \in K / \tag{17}$$

$$\sum_{j\in J}\sum_{m\in M} x^2_{jkm} \geq \varphi^2_k C^2_k / \forall k \in K / \tag{18}$$

$$\sum_{j\in J}\sum_{k\in K} x^2_{jkm} \leq VC^2_m / \forall m \in M / \tag{19}$$

$$x^2_{jkm} \leq N y^2_{jkm} / \forall j \in J, k \in K, m \in M / \tag{20}$$

$$\frac{\sum_{m\in M} \alpha^2_{jk} D^2_{jk} x^2_{jkm}}{P^2_{jk}} \leq \eta^2_{jk} / \forall j \in J, k \in K / \tag{21}$$

$$\sum_{j\in J}\sum_{k\in K}\sum_{m\in M} \mu^2_{jkm} D^2_{jk} X^2_{jkm} \leq F^2 \tag{22}$$

$$x^2_{jkm} \geq 0 / \forall j \in J, k \in K, m \in M / \tag{23}$$

$$y^2_{jkm} = \{0, 1\} / \forall j \in J, k \in K, m \in M / \tag{24}$$

Herein, Equations (13)–(15) present sustainable objective functions of the second-phase COVID-19 medical waste transport to minimise total potential infection risks, minimise total environmental risks and maximise total economic benefits, respectively. Equations (16)–(24) give the corresponding constraints. Constraint (16) indicates the flow balance of COVID-19 medical waste transport for each MWTTC. The meaning of Constraints (17)–(24) is similar to that of Constraints (5)–(12) involved in the first-phase model, respectively. More details that can be found in subsection 3.3 are not presented to make it concise here.

4. Solution strategies for tackling a two-phase multi-objective optimisation model

In terms of the multi-objective optimisation model, several well-understood methods have been applied to deal with multiple objectives. For example, Liu and Guo (2014), Moreno et al. (2018) used the lexicographic optimisation approach to solve the multiple objectives in humanitarian logistics. Boostani et al. (2021), Janatyan et al. (2021), and Cao et al. (2022) devised a linear weighted sum method to cope with such an issue. In this paper, a hybrid strategy integrating a lexicographic optimisation approach and linear weighted sum method is proposed to observe the priority of sustainable objectives in different phases, obtain the COVID-19 medical waste transport scheme, and test the impacts of multiple phases and infection probability on computational results.

4.1. Lexicographic optimisation approach

The main idea of the lexicographic optimisation approach is to add the objective function with relatively higher priority to the constraints. In this regard, the priority of objectives plays an indispensable role in the results. Thus, the lexicographic optimisation approach to solve the two-phase COVID-19 medical waste transport optimisation model is presented as follows. Note that this paper introduces a tolerance coefficient σ to capture the actual situation that the ideal optimum of sustainable objectives is not always obtained in practice due to a series of inevitably uncertain factors, such as the bounded rationality of multiple decision entities, sudden emergencies, improper personnel operations, and equipment failure. It is an adjustment coefficient to make the trade-off among the social, environmental, and economic objectives of sustainability (Liu and Guo, 2014).

Step 1 This section supposes that the priority of sustainable objectives in the first and second phases is $f_1^1 \succ f_3^1 \succ f_2^1$, and $f_1^2 \succ f_3^2 \succ f_2^2$. A typical characteristic of a major public health incident is the infection risks. For each phase, social sustainability (f_1^1,f_1^2) measured by total potential infection risks is assigned to the highest priority when transporting COVID-19 medical waste. Although the COVID-19 pandemic belongs to one of the major public health incidents, logistics service providers responsible for handling medical waste are still benefit-seeking. Thus, economic sustainability or maximum economic benefits (f_3^1,f_3^2) is attached to the second priority. Finally, environmental sustainability measured by total environmental risks (f_2^1, f_2^2) is considered into the COVID-19 medical waste transport problem.

Step 2 Resolve the single-objective mixed-integer programming model, which is defined by f_1^1 and Constraints (4)–(12) by applying CPLEX solver, then the optimal objective function value is denoted by f_1^{1*}.

Step 3 Tackle the single-objective mixed-integer programming model, which is defined by f_3^1, Constraints (4)–(12), and $f_1^1 \le (1+\sigma)f_1^{1*}$. Thus, the optimal objective function value is denoted by f_3^{1*}.

Step 4 Solve the single-objective mixed-integer programming model, which is defined by f_2^1, Constraints (4)–(12), $f_1^1 \le (1+\sigma)f_1^{1*}$, and $f_3^1 \ge (1-\sigma)f_3^{1*}$. Thus, the optimal objective function value is denoted by f_2^{1*}. In this context, the value of all sustainable objective functions and a COVID-19 medical waste transport scheme between MWGAs and MWTTCs are obtained.

Step 5 According to Constraint (16), it can be concluded that the optimal solution x_{ijm}^{1*} in the first phase would be treated as the input parameter of the second-phase optimisation issue. Thus, the COVID-19 medical waste transport optimisation model in the second phase only includes two types of decision variables, i.e., x_{jkm}^2 and y_{jkm}^2. In this sense, f_1^{2*}, f_2^{2*}, f_3^{2*}, and the optimal COVID-19 medical waste transport scheme between MWTTCs and MWDCs can be obtained following **Step1** to **Step4.**

Step 6 Output objective function value of social, environmental, economic sustainability, and the COVID-19 medical waste transport scheme for the whole decision period.

