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Research on Assignment Model and Optimization of Medical Waste Collection and Transportation Personnel Based on Task Equilibrium

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Abstract

During major epidemic outbreaks, the generation of medical waste has increased dramatically. Medical waste becomes more infectious than usual under these circumstances, and turnover personnel may be affected or become ill due to infection. These unforeseen factors have significantly increased the complexity of task assignment for medical waste turnover personnel. In addition, medical waste requires daily collection and disposal. To ensure the smooth collection of medical waste, the reasonable arrangement of turnover personnel is particularly important. It is well known that the fewer times medical waste turnover personnel are assigned to different temporary storage points for medical waste, the less likely cross-infection occurs. In this paper, aiming to minimize the number of assignments and the number of medical waste turnover personnel assigned, while ensuring a balanced collection task for the assigned medical waste turnover personnel, a multi-objective medical waste turnover personnel assignment model is established, aiming to minimize the number of assignments while ensuring a balanced workload among the assigned personnel. To facilitate solving, this paper converts nonlinear constraints in the model into linear constraints using the Big M method. Finally, based on the medical waste collection and disposal data of a medical waste disposal unit in a certain district of Chengdu city on April 13, 2022, relevant numerical examples are designed and solved using IBM ILOG Cplex Studio IDE 12.7.1, thereby verifying the efficiency and applicability of the model. Our model is designed to provide a relatively rational personnel scheduling plan under the context of major epidemic outbreaks, where the uncertainty for medical waste collection and transportation personnel is heightened. This model aims to minimize the number of personnel required for medical waste collection and transportation while ensuring a balanced workload distribution among them. In comparison to manual scheduling methods, our model significantly enhances the efficiency of scheduling.

Keywords: Infection risk, medical waste, collection personnel, assignment model.

1. Introduction

Medical waste refers to waste generated by medical institutions such as hospitals and clinics during diagnosis, treatment, testing, disposal, prevention, healthcare, and other related activities, possessing infectious, toxic, and other hazardous properties. During the collection and transportation of medical waste, there is a risk of infection due to possible contact with the interior or exterior of transit containers (bins) or single-use packaging containers, as well as contact with the interior walls or surfaces of medical waste transport vehicles. Daily clearance of medical waste is required. During sudden major outbreaks, the volume of medical waste increases dramatically, and the risk of infection from medical waste is higher, placing medical waste collection and transportation personnel at greater risk with more demanding tasks. Assignments and plans for medical waste collection personnel vary. During sudden major outbreaks, there are more temporary medical waste storage points, disrupting the routine assignment of medical waste collection tasks. The heavy workload and insufficient manpower in medical waste collection tasks make the already complex assignment of medical waste collection even more challenging. Therefore, it is of paramount importance to scientifically and reasonably allocate medical waste collection tasks to balance the workload of collection personnel and reduce the risk of cross-infection, which is crucial during sudden major outbreaks. A review reveals that research related to medical waste mainly focuses on three aspects: medical waste management, site selection for medical waste disposal centers, and management and optimization of medical waste transportation.

In the realm of medical waste management, research primarily focuses on the assessment, management, and disposal techniques in developing countries. This includes evaluations of medical waste management by healthcare facilities [1-4] and occupational exposure and protective measures for healthcare workers [5,6]. Zhao et al. proposed a robust infectious waste management model based on dual-objective scenarios, with particular attention to pandemics [7]. Regarding the selection of sites for medical waste disposal centers, considerations of sustainable logistics networks are paramount. Budak and Ustundag [8] addressed waste collection and disposal issues in Turkey through an adaptive large neighborhood search method to solve two-stage stochastic models with uncertain demands, studying location-allocation problems. Mantzaras and Voudrias [9] established optimization models to determine the locations and capacities of treatment plants and transfer stations. Gergin et al. [10] addressed facility location problems for waste treatment sites. Yao et al. [11] explored risk and cost mitigation in the allocation of medical waste disposal center sites. In terms of medical waste transportation, Alshraideh and Qdais [12] developed a stochastic route scheduling model for medical waste collection in northern Jordan. Osaba et al. [13] introduced a multi-attribute cluster vehicle routing problem (VRP) to address pharmaceutical distribution issues with a drug waste recovery process. Markov et al. [14] transformed waste collection problems into nonlinear stochastic inventory routing models based on uncertain container overflow and route failures. Kargar et al. [15] considered two types of medical waste: hazardous waste and general medical waste, studying a multi-trip reverse supply chain for medical waste. Govindan et al. [16] focused on site selection and transportation issues in medical waste management during the COVID-19 outbreak. They established a bi-objective MILP model and solved it using fuzzy goal programming methods. Tirkolaee et al. [17] addressed infectious waste related to coronaviruses, studying sustainable multi-tier LRPTW based on a two-tier medical waste management system of hospitals and medical stations to disposal sites. Considering temporary facilities in a four-tier network, Ghezavati et al. [18] abstracted waste disposal problems generated by hospitals and clinics into a multi-level location routing problem (MELRP). Ghezavati and Beigi [19], aiming to minimize location routing costs and collection times, constructed a multi-level problem with time windows. Wang et al. [20] explored a bi-objective 2ELRP with service time windows and shared transportation resources to optimize economic and environmental goals by minimizing the number of vehicles and operational costs.

