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A bi-objective location-routing problem for infectious waste reverse logistics during a pandemic

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Abstract: The correct recycling and disposal of medical waste has become increasingly important in society. Especially during the pandemic, the generation of infectious medical waste has shown explosive growth. Therefore, timely and safe collection and disposal have become a key point in the pandemic. This study considers a list of novel infectious waste management measures to face the pandemic, including setting up temporary transfer stations, applying movable disposal facilities, and using emergency disposal centers. With this in mind, this study develops a bi-objective location-routing model for the collection and transportation of infectious medical waste during the pandemic. Linearization of the nonlinear terms in the model is conducted, and the bi-objective model is transformed into a single-objective optimization model using the augmented ε-constraint method (AUGMECON), which is then solved by the CPLEX optimization solver. By analysing the trade-off curve between cost and risk during the pandemic, it is concluded that the solution in the sixth to seventh iteration is Pareto optimal. In summary, this study proposes a comprehensive framework for optimizing the collection and transportation of infectious medical waste during the pandemic and provides an effective solution to this important problem.

1. Introduction

Pandemic, which crosses internationally and affects a large number of people, is defined as an epidemic occurring worldwide or over a very wide area and going beyond the normal expectancy according to the World Health Organization(WHO)[1]. In human history, various pandemics have accompanied the development of human society. From the past smallpox and pestis to the present H1N1 influenza virus, Ebola, and COVID-19, those pandemics all impact the safety of human people, economic growth as well as social order[2]. The pandemic also impacts the healthcare waste management system. In general, about 85% of the total amount of waste generated by health-care activities is considered to be general. The remaining 15% is considered hazardous material that may be infectious, toxic, or radioactive. Specifically, infectious waste covers a diverse range of materials, including waste contaminated with blood and other bodily fluids (e.g. from discarded diagnostic samples), cultures and stocks of infectious agents from laboratory work (e.g. waste from autopsies and infected animals from laboratories), or waste from patients with infections (e.g. swabs, bandages, and disposable medical device[3]. The existing healthcare waste management system is facing a big challenge. Firstly, the substantial infectious waste exceeds the capacity of the management system. Take the COVID-19 pandemic as an example, though only 10-15% of healthcare waste typically generated from health service provision is infectious waste, many facilities and countries classified 100% of COVID-19 healthcare waste as infectious waste during the pandemic[4]. What has made the situation even worse is the sources of infectious medical waste have become more widespread. It improves the difficulty of collecting in the healthcare waste management system. To solve those problems, we need a cost-efficient and eco-friendly logistics system that can dispose of huge amounts of infectious and collect the waste timely.

As for infectious waste management, infectious waste disposal has three basic steps: collection in healthcare facilities, transport to treatment facilities, and final treatment and disposal[5]. Infectious waste transportation involves the transportation and management of waste generated within healthcare facilities to designated treatment locations[6]. Therefore, the location-routing problem becomes the key problem of infectious waste management. As for the location-routing problem of hazardous waste, Revelle et al. developed the first multi-objective location-routing model for nuclear waste[7]. As for the research in the field of infectious waste, Shih and Lin solved the routing and scheduling problem for Taiwan's infectious waste management system[8]. Nolz et al. designed a new collection system for infectious waste. They developed a mathematical model with two conflicting objective functions, cost objectives, and social objectives[9]. In recent years, especially after the COVID-19 crisis, more and more scholars focused on the location-routing problem of infectious waste during a pandemic. Zhao et al. developed a bi-objective location-routing model considering infectious waste collection, transportation, treatment, and final disposal. The model was applied in the case of the WuHan COVID-19 pandemic[10]. Tirkolaee et al. developed a new MTLRP-TW model for infectious waste management systems during the COVID-19 outbreak[11]. Govindan et al. developed a bi-objective MLP model considering cost objective as well as risk objective. They considered a lot of realistic situations including green VRPTW and vehicle failure, and applied a fuzzy goal programming approach to solve the model[12]. Despite the previous efforts[13][14], there still exists an insufficient quantity of research on infectious waste LRP during a pandemic. There are only three papers that consider both location decisions and routing decisions. To bridge this gap, we considered a new situation based on the management characteristics of infectious waste during a pandemic.