4.2. Linear weighted sum method

To observe the impacts of multiple phases and infection probability on the results, the insights of Cao et al. (2021), Cao et al. (2022) are leveraged and extended to design a linear weighted sum method to tackle the two-phase medical waste transport optimisation issue. The specific procedure is given as follows.

Step 1 *Resolve the single-objective mixed-integer programming model in the first phase*

In the first phase, the solver such as CPLEX is used to resolve a single-objective mixed-integer programming model for COVID-19 medical waste transport to optimise social, environmental, or economic sustainability performance, which is described by Equations (25) and (4)-(12).

$$optimize\ (max\ \text{or}\ min)\ f_1^1\ \text{or}\ f_2^1\ \text{or}\ f_3^1 \tag{25}$$

constraints (4)–(12).

Thus, the maximum and minimum total potential infection risks, total environmental risks, and total economic benefits are denoted by $f_1^{1,max}$ and $f_1^{1,min}$, $f_2^{1,max}$ and $f_2^{1,min}$, $f_3^{1,max}$ and $f_3^{1,min}$, respectively.

Step 2 *Transform the original multi-objective optimisation model into a single-objective one*

Following the output in **Step 1** of this subsection, a linear weighted sum approach and a global criteria method are incorporated to covert the COVID-19 medical waste transport multi-objective mixed-integer programming model into a single-objective one, which is denoted by Equations (26) and (4)-(12).

$$min\ F = \omega_1^1\left(\frac{f_1^1 - f_1^{1,min}}{f_1^{1,max} - f_1^{1,min}}\right) + \omega_2^1\left(\frac{f_2^1 - f_2^{1,min}}{f_2^{1,max} - f_2^{1,min}}\right) + \omega_3^1\left(\frac{f_3^{1,max} - f_3^1}{f_3^{1,max} - f_3^{1,min}}\right) \tag{26}$$

constraints (4)–(12).

Wherein, ω_1^1, ω_2^1 and ω_3^1 respectively represent the importance of the social, environmental, and economic sustainability objectives when delivering COVID-19 medical waste in the first phase. Their values would be determined based on the preference of decision entities. In addition, it should satisfy $\omega_1^1 + \omega_2^1 + \omega_3^1 = 1$.

Step 3 *Tackle the reformulated single-objective optimisation model*

In this context, CPLEX solver is also applied to tackle the reformulated single-objective mixed-integer programming model for COVID-19 medical waste transport, which is similar to **Step 1** of this subsection. Finally, the best transport scheme from MWGAs to MWTTCs (x_{ijm}^{1*}; y_{ijm}^{1*}), and the corresponding objective function values (f_1^{1*}, f_2^{1*}, f_3^{1*}) can be achieved.

Step 4 *Solve the single-objective mixed-integer programming model in the second phase and output the results*

In this step, the amount of COVID-19 medical waste transported by vehicle m from MWGA i to MWTTC j (x_{ijm}^{1*}) is regarded as the input parameter of the second-phase optimisation model. Thus, x_{ijm}^{2*}, y_{ijm}^{2*}, f_1^{2*}, f_2^{2*}, f_3^{2*} can be obtained by following the operations in **Step 1** to **Step 3** of this subsection.

5. Case study

5.1. Case study from Chongqing during the COVID-19 pandemic

This section investigates a case study from Chongqing to provide an effective medical waste transport strategy in the COVID-19 pandemic at the beginning of 2021. The goals are to observe the priority of social, environmental, and economic sustainability objectives, obtain the COVID-19 medical waste transport scheme, and test the influences of multiple phases and infection probability on results. As shown in Fig. 2, it intuitively presents the deployment of Chongqing's districts and the facilities regarding COVID-19 medical waste clean-up activities.

According to the Chongqing Municipal Health Commission, 174 fever clinics located in various districts are set as emergency healthcare facilities, which are regarded as COVID-19 medical waste generation areas (MWGAs) in this paper. In this sense, the amount of COVID-19 medical waste in 41 districts of Chongqing depends on the above-mentioned sources, which can be estimated by the number of hospital beds and the generation coefficient of medical waste. The following equation calculates COVID-19 medical waste generation mass.

$$Q = \rho \cdot H \tag{27}$$

Wherein, Q represents the amount of COVID-19 medical waste. ρ indicates the generation coefficient of COVID-19 medical waste, which can be assumed as 0.4 based on the studies of Cheng et al. (2009) and Komilis et al. (2012). H is the number of hospital beds, which is from the official public information on the hospital's website. Thus, the amount of COVID-19 medical waste generated in each district can be predicted by Equation (27), which can be found in Table A1 in Appendix A.