In conclusion, there is an abundance of research focusing on measuring infectious risk in medical waste, personal protection against infectious medical waste, site selection for medical waste disposal facilities or temporary transfer stations, as well as related studies on medical waste transportation. Nonetheless, a notable gap exists in the attention given to the assignment of medical waste collection tasks to personnel during sudden outbreaks of infectious diseases. Taking the minimization of medical waste collection personnel as the objective, with a particular emphasis on balancing the workload constraints, we initially established a nonlinear programming model. Subsequently, the large M method was applied to transform the nonlinear constraints into linear ones for solution. The resulting model is capable of assigning tasks to medical waste collection personnel during sudden outbreaks of major infectious diseases, thereby providing a decision-making reference for task allocation in emergency management.

2. Assignment Model for Medical Waste Collection Personnel

2.1 Problem description

During the process of medical waste collection, each medical waste storage point requires 2 personnel (including 1 driver and 1 escort). Typically, each group consists of 1 driver and 1 escort, who are jointly assigned to complete the medical waste collection tasks for the day. In the event of a major public health emergency, if any of the medical waste collection personnel become infected, the assignment plan is disrupted. Moreover, with the addition of temporary medical waste storage points, there is a severe shortage of collection personnel, necessitating urgent additions. Therefore, the scheduling arrangement of medical waste collection personnel during emergencies is imperative. Furthermore, during major public health emergencies, the generated medical waste inevitably includes waste from undiagnosed patients, which poses a significantly higher risk than regular medical waste. Naturally, minimizing the number of assignments simplifies the work arrangement. With fewer assignments, the collection personnel make fewer trips to the medical waste storage points, thereby reducing the risk of cross-infection. Excessive assignments not only complicate scheduling but also increase the likelihood of cross-infection. Hence, one of the objective functions of the model proposed in this paper is to minimize the total number of assignments for all medical waste collection personnel. Additionally, during major public health emergencies, where there is an acute shortage of personnel for medical waste collection tasks, minimizing the total number of assigned collection personnel is another objective. Simultaneously, in the allocation of medical waste collection tasks, efforts should be made to balance the work assignments of drivers and escorts, reflecting fairness. In summary, the assignment model established in this paper fully considers minimizing the total number of assignments, minimizing the total number of medical waste collection personnel, and balancing the work arrangements of drivers and escorts.

2.2 Assumptions

The model proposed in this paper is based on the following assumptions:

(1) It is assumed that the risk of infection for medical waste collection personnel is only related to the infectiousness of the medical waste at the storage points. Therefore, the risk of infection is the same for different medical waste collection personnel at the same storage point.

(2) During the recruitment process, medical waste disposal companies assign drivers and escorts to different positions. It is assumed that the division of labor between drivers and escorts is established at the beginning of the assignment.

(3) Medical waste from individual healthcare facilities or isolation units can be collected multiple times, but all waste must be collected and returned to the disposal center on the same day.

2.3 Parameters

I: Set of drivers, any driver $i \in I$;

J: Set of escorts, any escort $j \in J$;

K: Set of medical institutions or isolation units within the designated area responsible for generating medical waste, any medical institution or isolation unit $k \in K$;

q_k: Quantity of medical waste generated by each medical institution or isolation unit k (measured in units of barrels);

Q_i: Maximum number of barrels a driver i can handle in a single day;

R_i: Maximum number of barrels an escort j can handle in a single day;

C: Capacity of medical waste transportation vehicles (measured in barrels);

Decision Variables:

$x_{ijk} = \begin{cases} 1; \\ 0' \end{cases}$

When driver i and escort j are simultaneously assigned to collect medical waste from medical institution or isolation unit k, $x_{ijk} = 1$; otherwise, $x_{ijk} = 0$;

y_{ijk}: The quantity of medical waste (in barrels) assigned to driver i and escort j for collection from medical institution or isolation unit k;