The contribution of this paper is tripartite. First, we considered a new emergency condition of a pandemic. Because the amount of infectious waste generated during the epidemic far exceeds the disposal capacity of existing infectious waste disposal systems, many emergency infectious waste disposal technologies are used to face the pandemic, including movable disposal technologies and collaborative disposal technologies[15]. Thus, the existing infectious waste management system adopts some temporary measures during a pandemic, including transforming the regular facilities into ones that can collect and dispose of infectious waste and applying movable disposal facilities in situ disposal. Second, we developed a bi-objective location-routing model. The model considered both the cost of the infectious waste disposal systems and the risk of facilities and paths. Third, we apply an augmented ε-constraint (AUGMECON) algorithm to deal with a bi-objective model as the methodological contribution of this study. Moreover, we apply the model to a real-world case of Chenghua district, Chengdu during the COVID-19 pandemic.

The article structure is as follows: After an overview of the background and the relevant literature in Section 1, the problem description is provided in Section 2. For the major component of this research, Section 3 constructs a novel bi-objective LRP model. Section 3 also expounds AEC algorithm that we used to solve the model. A realistic case study of Chenghua district, Chengdu is reported in Section 4, Finally, Section 5 provides the concluding remarks and future research directions.

2. Problem Description

Our study tries to describe a new status during a pandemic. Due to the significant danger of infectious waste, we consider not only the total cost as well as the risk in each step of disposal. Particularly, we also consider the amount of infectious exceeds the bottleneck of the infectious disposal system. Under such circumstances, we reform the existing infectious waste management system during a pandemic. The novel system divides the waste generation node into small infectious waste generation nodes and large infectious waste generation nodes. It also takes some temporary measures including temporary transfer stations and movable disposal facilities into account. The measures assist the system in disposing of infectious waste timely and entirely.

The two-echelon logistics network proposed has three layers. The first layer is a small infectious waste generation node (eg. clinics, nuclein testing points, etc.), and the infectious waste generated is collected by collection vehicles to temporary transfer stations or large medical waste generation nodes for temporary storage; The second layer is composed of temporary transfer stations and large medical waste generation nodes. The generated infectious waste collected from small infectious waste generation nodes is transported by transportation vehicles to the disposal center for centralized disposal. The third layer is a professional disposal center and an emergency coordination disposal center (eg. garbage incineration plants and cement kilns) in the face of major epidemics, responsible for the centralized disposal of medical waste transported. In addition, to cope with the insufficient transportation and disposal capacity during the extremely serious epidemic, movable infectious waste disposal facilities are introduced, which are dispatched by the medical waste disposal center to the second layer for disposal, without the necessary transportation to the disposal center for centralized disposal. The proposed infectious waste logistics network is shown in the Figure 1.

The proposed model takes a range of realistic aspects into account, including facility capacity and vehicle capacity. The model simultaneously optimizes economic and risk objectives. The decisions of the model involve (1) the location of the temporary transfer station and the emergency coordination disposal center; (2) the location of movable disposal facilities; (3) the routes of both collection vehicles and transportation vehicles.

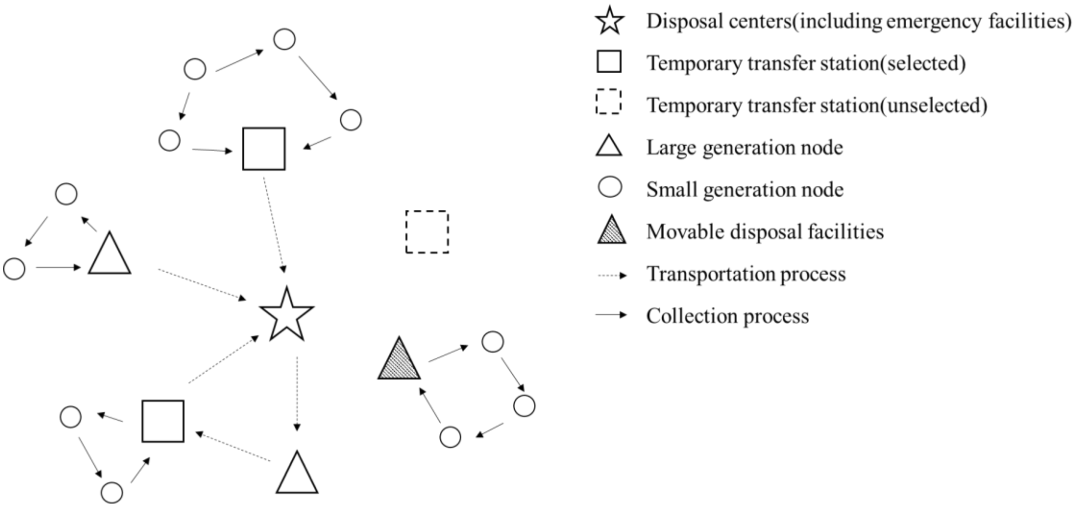

Figure 1: Logistics network of infectious waste disposal system.

