

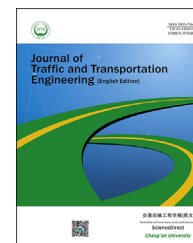


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## Original Research Paper

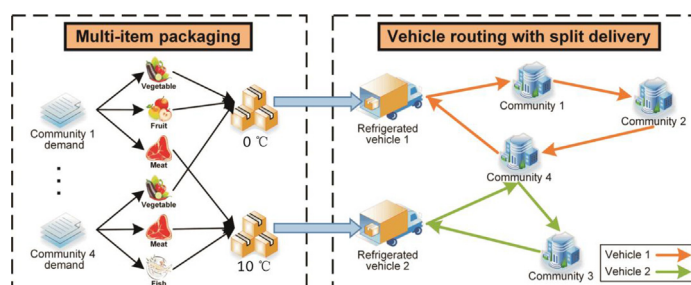
# Integrated multi-item packaging and vehicle routing with split delivery problem for fresh agri-product emergency supply at large-scale epidemic disease context

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## HIGHLIGHTS

- An optimization model on fresh agri-product emergency supply is formulated.
- Model considers the response time, infectious risk and transportation resource.
- Multi-item packing and vehicle routing with split delivery are determined jointly.
- A case on COVID-19 is used to illustrate practical application of the model.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Fresh agri-product emergency supply is crucial to secure the basic livelihood of residents at large-scale epidemic disease context. Considering the massive demand and limited transportation resources, this study integrates multi-item packaging and vehicle routing with split delivery to improve the emergency supply capacity. Firstly, three specific objectives of fresh agri-product emergency supply at large-scale epidemic disease context are formulated, i.e., average response time, infectious risk possibility and transportation resource utilization. Then, a multi-item packaging strategy is proposed to consolidate different categories of fresh agri-products according to the food cold chain temperatures. An optimization model integrating multi-item packaging and vehicle routing with split delivery is developed to jointly decide the optimal packaging scheduling, vehicle assignment and delivery routing. Next, an improved genetic algorithm based on solution features

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Multi-item packaging  
Vehicle routing with split delivery  
Corona virus disease 2019  
(COVID-19)

(IGA-SF) is designed to solve the integrated model with multiple decision variables. Finally, a case on fresh agri-product emergency supply of Huangpi District, Wuhan in the context of the Corona Virus Disease 2019 (COVID-19) is carried out to illustrate the efficiency and feasibility of the proposed model. The numerical results of medium-to-large scale cases demonstrate that the proposed IGA-SF could save 23.91% CPU time and 37.80% iteration number on average than genetic algorithm. This study could satisfy different emergency scenario requirements flexibly, and provide scientific decision support for provincial and national governments on fresh agri-product emergency supply.

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## 1. Introduction

The recent outbreak of Corona Virus Disease 2019 (COVID-19) has caused the severe supply-demand disequilibrium of relief resources (e.g., medical supplies, daily necessities) due to social isolation and traffic control (Ivanov, 2020). Fresh agri-product as an essential category in daily necessities, how to ensure their stable supply has become of primal importance in such public health events (Pu and Zhong, 2020; Yang et al., 2020). Considering the massive demands and diverse categories of fresh agri-products, the coordination and pooled distribution of central government have provided the effective support for fresh agri-product emergency supply (China Daily, 2020). At large-scale epidemic disease context, the central government effectively integrates the demand information on a community basis, and distributes fresh agri-products as quickly as possible. In this context, how to design the multi-item packaging strategy and improve the emergency supply efficiency is the critical issue to secure the basic livelihood of residents.

The complication of fresh agri-product emergency supply problem at large-scale epidemic disease context comes from packaging strategy, vehicle assignment and delivery routing. Firstly, a critical multi-item packaging decision needs to consider the weight, compatibility and demand distribution of fresh agri-products simultaneously. Secondly, the massive demands and limited transportation resources pose more requirements and restrictions for the vehicle assignment than usual. Finally, the fresh agri-product emergency supply needs to schedule the optimal vehicle routing with consideration of split delivery and time urgency.