$w_i = \begin{cases} 1, & \text{Driver } i \textit{ is assigned to participate in the medical waste collection task} \\ 0, & \text{otherwise} \end{cases};$

$z_j = \begin{cases} 1, & \textit{escort } j \textit{ is assigned to participate in the medical waste collection task} \\ 0, & \textit{otherwise} \end{cases}.$

2.4 Model

Considering the issue of balancing the collection tasks between drivers and escorts, this study requires that the difference in collection volume between different personnel be less than the capacity of a single medical waste transportation vehicle per trip. The research objective is to minimize the total number of assignments for all medical waste collection personnel and minimize the total number of required medical waste collection personnel. Based on this, the model is formulated as shown in Equations (1) to (10).

$$min\left(\sum_I \sum_J \sum_k x_{ijk}\right) \tag{1}$$

$$min\left(\sum_I w_i + \sum_J z_j\right) \tag{2}$$

$$w_i = min\left(\sum_J \sum_K x_{ijk}, 1\right), \forall i \in I, j \in J, k \in K \tag{3}$$

$$z_j = min\left(\sum_I \sum_K x_{ijk}, 1\right), \forall i \in I, j \in J, k \in K \tag{4}$$

$$\sum_{i \in I} \sum_{j \in J} y_{ijk} = q_k, i \in I, \forall j \in J, \forall k \in K \tag{5}$$

$$\sum_{j \in J} \sum_{k \in K} y_{ijk} \le Q_i, \forall i \in I, j \in J, k \in K \tag{6}$$

$$\sum_{i \in I} \sum_{k \in K} y_{ijk} \le R_j, \forall i \in I, j \in J, k \in K \tag{7}$$

$$y_{ijk} = y_{ijk} * x_{ijk}, \forall i \in I, j \in J, k \in K \tag{8}$$

$$\max\left(\sum_{j \in J} \sum_{k \in K} y_{ijk}\right) - \min\left(\sum_{j \in J} \sum_{k \in K} y_{ijk}\right) \le c, \forall i \in I, j \in J, k \in K \tag{9}$$

$$\max\left(\sum_{i \in I} \sum_{k \in K} y_{ijk}\right) - \min\left(\sum_{i \in I} \sum_{k \in K} y_{ijk}\right) \le c, \forall i \in I, j \in J, k \in K \tag{10}$$

Equation (1) reflects the objective of minimizing the total number of assignments for medical waste collection personnel.

Equation (2) represents the objective of minimizing the total number of required medical waste collection personnel.

Equation (3) indicates that if driver i has participated in a medical waste collection task, it is assigned a value of 1; otherwise, it is assigned a value of 0.

Equation (4) indicates that if escort j has participated in a medical waste collection task, it is assigned a value of 1; otherwise, it is assigned a value of 0.

Equation (5) explains that medical waste from individual medical institutions or isolation units k can be collected multiple times, with daily clearance.

Equation (6) illustrates that there is an upper limit on the collection task for driver i on a given day.

Equation (7) illustrates that there is an upper limit on the collection task for escort j on a given day.

Equation (8) explains that for driver i and escort j to complete the collection task at medical institution or isolation unit k, it is necessary for both driver i and escort j to be assigned to the same medical institution or isolation unit k.

Equation (9) states that the difference in collection volume between drivers should not exceed the capacity of a single medical waste transportation vehicle.

Equation (10) states that the difference in collection volume between escorts should not exceed the capacity of a single medical waste transportation vehicle.

It is evident that Equation (8) represents a nonlinear constraint condition, which can be converted into the following linear constraint condition using the Big M method.

$$y_{ijk} >= x_{ijk}$$

$$y_{ijk} <= M * x_{ijk}$$

Therefore, the aforementioned nonlinear model is transformed into the following linear programming model:

$$min\left(\sum_I \sum_J \sum_k x_{ijk}\right) \tag{11}$$

$$min\left(\sum_I w_i + \sum_J z_j\right) \tag{12}$$

$$w_i = min\left(\sum_J \sum_K x_{ijk}, 1\right), \forall i \in I, j \in J, k \in K \tag{13}$$

$$z_j = min\left(\sum_I \sum_K x_{ijk}, 1\right), \forall i \in I, j \in J, k \in K \tag{14}$$

$$\sum_{i \in I} \sum_{j \in J} y_{ijk} = q_k, i \in I, \forall j \in J, \forall k \in K \tag{15}$$

$$\sum_{j \in J} \sum_{k \in K} y_{ijk} \leq Q_i, \forall i \in I, j \in J, k \in K \tag{16}$$

$$\sum_{i \in I} \sum_{k \in K} y_{ijk} \leq R_j, \forall i \in I, j \in J, k \in K \tag{17}$$