All information is summarised based on the news and published statistics in terms of MWTTCs and MWDCs. For the former, Chongqing has set up MWTTCs that can temporarily store infectious medical waste in 13 districts, and the corresponding maximum capacity is shown in Table A2 in Appendix A. Regarding MWDCs, the four disposal centres with the license or qualification to handle COVID-19 medical waste are in Beibei, Bishan, Changshou, and Jiangbei districts. Their maximum capacity can be seen in Table A3 in Appendix A. In addition, transport distance and population in the two phases are depicted in Table A4-A7 in Appendix A. The distance between the two facilities is obtained from Baidu Map. The population on transport routes are collected based on Chongqing Statistics Bureau (http://tjj.cq.gov.cn/). Regarding infection probability, since COVID-19 medical waste transport activities in the first phase are usually occurred in areas with a relatively high population density, it is defined as $\alpha^1_{ij} = 0.5$. However, infection risks caused by the transport activities in the second phase are relatively low because MWDCs are often located in sparsely populated areas. It is thus denoted as $\alpha^2_{jk} = 0.2$. The potential risks on environment caused by accidents during transport activities are set as $\beta^1_{ij} \in [0,1]$, and $\beta^1_{jk} \in [0,1]$. According to the type of medical waste transport vehicles, carbon emission is considered as $\gamma^1_{ijm} \in [0,1]$, and ,$\gamma^2_{jkm} \in [0,1]$. The preference of decision entities for infection risks for each person in the first and second phases is 0.00003 and 0.0002, respectively. The service level of MWTTCs and MWDCs is $\varphi^1_j = 0.4$, and $\varphi^2_k = 0.3$, respectively. The risk coefficient of carbon emissions in the first and second phases is $\varepsilon^1 = \varepsilon^2 = 0.5$. In addition, unit economic benefit in *yuan* obtained from the first- and second-phase transport activities is $\theta^1_{ij} \in [5,20]$, and $\theta^2_{jk} \in [5,18]$. Unit transport cost in *yuan* in the first and second phases is $\mu^1_{ijm} \in [13,20]$, and $\mu^2_{jkm} \in [13,20]$. Total budget in *yuan* for the first- and second-phase transport activities is $F^1 = 4 \times 10^4$, and $F^2 = 7 \times 10^4$. Let the sufficiently large positive constant $N = 1 \times 10^9$. Finally, there are three types of medical waste transport vehicles, i.e., 1 ton, 5 tons, and 10 tons, with the number of 8 vehicles (namely 1~8), 4 vehicles (namely 9~12), and 2 vehicles (namely 13~14), respectively. In addition, all experiments are implemented by CPLEX (12.9.0) solver on a computer with a 1.8 GHz 64-bit Core (TM) i5-8265U CPU under Windows 10 Professional.

5.2. Priority of sustainable objectives from society, environment, and economy

It should be acknowledged that the holistic optimisation of achieving social, environmental, and economic sustainable objectives in the two-phase COVID-19 medical waste transport problem is critical but challenging. To tackle it, the lexicographic optimisation approach is used to determine the priority of the three objectives in each phase of the subsequent research. Note that the tolerance coefficient is set as $\sigma \in [0, 0.5]$ because the goals are always affected by various factors, and it is difficult to reach the optimal solution in practice. Specifically, there are 6 scenarios to indicate different social, environmental, and economic

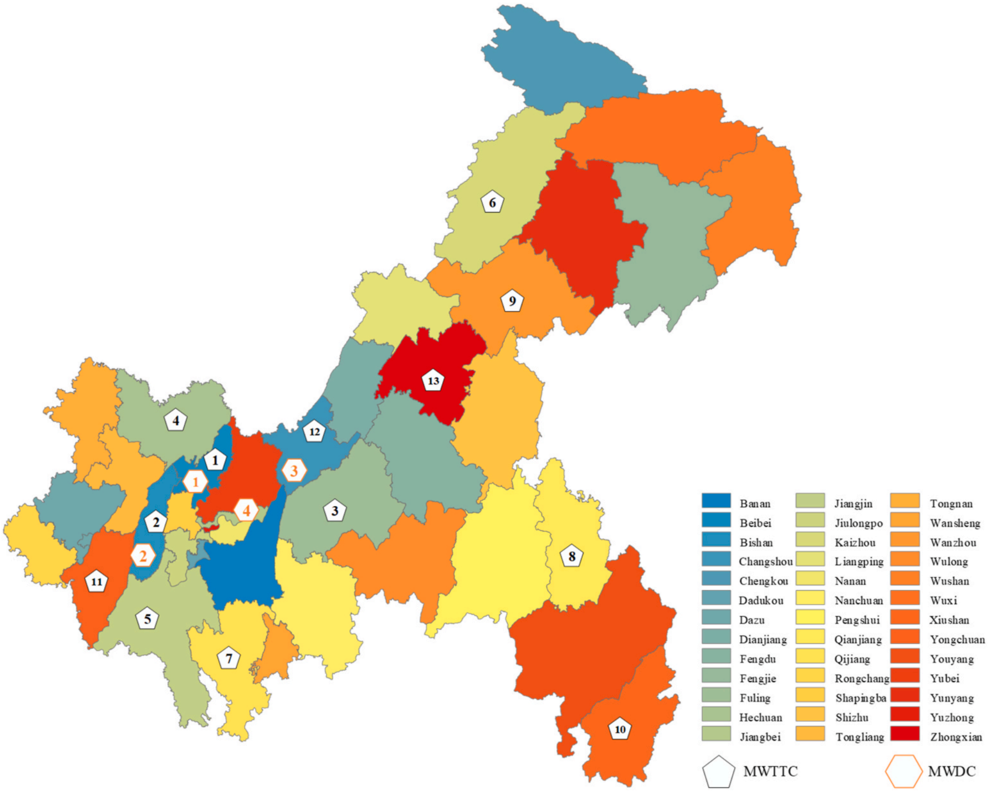


Fig. 2. Deployment of districts and related facilities in Chongqing.