3. Mathematical Model and Algorithm

In this section, we first introduce notation, and then develop the bi-objective mathematical model of infectious during a pandemic. At last, we provide an efficient solution to solve the bi-objective model.

3.1. Notation

The following sets, parameters, and decision variables used in our mathematical model are shown in Table 1.

Table 1: Notation.

Sets	
$G(V,E)$	The network G with vertex set V and edge set E, where $V = S \cup L \cup T \cup D^* \cup D$
S	Sets of small infectious waste generation nodes
L	Sets of large infectious waste generation nodes
T	Sets of temporary transfer nodes
D^*	Sets of existing disposal center
D	Sets of temporary disposal centers
V_2	Sets of the second layer nodes, $V_2 = L \cup T$
V_3	Sets of the third layer nodes, $V_3 = D \cup D^*$
K	Sets of collection vehicles
H	Sets of transportation vehicles
Parameters	
g_i	The amount of infectious waste generated in node $i \in S \cup L$
d_{ij}	The distance between node $i \in V$ and node $j \in V$
FCT_i	The fixed cost of selecting node $i \in T$ as the temporary transfer station
VCT_i	The variable cost of storing one unit of infectious waste at temporary transfer station $i \in T$
QT_i	The capacity of temporary transfer station $i \in T$
FCM	The fixed cost of using a movable disposal facility
VCM	The variable cost of disposing one unit of infectious waste at movable disposal facilities
MT	The capacity of a movable disposal facility
QL_i	The capacity of large infectious waste generation node $i \in L$
$VCLG_i$	The variable cost of storing one unit of infectious waste at large generation node $i \in L$
FCD_i	The fixed cost of opening the temporary disposal center $i \in D$
VCD_i	The variable cost of disposing one unit of infectious waste in the disposal center $i \in D^* \cup D$
QD_i	The capacity of disposal center $i \in D^* \cup D$
CCV	The transportation cost per kilometer for collecting infectious waste
TCV	The transportation cost per kilometer for transporting infectious waste
FCV_c	The fixed cost for a collection vehicle

FCV_t	The fixed cost for a transportation vehicle
QVC	The capacity of a collection vehicle
QVT	The capacity of a transportation vehicle
POP_i	The population around the node $i \in V$
POP_{ij}	The population on the path $(i, j) \in E$
n	The amount of movable disposal facilities
Decision variable	
z_i	1, if select node $i \in T$ as the temporary transfer station; 0, otherwise
ω_i	1, if open the temporary disposal center $i \in D$;0, otherwise
λ_{ij}	1, if the small generation node $i \in S$ serviced by the node $j \in L \cup T$;0, otherwise
η_{ij}	1, if the node $i \in L \cup T$ serviced by node $i \in D^* \cup D$;0, otherwise
τ_i	1, if apply the movable disposal facility at the node $i \in L \cup T$;0, otherwise
x_{ijh}	1, if the transportation vehicle $h \in H$ is selected to travel at the edge (i, j), $i, j \in L \cup T \cup D^* \cup D$; 0, otherwise
y_{ijk}	1, if the collection vehicle $k \in K$ is selected to travel at edge (i, j) , $i, j \in S \cup L \cup T$; 0, otherwise
Auxiliary variable	
t_i	The amount of infectious waste collected in the transfer station or large generation node $i \in L \cup T$
c_i	The amount of infectious waste disposed of in the exciting and temporary disposal center $i \in D^* \cup D$
n_{ijk}	The collection vehicle $k \in K$ load on the path (i, j), $i, j \in S \cup L \cup T$
m_{ijh}	The transportation vehicle $h \in H$ load on the path (i, j), $i, j \in L \cup T \cup D^* \cup D$