$$y_{ijk} >= x_{ijk}, \forall i \in I, j \in J, k \in K \tag{18}$$

$$y_{ijk} <= M * x_{ijk}, \forall i \in I, j \in J, k \in K \tag{19}$$

$$\max(\sum_{j\in J}\sum_{k\in K}y_{ijk})-\min(\sum_{j\in J}\sum_{k\in K}y_{ijk})\le c,\forall i\in I,j\in J,k\in K \tag{20}$$

$$\max(\sum_{i\in I}\sum_{k\in K}y_{ijk})-\min(\sum_{i\in I}\sum_{k\in K}y_{ijk})\le c,\forall i\in I,j\in J,k\in K \tag{21}$$

3. Results

3.1 Description of experimental data

To verify the efficiency of the model, research data from a medical waste disposal unit in Chengdu City was utilized. It was found that each medical waste collection personnel can make a maximum of 3 trips per day, and each medical waste transportation vehicle can carry up to 46 barrels. Therefore, the maximum collection capacity for one medical waste collection personnel per day is 138 barrels. Under normal circumstances, there are 49 medical institutions in the area (this number may vary due to changes in medical institutions) that generate medical waste requiring collection. The medical waste disposal unit is equipped with 5 drivers and 5 escorts responsible for medical waste collection in this area. During emergencies, temporary collection points for infectious medical waste may be added. On April 13, 2022, it was found from the medical waste collection data in the area that 9 temporary medical waste collection points were added. Thus, in this example, a total of 58 medical waste collection points require collection. During a major public health emergency, due to the heavy workload, it is possible to add an additional collection task temporarily. Thus, each medical waste collection personnel can make a maximum of 4 trips in a single day, with a maximum collection capacity of 184 barrels. Currently, there are 18 drivers and 18 escorts in the medical waste disposal unit. Due to changes in the actual generation of medical waste by medical institutions, and considering the practical difficulties in collecting some data, this paper combines research data to form the example data shown in Table 1.

Table 1 Example data

Medical Waste Storage Point Number	Pending Barrels	Medical Waste Storage Point Number	Pending Barrels	Medical Waste Storage Point Number	Pending Barrels	Medical Waste Storage Point Number	Pending Barrels
1	10	16	10	31	20	46	12
2	10	17	10	32	20	47	12
3	10	18	18	33	20	48	12
4	10	19	18	34	20	49	12
5	10	20	18	35	20	50	330
6	10	21	18	36	20	51	287
7	10	22	18	37	20	52	240
8	10	23	18	38	12	53	150
9	10	24	20	39	12	54	89
10	10	25	20	40	12	55	212
11	10	26	20	41	12	56	75
12	10	27	20	42	12	57	345
13	10	28	20	43	12	58	550
14	10	29	20	44	12		
15	10	30	20	45	12		

3.2 Experimental Results

Combining the data from Table 1, the sum of Equations (11) and (12) serves as the objective function for the entire model. Programming and solving were conducted using IBM ILOG Cplex Studio IDE 12.7.1. The resulting objective function value is 99. The specific assignment results are shown in Table 2.

Table 2 Model solution results

Medical Waste Storage Point Number	Driver Number	Escort Number	Collected Barrels	Medical Waste Storage Point Number	Driver Number	Escort Number	Collected Barrels

1	14	24	10	34	3	24	20
2	14	24	10	35	12	23	20
3	2	35	10	36	17	30	20
4	1	22	10	37	12	30	20
5	2	21	10	38	1	19	12
6	3	23	10	39	1	21	12
7	14	21	10	40	3	30	12
8	2	25	10	41	14	24	12
9	2	24	10	42	3	30	12
10	2	35	10	43	16	21	12
11	12	31	10	44	1	21	12
12	14	24	10	45	3	24	12
13	13	19	10	46	12	31	12
14	1	24	10	47	3	31	12
15	2	35	10	48	12	24	12
16	1	25	10	49	1	29	12
18	2	21	18	50	15	27	184
19	12	35	18		16	22	146
20	2	30	18	51	1	31	103
21	2	23	18		11	32	184
22	12	23	18	52	5	28	136
23	3	23	18		14	21	104
24	2	24	20	53	13	29	150
25	14	24	20	54	7	35	89
26	5	35	20	55	2	28	48
27	3	35	20		18	25	164
28	3	30	20	56	7	23	75
29	12	30	20	57	6	26	184
30	12	30	20		17	19	161
31	3	23	20	58	8	34	184
32	13	24	20		9	36	184
33	3	29	20		10	20	182