priorities for each phase, thus obtaining 36 scenarios for the whole decision period in total. The specific meaning of these scenarios can be found in Table A8 in Appendix A. On the other hand, the tolerance coefficient can be discretely subdivided into 6 cases. That is, $\sigma = 0, 0.1, 0.2, 0.3, 0.4, 0.5$. In this context, 36 × 6 combined cases are furnished to observe the impacts of the tolerance coefficient and priority of sustainable objectives on computational results. Finally, this section presents 56 cases in total, which is depicted in Table 2. Note that computational results are the same when $\sigma = 0.4, 0.5$, thus presenting only those with $\sigma = 0.4$.

To evaluate the results under different cases, this section leverages the idea and insight of Moreno et al. (2018) and Cao et al. (2018) to construct an indicator (i.e., *Gap*). The *Gap* is introduced to measure the deviation between sustainable objective function value and the corresponding best one among all cases. The *Gap* can be calculated by Equations (28) and (29).

$$Gap = \frac{OBJ_{f_i} - BEST}{BEST} \times 100\% \tag{28}$$

$$Gap = \frac{BEST - OBJ_{f_i}}{BEST} \times 100\% \tag{29}$$

Equations (28) and (29) are suitable for the optimisation model with the minimisation and maximisation cases, respectively. OBJ_{f_i} denotes the sum of the optimal value of objective function i for the whole decision period by using a lexicographic optimisation approach. *BEST* represents the best one of 56 combined cases for each OBJ_{f_i}. Computational results and the *Gap* under 56 combined cases are depicted in Table A9 in Appendix A. In particular, Fig. 3 gives the total *Gap* of all sustainable objectives.

Several remarks can be concluded based on the results in Table A9 and Fig. 3. Firstly, it is evident that the overall sustainable performance is poor when the tolerance coefficient is 0, which is reflected in the high infection and environmental risks, low economic benefits, and large fluctuation of *Gap*. In other words, it is detrimental to the overall performance of COVID-19 medical waste transport activities if decision entities only put one goal as the top priority and ignore other objectives from a holistic standpoint. Secondly, when the tolerance coefficient is increased to 0.3, the priority of sustainable objectives is interchangeable and ambiguous in the first and second phases of the COVID-19 medical waste transport network. Thirdly, when the tolerance coefficient gradually increases from 0.4 to 0.5, a similar tendency concerning all sustainable objectives is observed in the two phases. That demonstrates that the intervention measures of decision entities exert no significant influence on COVID-19 medical waste transport activities. Finally, when the tolerance coefficient is 0.1 and 0.2, the priority of sustainability objectives can be clearly identified for each phase. However, there is a better overall sustainability performance and less fluctuation of *Gap* when the tolerance coefficient is 0.2 relative to 0.1.

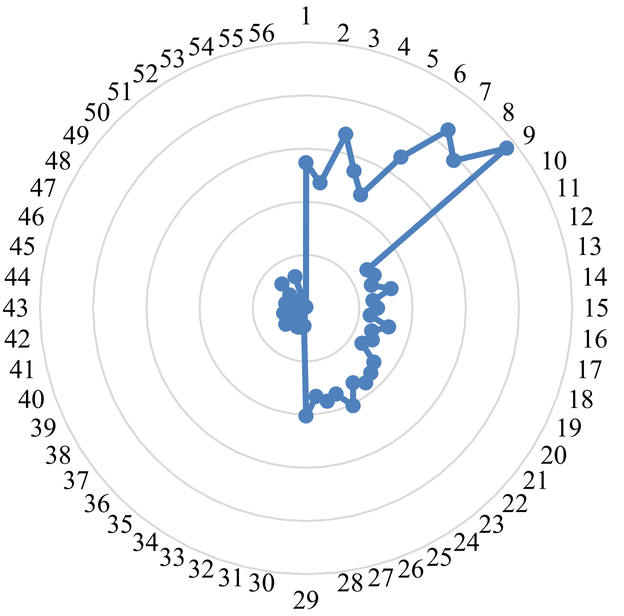


Fig. 3. Total *Gap* regarding three sustainable objectives for the whole decision period.

To summarise, global thinking of simultaneously considering multiple sustainable objectives is favourable for the decision-making of the local and upper-level authorities in COVID-19 medical waste transport activities. The fact that an appropriate tolerance coefficient (0.2) is conducive to improving the overall performance of COVID-19 medical waste transport shows strong support for the above viewpoint. In this context, the tolerance coefficient equals 0.2 in the following experiments except for the otherwise specified. Besides, Fig. 3 demonstrates a stable trend for all objectives under such a parameter setting. Consequently, case No.35 is regarded as the optimal scheme to transport COVID-19 medical waste, which denotes the priority of different objectives as social, economic, and environmental sustainability. The conclusion of prioritizing social sustainability objectives is also supported by Liu and Guo (2014), Laguna-Salvadó et al. (2019), and Boostani et al. (2021). It can be explained that once an accident occurs and the contaminated medical waste is exposed in transport activities, it would result in a severe and large-scale novel coronavirus transmission with considerable threats to society and residents. Then, for contractors (such as environmental protection companies), such large-scale medical waste clean-up activities require fund support. Thus, economic sustainability is treated as the second priority. Finally, when delivering COVID-19 medical waste, the carbon dioxide released and accidents would cause irreversible damage to the ecological environment.