Fresh agri-product emergency supply is vital to secure the basic livelihood of residents at large-scale epidemic disease context (Annarelli and Nonino, 2016; Utomo et al., 2017). The most relevant literature is regarding humanitarian logistics (Bruni et al., 2018; Loree and Aros-Vera, 2018; Qureshi and Taniguchi, 2020), emergency resource allocation (Doan and Shaw, 2019; Su et al., 2016), agricultural supply chain (Borodin et al., 2016; Li and Wang, 2019), vehicle routing problem with split delivery (Bortfeldt and Yi, 2019; Gschwind et al., 2019) and multi-item packaging (Zhang et al., 2019). Generally, these studies have provided many methods to improve the rescue efficiency of emergency resources from different aspects, especially for medical resources. However,

available literature has seldom aimed at the fresh agri-products with perishability and massive demands to develop the specific emergency supply scheduling. In this study, the characteristics of fresh agri-product demand are captured to design the multi-item packaging strategy. An optimization model integrating multi-item packaging and vehicle routing with split delivery is proposed to satisfy the strict requirements of time and transportation resources at large-scale epidemic disease context.

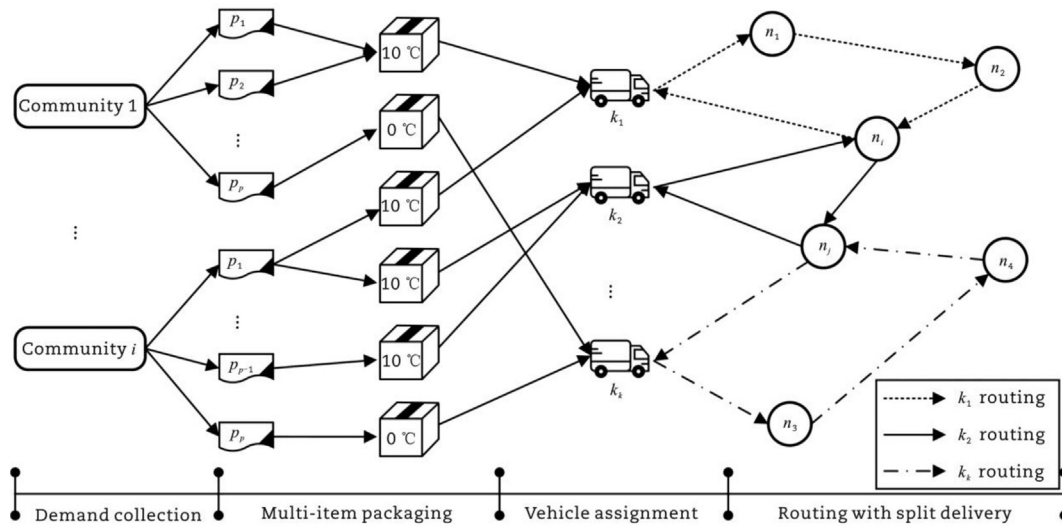
The contributions in this study contain four aspects as follows. (1) Capture the average response time, infectious risk possibility and transportation resource utilization as emergency supply objectives simultaneously. (2) Design a multi-item packaging strategy with consideration of fresh agri-product category, vehicle capacity limitation and demand distribution. (3) Formulate a joint optimization model on fresh agri-product emergency supply by integrating multi-item packaging and vehicle routing with split delivery. (4) Propose an improved genetic algorithm based on solution features (IGA-SF) to solve the multiple decision variable model.

This paper is organized as follows. Section 2 reviews the related works. Section 3 formulates the fresh agri-products emergency supply model by integrating multi-item packaging and vehicle routing with split delivery. In Section 4, an improved genetic algorithm based on solution features is designed to solve the proposed model. Section 5 reports the numerical results of the case on fresh agri-product emergency supply of Huangpi District, Wuhan. Finally, Section 6 discusses the conclusions and suggests future works.

## 2. Literature review

Our work is related to three research streams: multi-item packaging, vehicle routing problem and emergency resource supply.

Multi-item packaging is an effective strategy to reduce distribution costs and order fulfillment time (Howard and Marklund, 2011; Mousavi et al., 2014). Jasin and Sinha (2015) consolidated different items to minimize the costs over a finite horizon. Wisittipanich and Hengmeechai (2017) packaged multiple product types together to reduce the waiting time and fulfillment time. Stenius et al. (2018) demonstrated that multi-item packing was conducive to



**Fig. 1 – Diagram for integrated multi-item packaging and vehicle routing with split delivery for fresh agri-product emergency supply.**

reducing total costs and transportation emissions. Zhang et al. (2019) presented a package consolidation approach to consolidate multiple items in different warehouses. Cui et al. (2020) emphasized the significance of reducing order fulfillment time by delivering multi-item jointly. These research results revealed that the multi-item package has an effective impact on the cost and time savings of industrial product delivery. However, there are few works to introduce this strategy into the fresh agri-product supply due to multiple categories and perishability.