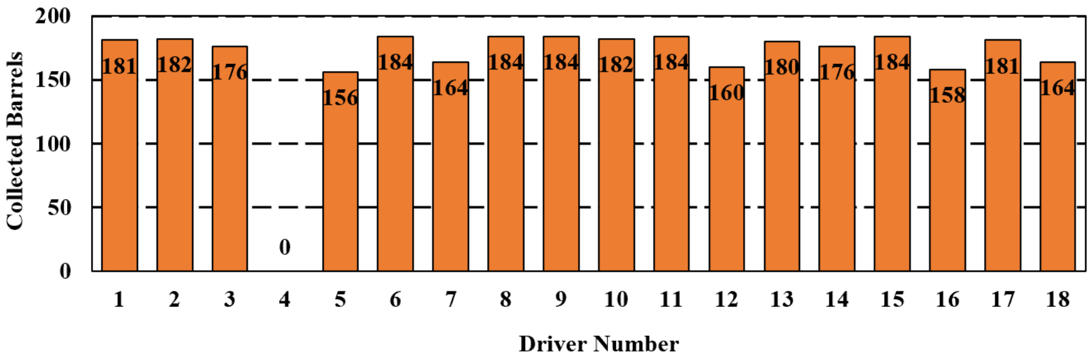

Figure 1 Workload statistics for drivers

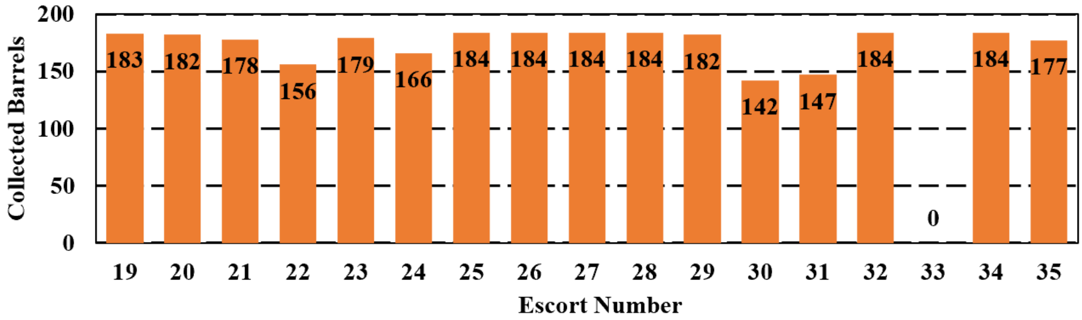

Figure 2 Workload statistics for escort

Table 2 provides the assignment results for drivers and escorts in this study. It demonstrates that the model can minimize the number of assignments for drivers and escorts while considering the given pending collection volumes for each medical waste storage point, the number of drivers and escorts, and the maximum collection limits. This enables the model to propose the optimal assignment plan for medical waste collection, ensuring efficient task assignments for personnel during sudden outbreaks of public health emergencies. Figure 1 illustrates that Driver Number 4 has no collection tasks, indicating the effectiveness of the model's objective to minimize the participation of drivers in collection tasks. The maximum collection capacity for drivers is 184 barrels, while the minimum is 156 barrels, with a difference of 26 barrels between the maximum and minimum collection capacities, thus satisfying the constraint of balancing the workload among drivers. Figure 2 shows that Escort Number 33 has no collection tasks, indicating the effectiveness of the model's objective to minimize the participation of escorts in collection tasks. The maximum collection capacity for escorts is 184 barrels, while the minimum is 142 barrels, with a difference of 42 barrels between the maximum and minimum collection capacities, thus satisfying the constraint of balancing the workload among escorts.

4. Conclusion

In this paper, we delve into the task assignment problem of collecting medical waste from various transfer stations amidst a surge in medical waste generation during significant epidemic outbreaks. We also incorporate the workload balancing constraint for medical waste collection and transportation personnel. We establish a nonlinear programming model. Subsequently, we employ the Big-M method to transform this nonlinear model into a linear programming model, facilitating its solution. Furthermore, we design experiments to validate the effectiveness of our proposed model. The findings of this study provide valuable decision-making references for medical waste management enterprises in allocating personnel for medical waste collection and transportation tasks during sudden and major epidemic situations.

When establishing the model, we strive to simulate real-world scenarios. However, it is acknowledged that the arrangement of medical waste collection and transportation personnel during a major sudden epidemic is inherently more complex, with numerous additional factors to consider. As a result, future research will incorporate these additional factors, such as the work experience of collection personnel and differences in infection risks due to variations in proficiency during medical waste collection. The ultimate goal is to establish a task assignment model that is more closely tailored to the actual situation of medical waste collection.

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