Table 2

Combined cases of different scenarios and tolerance coefficients.

No.	σ	Scenarios	No.	σ	Scenarios	No.	σ	Scenarios	No.	σ	Scenarios
1	0	1,2,7,8	15	0.1	8	29	0.1	35,36	43	0.2	26
2	0	3,4,9,10	16	0.1	10	30	0.2	1,3,13,15	44	0.2	28
3	0	5,6,11,12	17	0.1	11,12	31	0.2	2,14	45	0.2	29,30
4	0	13,14,19,20	18	0.1	19,21	32	0.2	4,16	46	0.2	31,33
5	0	15,16,21,22	19	0.1	20	33	0.2	5,6,17,18	47	0.2	32
6	0	17,18,23,24	20	0.1	22	34	0.2	7,9	48	0.2	34
7	0	25,26,31,32	21	0.1	23,24	35	0.2	8	49	0.2	35,36
8	0	27,28,33,34	22	0.1	25,27	36	0.2	10	50	0.3	1-6,13-18
9	0	29,30,35,36	23	0.1	26	37	0.2	11,12	51	0.3	7-12,25-30
10	0.1	1,3,13,15	24	0.1	28	38	0.2	19,21	52	0.3	19–24
11	0.1	2,14	25	0.1	29,30	39	0.2	20	53	0.3	31–36
12	0.1	4,16	26	0.1	31,33	40	0.2	22	54	0.4	1-6,13-18
13	0.1	5,6,17,18	27	0.1	32	41	0.2	23,24	55	0.4	7-12,25-30
14	0.1	7,9	28	0.1	34	42	0.2	25,27	56	0.4	19-24,31-36

Environmental objective relative to social and economic one shows a relatively lower priority due to the need for reducing infection risks and boosting the economy in the early stage of 2021.

5.3. Optimal scheme obtained by a lexicographic optimisation approach

According to the conclusion in subsection 5.2, given the priority of sustainable objectives (society $\succ$ economy$\succ$ environment), the two-phase COVID-19 medical waste transport scheme and the corresponding objective function values can be obtained, which are depicted in Fig. 4.

According to Fig. 4, the following remarkable conclusions can be summarised. Firstly, the minimum total potential infection risks, maximum total economic benefits, and minimum total environmental risks regarding COVID-19 medical waste transport in the first phase are 896, 39680, and 943, respectively. In the second phase, social, economic, and environmental sustainability performance is 662, 48077, and 2464, respectively. Secondly, it implies that the type of available vehicles imposes indispensable impacts on the COVID-19 medical waste transport strategy. In terms of the small-capacity vehicles marked by 1–8, the less-than-carload transport strategy is desirable, which indicates the potential advantages of flexible and convenient transport for a fraction of COVID-19 medical waste. Regarding the large-capacity vehicles labelled by 9–14, a full truck-loading transport strategy is encouraged to improve efficiency and save costs. Thirdly, for long-distance transport activities, multi-type vehicles with both small- and large-capacity are recommended to alternate the adoption of only large-capacity vehicles. The main reason is that small-capacity vehicles usually have a relatively low energy consumption. After the outbreak of the COVID-19 pandemic, sometimes medical waste clean-up is batch shipping in some areas. Both are conducive to achieving better social, economic, and environmental sustainability when the related workers deliver COVID-19 medical waste. Fourthly, it furnishes decision entities with constructive guidelines concerning the capacity building and deployment of MWTTCs and MWDCs (Tirkolaee et al., 2021). For instance, Fig. 4 demonstrates that Beibei transfer centre (MWTTC 1) and Beibei medical waste disposal centre (MWDC 1) have undertaken the main tasks of transferring and disposing of COVID-19 medical waste, which is attributed to their large capacity and superior geographical locations.

5.4. Computational results in the context of single- and two-phase transport

Studies indicated that decision modes spanned single- and multi-period, single- and multi-phase, and others in handling COVID-19 medical waste. As above mentioned, the existing studies concentrated on single and multi-period medical waste decision-making. In this subsection, the influences of multiple phases on computational results are tested by a linear weighted sum method, as depicted in Table 3. Such action highlights the motivation to focus on a two-phase COVID-19 medical waste transport network. The *Gap* can be estimated by a similar approach to Equations (28) and (29). Let $\omega_1^1 = \omega_1^2 = 0.5$, $\omega_2^1 = \omega_2^2 = 0.1$, and $\omega_3^1 = \omega_3^2 = 0.4$ based on the priority of sustainable objectives identified in subsection 5.2.