3.2. Objective functions

This model considers two main objectives to minimize the total cost and the total risk. The first objective includes five components related to the fixed and storing cost of a temporary transfer station TC, the storing cost of large generation nodes GC, the fixed and disposal cost of movable disposal facilities MC, the fixed and disposal cost of disposal centers DC, and the transportation cost TR in Eq(1)-Eq(5). The first objective aims to minimize the total cost $Z^{\cos t}$ in Eq(6).

$$TC = \sum_{i \in T} z_i FCT_i + \sum_{i \in T} t_i VCT_i \tag{1}$$

$$GC = \sum_{i \in L} t_i VCLG_i \tag{2}$$

$$MC = \sum_{i \in V_2} \tau_i FCM + \sum_{i \in V_2} \tau_i t_i VCM \tag{3}$$

$$DC = \sum_{i \in V_3} c_i VCD_i + \sum_{i \in D} \omega_i FCD_i \tag{4}$$

$$TR = \sum_{i \in V_3} \sum_{j \in V_2} \sum_{h \in H} x_{ijh} FCV_t + \sum_{i \in V_2} \sum_{j \in S} \sum_{k \in K} y_{ijk} FCV_c + \sum_{i,j \in V_2 \cup V_3} \sum_{h \in H} x_{ijh} d_{ij} TCV + \sum_{i,j \in S \cup V_2} \sum_{k \in K} y_{ijk} d_{ij} CCV \tag{5}$$

$$Z^{\text{cost}} = TC + GC + MC + DC + TR \tag{6}$$

The second objective aims to minimize the total risk, given in Eq(7)-Eq(9). The risk objective decomposes into location risk and routing risk. The location risk is related to the population exposed to the opened facilities. The routing risk is related to the population around the selected path.

$$RN = \sum_{i \in T} z_i POP_i + \sum_{i \in D} \omega_i POP_i \tag{7}$$

$$RE = \sum_{h \in H} \sum_{i,j \in D \cup L \cup T} x_{ijh} d_{ij} POP_{ij} + \sum_{k \in K} \sum_{i,j \in S \cup L \cup T} y_{ijk} d_{ij} POP_{ij} \tag{8}$$

$$Z^{risk} = RN + RE \tag{9}$$

3.3. Constraints

$$t_j = \sum_{i \in S} \lambda_{ij} g_i, \qquad \forall j \in V_2 \tag{10}$$

$$\sum_{i \in S \cup V_2} \sum_{k \in K} y_{ijk} = 1, \qquad \forall j \in S \tag{11}$$

$$\sum_{i \in D \cup L \cup T} \sum_{h \in H} x_{ijh} = z_j, \qquad \forall j \in T \tag{12}$$

$$\sum_{i \in D \cup L \cup T} \sum_{h \in H} x_{ijh} = 1, \qquad \forall j \in L \tag{13}$$

$$\sum_{j \in S \cup L \cup T} y_{ijk} = \sum_{j \in S \cup L \cup T} y_{jik}, \qquad \forall i \in S \cup V_2, \;\; i \neq j, k \in K \tag{14}$$

$$\sum_{j \in V_2 \cup V_3} x_{ijh} = \sum_{j \in V_2 \cup V_3} x_{jih}, \forall i \in V_2 \cup V_3, \;\; i \neq j, h \in H \tag{15}$$

$$\sum_{i \in V_2} \sum_{j \in S} y_{ijk} \leq 1, \qquad \forall k \in K \tag{16}$$

$$\sum_{i \in D} \sum_{j \in V_2} x_{ijh} \leq 1, \qquad \forall h \in H \tag{17}$$

$$\sum_{j \in V_2} \sum_{i \in V_2} y_{ijk} = 0, \qquad \forall k \in K \tag{18}$$

$$\sum_{t \in V_2} x_{itk} + \sum_{t \in V_2 \cup V_3, t \neq j} x_{tjk} \leq 1 + \eta_{ij}, \qquad \forall i \in V_3, \;\; j \in V_2, k \in K \tag{19}$$

$$\sum_{t\in S} y_{itk} + \sum_{t\in S\cup V_2, t\neq j} y_{tjk} \le 1+\lambda_{ij}, \qquad \forall i\in V_2,\ j\in S, k\in K \tag{20}$$