According to Table 3, although total economic benefits obtained by the single-phase decision model outperform those obtained by the two-phase optimisation model by 21.25%, both total potential infection and environmental risks in the context of two-phase transport are prior to those under single-phase one with 30.13%. Overall, the two-phase decision mode is superior to the single-phase one from a global standpoint, which embraces the motivation of the topic discussed in this paper. Secondly, for the single-phase COVID-19 medical waste transport optimisation problem, since it would need to cope with more uncertainties, available resources such as transfer and disposal facilities are very limited, and it is hard to completely control such a large-scale reverse logistics supply chain network, a worse social and environmental sustainability performance is achieved. In terms of two-phase COVID-19 medical waste clean-up activities, some facilities outside cities with a low population density are available because there are usually multiple decision entities. Thus, long-distance transport creates more economic benefits based on the economic sustainability objective function setting. Thirdly, although total economic benefits obtained by a single-phase model are better than those by a two-phase one, it does not mean it would work well in practice. The main reason is that the main goal is to control novel coronavirus transmission rather than make money during the COVID-19 pandemic. Fourthly, for major public health incidents such as the COVID-19 pandemic, a decentralised medical waste transport network is preferred at the province or state, country, and internation level. A centralised decision mode may be better for dealing with small-scale incidents and designing the sub-network of COVID-19 medical waste transport at the community, municipality, and county levels (Cao et al., 2018).

5.5. Impacts of infection probability on computational results

The above three subsections implement the experiments with a given infection probability. However, it is difficult to accurately predict infection probability due to various factors in the COVID-19 pandemic. Therefore, this subsection intends to further test the influences of infection probability on results by using a linear weighted sum method. Note that infection probability is subdivided into 10 points from 0.1 to 1. The weights of sustainable objectives in the first and second phases are the same as those in subsection 5.4. In this context, the impacts of infection probability on sustainable objectives of two-phase COVID-19 medical waste transport are depicted in Fig. 5. The horizontal coordinate represents infection probability in the second phase, the vertical coordinate is the value of sustainable objective functions, while the legend denotes the first-phase infection probability. In addition, the details corresponding to Fig. 5(a)-(c) are shown in Table A10 in Appendix A.

According to the results depicted in Fig. 5(a) and (b), when infection probability increases from 0.1 to 0.4, social sustainability performance always demonstrates an ascending tendency, yet environmental sustainability performance stands still. Studies indicate that more attention should be attached to total potential infection risks in transporting COVID-19 medical waste even though the infection probability is relatively lower. Both total potential infection risks and total environmental risks present a soaring trend when infection probability is within the interval [0.5, 1.0]. It can be inferred that if infection probability is more than a threshold, it would also impose significant influences on the environmental objective of the COVID-19 medical waste transport scheme. Therefore, whatever the infection probability is, total potential infection risks are always the focus of handling COVID-19 medical waste for the whole system, which is supported by Kargar et al. (2020). However, the consideration of the environmental sustainability aspect depends on the magnitude of infection probability via contaminated medical waste.

Computational results in Fig. 5(a) and (c) demonstrate that potential infection risks increase when infection probability changes from 0.1 to 1.0. However, total economic benefits remain a favourable point at interval [0.1, 0.3], then decrease from 0.4. It is evident that more efforts (e.g., investment in human, financial, and material resources for COVID-19 medical waste transport activities) need to be made to cope with the unexpected issues caused by a relatively higher infection probability, thus further combating the COVID-19 pandemic. Overall, minimum total potential infection risks relative to maximum total economic benefits are still the most important concern for delivering COVID-19 medical waste (Yu et al., 2020a), which further highlights the conclusion in subsection 5.2.

In summary, total potential infection risks show a sharply increasing trend when infection probability goes from 0.1 to 1, while total

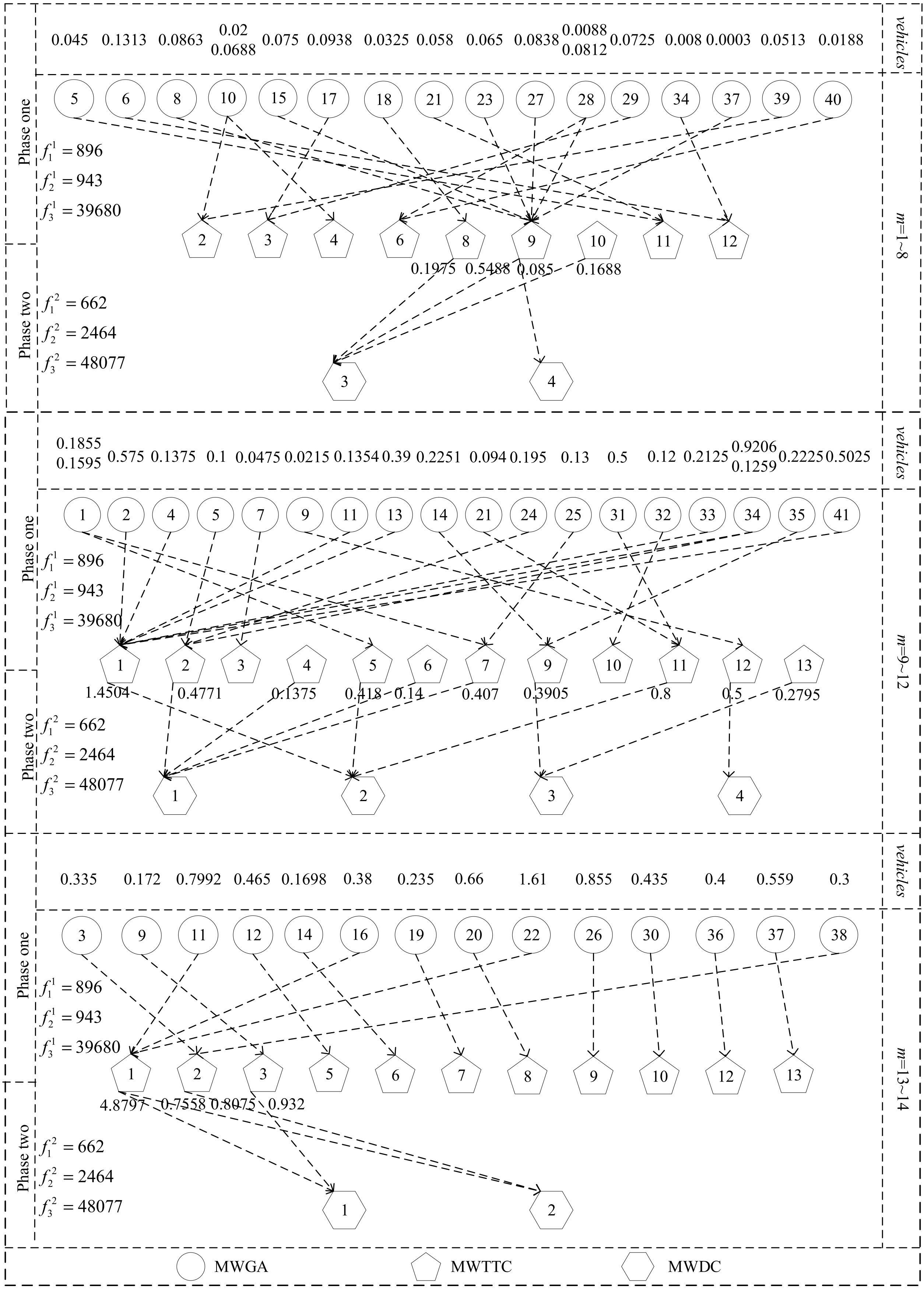
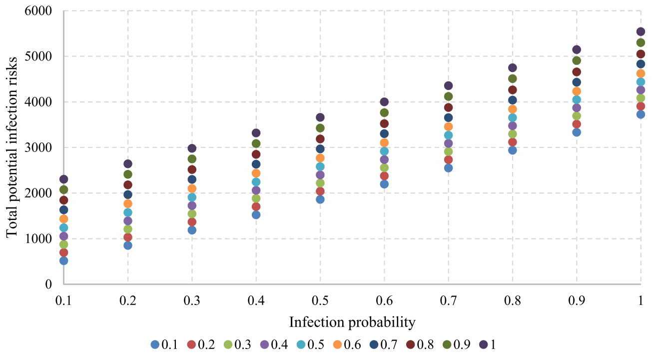


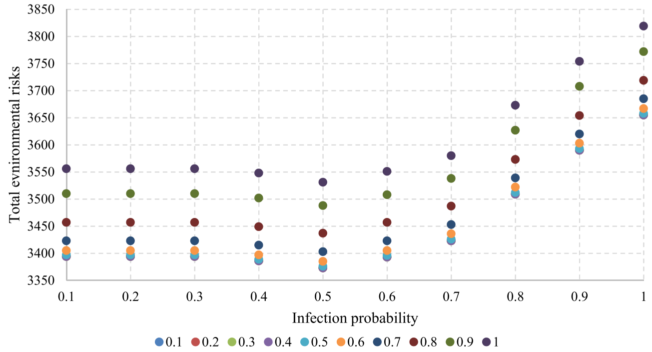
Fig. 4. Optimal scheme regarding two-phase COVID-19 medical waste transport.

Table 3
Computational results under single- and two-phase decision.

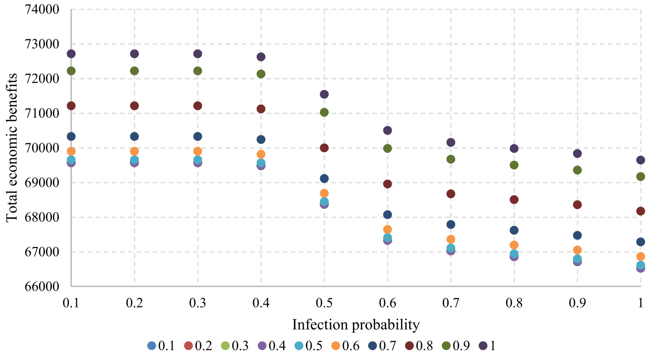
Decision mode	f_1	f_2	f_3	Gap_1	Gap_2	Gap_3	Total
Single-phase	1798	3932	88458	14.38%	15.75%	0%	30.13%
Two-Phase	1572	3397	69657	0%	0%	21.25%	21.25%



(a) Social sustainability performance



(b) Environmental sustainability performance



(c) Economic sustainability performance

Fig. 5. Impacts of infection probability on sustainability performance.

environmental risks and economic benefits present slight fluctuations. Obviously, the fluctuation of infection probability exerts significant impacts on the sustainability performance of society, which encourages decision entities to make risk prevention measures concerning COVID-19 medical waste transport. For example, specialised equipment to store and dispose of medical waste, personal protective equipment, and strict disposal procedure is required to handle those contaminated COVID-19 medical waste. In addition, to curb novel coronavirus transmission, both tightening home quarantine and keeping social distance are implemented during the COVID-19 pandemic (Bertsimas et al., 2022). When infection probability is more than a certain threshold, importance should be attached to environmental and economic aspects of sustainability.