$$\sum_{j\in V_2} \lambda_{ij} = 1, \qquad \forall i\in S \tag{21}$$

$$\sum_{j\in V_3} \eta_{ij} = 1, \qquad \forall i\in V_2 \tag{22}$$

$$\sum_{j\in T} \lambda_{ij} \ge z_j, \qquad \forall i\in S \tag{23}$$

$$\lambda_{ij} \le z_j, \qquad \forall i\in S,\ j\in T \tag{24}$$

$$\sum_{j\in V_3} \eta_{ij} \ge \omega_j, \qquad \forall i\in V_2 \tag{25}$$

$$\eta_{ij} \le \omega_j, \qquad \forall i\in V_2,\ j\in D \tag{26}$$

$$\sum_{j\in L\cup T} \tau_j x_{ijh} = 0, \qquad \forall i\in V_2\cup V_3,\ h\in H \tag{27}$$

$$\sum_{i\in L\cup T} \tau_i \le n \tag{28}$$

$$c_i = \sum_{j\in L} (g_j + \sum_{s\in S} \lambda_{sj} g_s)\eta_{ji} + \sum_{s\in S}\sum_{j\in T} \lambda_{sj} g_s \eta_{ji}, \qquad \forall i\in V_3 \tag{29}$$

$$c_i \le QD_i, \qquad \forall i\in V_3 \tag{30}$$

$$\sum_{i\in L}\sum_{j\in V_2\cup V_3} (g_i+t_i)x_{ijh} + \sum_{i\in T}\sum_{j\in V_2\cup V_3} t_i x_{ijh} \le QVT, \qquad \forall h\in H \tag{31}$$

$$t_i \le QT_i, \qquad \forall i\in T \tag{32}$$

$$t_i + g_i \le QL_i, \qquad \forall i\in L \tag{33}$$

$$\sum_{j\in S}\sum_{i\in S\cup L\cup T} y_{ijk} g_j \le QVC, \qquad \forall k\in K \tag{34}$$

$$n_{itk} - g_t = n_{tjk}, \qquad \forall i, j\in S\cup V_2, t\in S, k\in K \tag{35}$$

$$m_{ith} - t_t = m_{tjh}, \qquad \forall i, j\in V_2\cup V_3, t\in T, h\in H \tag{36}$$

$$m_{ith} - (t_t + g_t) = m_{tjh}, \qquad \forall i, j\in V_2\cup V_3, t\in L, h\in H \tag{37}$$

$$\mathrm{z}_i \in \{0,1\}, \qquad \forall i\in T \tag{38}$$

$$\lambda_{ij} \in \{0,1\}, \qquad \forall i\in S, j\in V_2 \tag{39}$$

$$\eta_{ij} \in \{0,1\}, \qquad \forall i\in V_2, j\in V_3 \tag{40}$$

$$\tau_j \in \{0,1\}, \quad \forall i \in V_2 \tag{41}$$

$$x_{ijh} \in \{0,1\}, \quad \forall i, j \in V_2 \cup V_3, h \in H \tag{42}$$

$$y_{ijk} \in \{0,1\}, \quad \forall i, j \in S \cup V_2, k \in K \tag{43}$$

In the model constraints, Eq(10) represents the calculation method for the amount of medical waste collected to second layer nodes (temporary transfer points, large generation nodes); Eq(11) indicates that each small generation node is collected only once by the collection vehicle; Eq(12) and (13) indicate that temporary transfer station and large generation nodes that are only transported once by collection vehicles, and if not open and unreachable; Eq(14) and (15) indicate that each collection network node (small generation node, temporary transfer station, large generation node) and each transportation network node (temporary transfer station, large generation node, disposal center) have the same output, that is, the vehicles entering and exiting are the same; Eq(16) and (17) indicate that the collection vehicles and transportation vehicles are either not used or only be used once at most; Eq (18) indicates that there is no path between the second layer nodes for the collection vehicle; Eq (19) and (20) indicate that all demand nodes on each collection path and transportation nodes only served by the second or third layer nodes on that path; Eq(21) and (22) indicate that waste from small generation node are collected only to one temporary transfer station or large waste generation node, while waste from second layer nodes is transported only to one disposal center; Eq(23) and (24) indicate that waste from small waste generation nodes can only be collected at assigned temporary transfer stations or large waste generation nodes; Eq(25) and (26) indicate that waste from second layer nodes can only be transported to the assigned disposal center; Eq (27) indicates that if the second layer node enables movable disposal facilities, the disposal of medical waste is completed and no longer needs to be transported to the disposal center; Eq (28) represents the quantity constraint of movable disposal facilities; Eq (29) represents the calculation of the amount of medical waste disposed of by the disposal center; Eq (30) represents the disposal capacity constraint of the disposal center; Eq (31) represents the capacity constraint of the transportation vehicle; Eq(32) and (33) represent the capacity constraint of the temporary transfer stations and large generation nodes; Eq (34) represents the capacity constraint of the collected vehicles during the collection process; Eq(35), (36), and (37) represent the quantitative relationship between the load of vehicles during the collection and transportation processes on a continuous path; Eq(38) to (43) represent the domain of definition for decision variables.

3.4. Solution approaches

3.4.1. Linearization

In the proposed model, Eq(29) has a nonlinear term which is the product of two binary variables λ_{ij}, η_{jk}. Set new variables $o_{ijk} = \lambda_{ij} \times \eta_{jk}$. Convert the nonlinear constraints of the model into the following Eq(44)-Eq(47):

$$c_i = \sum_{j \in L} g_j \eta_{ji} + \sum_{s \in S} \sum_{j \in V_2} g_s o_{sji}, \quad \forall i \in V_3 \tag{44}$$

$$o_{ijk} - \lambda_{ij} - \eta_{jk} + 1.5 \geq 0, \quad \forall i \in S, j \in V_2, k \in V_3 \tag{45}$$

$$1.5 \times o_{ijk} - \lambda_{ij} - \eta_{jk} \leq 0, \quad \forall i \in S, j \in V_2, k \in V_3 \tag{46}$$

$$o_{ijk} = \{0,1\}, \qquad \forall i \in S, j \in V_2, k \in V_3 \tag{47}$$

3.4.2. Augmented ε-constraint (AUGMECON) method

To solve the multi-objective problem, previous research provided different methods. In general, the weighting methods and ε-constraint method are used most widely. Compared with the goal programming methods, the ε-constraint method has more advantages. A novel format of the ε-constraint method proposed by Mavrotas[16], the Augmented ε-constraint(AUGMECON) method, can avoid product weakly Pareto optimal solutions and accelerate the whole iterative process[17]. Accordingly, we apply this method to solve our model. As for a bi-objectives model, AUGMECON keeps the first objective $f_1(x)$ as the primary objective and reforms the second objective $f_2(x)$ to a new constraint of the model. AUGMECON's basic form is as follows:

$$\begin{aligned}
&\min \ f_1(x) - eps \times (\delta / r) \\
&s.t. \\
&\qquad f_2(x) + \delta = \varepsilon \\
&\qquad B(x,b) = 0 \\
&\qquad \delta \geq 0
\end{aligned} \tag{48}$$

The symbols ε, δ respectively represent the upper bound of the second objective and the corresponding relaxation variable of the constraint; r values in the upper bound to the lower bound of the second objective function; Adjust the value for the corresponding Pareto solution by dividing r into k equal intervals. eps is a parameter that is small enough, and its range is generally above $[10^{-6}, 10^{-3}]$. Accordingly, the proposed model can be rewritten as:

$$\begin{aligned}
&\min Z_{\cos t} - eps \times (\delta / r): \\
&s.t. \\
&\qquad \text{(10)-(28) and (30)-(46)} \\
&\qquad Z_{risk} + \delta = \varepsilon \\
&\qquad \delta \geq 0
\end{aligned} \tag{49}$$

4. Case study

The case study is based on a real-world situation in Chenghua district, Chengdu during the pandemic of COVID-19 in 2021. The waste generation data is provided by the Chengdu Medical Waste Management Center. We consider 25 infectious waste generation nodes and prepare 8 temporary transfer stations and 3 emergency disposal centers. We divide the generation nodes into the small generation nodes and the large generation nodes by the amount of infectious waste. The nodes are shown in Figure 2.