6. Conclusions

This section concludes the key findings, provides implications for theory and practice, and presents the limitations and future studies.

6.1. Summary of key conclusions

The focus of this paper is to design a two-phase COVID-19 medical waste transport network with the concern of multi-type vehicle selection, sustainability, infection probability, preference of decision entities to minimum service level and infection risks, budget, and multiple generation areas and disposal centres. A multi-objective optimisation approach is used to model this problem with the goal of optimising social, economic, and environmental sustainability performance. In addition, a hybrid solution strategy is devised to tackle the multi-objective mixed-integer programming model. Finally, a real-world case from Chongqing is used to illustrate the proposed methodology.

Results demonstrate when making an operational decision on COVID-19 medical waste transport, the priority of the pursuing objectives is recommended as social, economic, and environmental sustainability. The adoption of a multi-type vehicle is conducive to achieving better social, environmental, and economic sustainability performance. In the context of the COVID-19 pandemic, a decentralised medical waste transport network is preferred at the province or state, country, and inter-nation levels. Whatever the infection probability is, infection risks are the most important goal in the COVID-19 medical waste clean-up activities. The environmental and economic aspects of sustainability also should be a concern when infection probability is more than a certain threshold.

6.2. Implications for theory and practice

Several managerial insights are presented from a theory standpoint.

Firstly, this paper links sustainability thinking, multi-objective and two-phase optimisation theory with the COVID-19 medical waste transport problem to decrease potential infection risks, reduce environmental risks, and increase economic benefits from a holistic perspective.

Secondly, infection risks, environmental risks, and economic benefits are applied to measure social, environmental, and economic sustainability, which enriches the existing indicators to quantify sustainability considered in COVID-19 medical waste transport activities, even in sustainable humanitarian supply chains.

Thirdly, the conclusions pertaining to the priority of sustainable objectives, multi-type vehicle selection, and the impacts of multi-phase and infection probability on results fill the gaps in the field of COVID-19 medical waste management from the viewpoint of theory.

The following implications are given to practitioners or policymakers.

Firstly, differing from other optimisation issues in the reverse logistics supply chain, decision entities (e.g., public health authorities) should always attach the highest priority to the social objective of sustainability, i.e., total potential infection risks for COVID-19 medical waste transport problem due to the inherent nature of the COVID-19 pandemic. In terms of the environmental and economic objective of sustainability, although there is a definite priority in this paper, it is interchangeable due to many factors (e.g., preference of policymakers, current situation on the evolution of the pandemic) in practice.

Secondly, decision entities could achieve the trade-off of the social, environmental, and economic objectives of sustainability by adjusting the minimum service level, potential infection risk level, and tolerance coefficient.

Thirdly, this paper uses a lexicographic optimisation approach with a tolerance coefficient to identify the priority of sustainable objectives in the first and second phases. In addition, a linear weighted sum method is applied to observe the impacts of multi-phase and infection probability on the results. Such action encourages decision entities or policymakers to tackle the COVID-19 medical waste transport optimisation problem by using an integrated approach, thus improving sustainability performance from a systematic standpoint.

Fourthly, the sustainability indicators, optimisation model, and integrated approach could be simultaneously embedded to develop commercial software as a decision tool, thus assisting decision entities (e.g., public health authorities) in making operational decisions on COVID-19 medical waste transport and combating the COVID-19 pandemic.

Fifthly, although this paper only applies Chongqing as a real-world case to illustrate the proposed methodology, decision entities still could make the COVID-19 medical waste transport scheme for other cities by updating the value of input parameters in two-phase transport network consisting of MWGAs, MWTTCs, and MWDCs.

6.3. Limitations and future studies

Future studies can be extended from the following aspects. Firstly, a series of uncertainties in the amount of medical waste, costs, and infection probability can be further incorporated into the two-phase COVID-19 medical waste transport issue by using the robust optimisation approach (Gao et al., 2022). Secondly, a multi-objective optimisation approach is applied to capture horizontal relations among stakeholders in medical waste transport activities, yet how to use bi-level optimisation theory to characterise hierarchical relations and how to use game theory to investigate the collaboration mechanism of the stakeholders is a promising issue in the future (Valizadeh et al., 2021a; Prakash et al., 2022). Thirdly, it is reported that both locations of the critical facilities and emergency personnel allocation play an indispensable role in the performance of reverse logistics supply chains. Joint decisions concerning the location and transport of medical waste, and healthcare team allocation in the context of the COVID-19 pandemic need to be further studied (Wang et al., 2018; Tirkolaee et al., 2021). Fourthly, this paper only considers a transport network including MWGAs, MWTTCs, and MWDCs, the following work would incorporate the route of COVID-19 medical waste being directly transported to the MWDCs into the above issue. Fifthly, although sustainability thinking is incorporated into COVID-19 medical waste transport, how to use digital technologies such as digital twin and blockchain to study such issues remains an open question (Dubey et al., 2020).

CRediT authorship contribution statement

Cejun Cao: Supervision, Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Yuting Xie:** Methodology, Software, Writing – original draft. **Yang Liu:** Supervision, Validation, Writing – review & editing. **Jiahui Liu:** Methodology, Writing – review & editing. **Fanshun Zhang:** Conceptualization, Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is available in the supplementary file.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.135985.

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