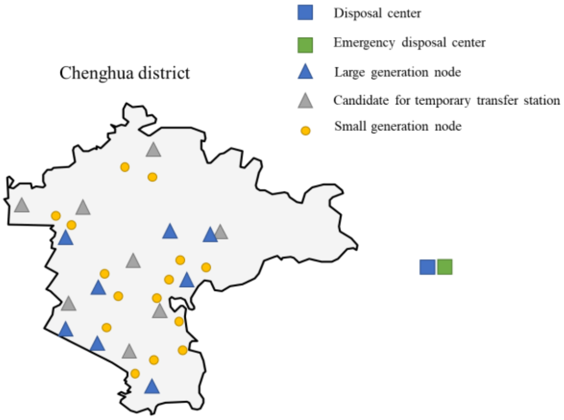

Figure 2: Infectious waste logistics node of Chenghua district during the pandemic.

4.1. Relevant data

According to the infectious waste management policy during the COVID-19 pandemic, there are three kinds of infectious waste generation nodes, including isolation zones, quarantine facilities, COVID-19 designated hospitals. Thanks to infectious waste management information systems, we got accurate data on infectious waste. The average amount of infectious waste generated at 25 infectious waste generation nodes during the pandemic is listed in Table 2.

Table 2: The amount of infectious waste generated during the pandemic.

Node	No.	Name	Amount of waste generation (kg)
Small Generation Node	1	Chengdu Yumei Hospital	180
	2	Chengdu Dongli Hospital	460
	3	Chengdu Second People's Hospital	205
	4	Chengdu Xinhua Hospital	163
	5	Quarantine Community 1	1320
	6	Quarantine Community 2	1380
	7	Quarantine Community 3	510
	8	Quarantine Community 4	486
	9	Quarantine Community 5	1540
	10	Shuangqiaozi Street Office	900
	11	Quarantine Hotel 1	850
	12	Quarantine Hotel 2	780
	13	Quarantine Hotel 3	950
	14	Quarantine Hotel 4	1380
	15	Quarantine Community 6	747
Large Generation Node	16	Chengdu Sixth People's Hospital	2213
	17	Nuclear Industry 416 Hospital	2056
	18	Quarantine Hotel 5	2250
	19	Chenghua Centralized isolation node	2640
	20	Erxianqiao Street Office	1480
	21	Qinglong Street Office	2300
	22	Tiaodenghe Street Office	2350
	23	Quarantine Community 6	1890
	24	Quarantine Community 7	2280
	25	ChengduDong Railway Station	2465

The proposed network has 8 temporary transfer station candidates determined by the competent department and 3 disposal centers including 2 emergency disposal centers. According to our survey, each transfer station has a capacity of 3 tons, and the whole Medical Waste Disposal Center can dispose of 240 tons of infectious waste per day. The capacity of the disposal center allocated to Chenghua District is 15 tons per day. The fixed cost and the variable cost of the facilities are shown in Table 3.

Table 3: The parameters of the facilities.

Node	No.	Name	Fixed Cost (CNY/ton)	Variable cost (CNY/ton)	Capacity (ton)
Temporary Transfer Station	26	Longtan Temple Station	5000	1950	3
	27	Qinglong Station	5000	1950	3
	28	Shengdeng Station	5000	1950	3
	29	Zhandong Station	5000	1950	3
	30	Dongzikou Station	5000	1950	3
	31	Duobao Temple Station	5000	1950	3
	32	Wannian Station	5000	1950	3
	33	Chenghua Maternal and Child Care Hospital	5000	1950	3
Disposal Center	34	Garbage Disposal Incinerator 1	30000	2600	15
	35	Garbage Disposal Incinerator 2	30000	2600	15
	36	Medical Waste Disposal Center	-	1560	15

For vehicle capacity and transportation costs, there are two types of vehicles in the model, namely collection vehicles and transfer vehicles, with different sizes and operating costs. The collection vehicle has a small capacity, with a maximum load capacity of 1.5 tons, while the transfer vehicle has a maximum load capacity of 5 tons. The fixed cost for collecting vehicles is 500 CNY, and the transportation cost is 20 CNY/ton/km. The fixed cost of the transportation process for transfer vehicles is 1000 CNY. Due to their fewer stops and longer transportation paths, the transportation cost is 15 CNY /ton/km. The start-up cost of the movable disposal facilities is about 8000 CNY, the operation cost is 3600 CNY /ton, and the disposal capacity of the movable disposal facilities is 3 ton.

4.2. Results

In this section, we apply the bi-objective model to the proposed realistic case. The model with the case study is implemented on a personal computer equipped with AMD 5800H 3.2GHz CPU, and 8.00G RAM using the solver CPLEX 20.1.

At first, we minimize a single objective separately to find the extreme Pareto solutions. As for the “min cost” solution, the total cost is 2.191×10^5 CNY, and the total risk is 1.352×10^5 people. As to the ‘min risk’ solution, the total cost is 2.406×10^5 CNY, and the total risk is 1.132×10^5 people. Compared with these two extreme Pareto solutions, we find that when cost increases by 9.80%, the risk decreases by 16.28%. Secondly, we applied AUGMECON to solve the bi-objective model. We solve the model iteratively with the parameter of AUGMECON $k=15$. From the "min cost" solution, with less than 0.96% additional cost, risk can be reduced by nearly 2.21%. For the two intervals close to the "min risk" solution, an average cost increase of about 1.3% can lead to an average risk reduction of 1.6%. The biggest cost gap exists in the ninth iterations of the "intermediate" solution, where a 3.1% risk change only requires approximately 0.1% additional cost. Based on the results, we can obtain a relatively optimal compromise solution, the Pareto optimal solution. Its cost objective is 2.299×10^5 CNY and the risk objective is 1.258×10^5 people. The trade-off analysis method based on Zhao et al.[10]. Figure 3 depicts the trade-off curve and we highlight the “min cost” solution, the “min risk” solution, and the “Intermediate Solution”. Based on the “Intermediate Solution”, Table 4 shows the location-routing solution for the infectious waste logistics network.

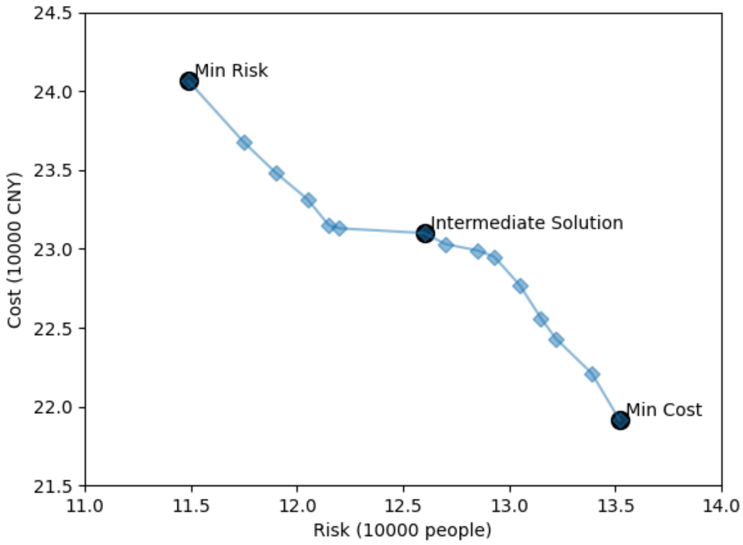

Figure 3: trade-off curve.

Table 4: Location-routing plan of the “intermediate” solution.

decision		results
Location of temporary transfer stations		29, 28, 31
Location of movable disposal facilities		23, 16
Emergency disposal center		34, 35
path	Collection Path	24→3→6→24; 19→14→19;28→8→7→1→28; 31→12→15→31;22→2→22; 29→13→4→10→29
	Transportation Path	33→21→17→33; 33→24→33; 33→28→30→33; 34→19→20→34; 34→31→22→34; 34→18→35; 35→22→29→35

5. Conclusion

This research aims to address key issues such as how to safely and timely dispose of infectious waste during a pandemic, how to optimize the overall allocation of disposal and transportation resources, and how to upgrade the existing logistics networks that can not deal with the explosive growth of infectious waste. By establishing a bi-objective model that minimizes costs and risks, this study optimizes the location for temporary transfer stations and mobile disposal facilities as well as the corresponding collection and transportation routes. We adapted the AUGMECON method to solve the model and applied the proposed model and algorithm to the pandemic case in Chenghua

District, Chengdu, from which the solutions can benefit the government and other stakeholders.

For future research, we would like to discuss the uncertainty during a pandemic and the risk assessment methods during the pandemic. Furthermore, it is interesting to explore the relationship between different parties, including the government, the operator, and so on. Different parties have different decision preferences on the objectives. At last, we also can add more objectives to the model, like the carbon emission and the operation performance of electric vehicles.

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