Vehicle routing problem has been well recognized and motivated many problem variants (Lahyani et al., 2015; Liu et al., 2020; Sun et al., 2012; Vidal et al., 2020). Especially for different emergency scenarios, designing a vehicle routing problem with proper attributes is crucial. Chang et al. (2013) applied the time-dependent travel time information into the delivery of sporadic orders to reduce the distribution costs and traffic congestion. Yan et al. (2015) modeled a split delivery vehicle routing problem with time windows to minimize the total cost in daily distribution. Zhang and Xiong (2018) modeled the gain emergency supply as a vehicle routing problem with time windows, and optimized the satisfaction of emergency needs, distribution cost and time. Chen et al. (2019) proposed a multi-compartment vehicle routing model to solve the cold-chain distribution problem. Huizing et al. (2020) studied the emergency logistics with non-emergency jobs, and formulated it as a median routing problem to minimize the expected response time. Generally, the vehicle routing problem has many application prospects. In practice, it is vital to formulate the vehicle routing problem based on the characteristics of fresh agri-product emergency supply.

Emergency resource supply is quite different from the traditional freight supply (Hu et al., 2019; Huang et al., 2015). The objectives of traditional freight supply are often to pursue economic costs, time window requirements and consumer satisfaction (Li and Lu, 2014; Szymczyk and Kadlubek, 2019). However, in emergency resource supply,

the basic demands need to be satisfied to the greatest extent possible within a limited time. Rey et al. (2018) collected and re-distributed the perishable food with envy-free allocations and least distribution cost. Gökçe and Ercan (2019) designed the optimal routing within the expiration dates of emergency resources. Huang and Rafiei (2019) designed a relief distribution network with time window and split delivery to weigh the delivery quantities and times. Qi and Hu, 2020 presented an emergency cold chain logistics optimization model with objectives of minimizing the loss cost of refrigerated vehicles and damage cost of goods over time. These works mainly focus on the specific rescue resources, such as medicines and tents, and provide inspiration for fresh agri-product emergency supply.

In summary, few studies have addressed the fresh agri-product emergency supply at large-scale epidemic disease context despite its importance and particularity. In practice, capturing the perishable characteristics and demand distribution is complicated for formulating the fresh agri-product emergency supply. Therefore, this study designs an integrated multi-item packaging and vehicle routing with split delivery model to consolidate different category fresh agri-products and minimize the delivery time.

### 3. Model development

#### 3.1. Problem description

The interventions of epidemic disease often causes the disruption of fresh agri-product supply chain. Rapid and efficient fresh agri-product supply mode is urgently needed to secure the basic livelihood of residents and contain epidemic evolution. The crucial issue in this study is how to integrate multi-item packaging and vehicle routing with split delivery to solve the problems of massive demands and limited transportation resources. The proposed fresh agri-product emergency supply mode contains the demand collection,

multi-item packaging, vehicle assignment and routing with split delivery. This study focuses on decision-making in the process of multi-item packaging, vehicle assignment and routing with split delivery. Assume that there are multiple communities geographically dispersed and centrally served by a single emergency distribution center. The government collects community demands online, and then delivers these fresh agri-products to the emergency distribution center. As shown in Fig. 1, the fresh agri-products of each community demand are divided into multiple categories (denoted as  $p_1, p_2, \dots, p_p$ ), such as vegetable, fruit, meat, etc. To reduce infectious risks and improve delivery efficiency, a multi-item packaging strategy is proposed to consolidate fresh agri-products according to the category compatibility, vehicle capacity limitation and demand distribution. That is to say, some fresh agri-products with similar food cold chain temperature could be delivered in one refrigerated vehicle. After that, the government decides the number of vehicle  $K = \{k_1, k_2, \dots, k_k\}$  and loaded quantity according to the package attributes and maximum capacity  $w_k$ . Finally, the optimal vehicle routing is programmed to fulfill the fresh agri-product emergency supply of all communities. It is noteworthy that, the community demand could be served by multiple vehicles to improve emergency supply efficiency.

Generally, the integrated multi-item packaging and vehicle routing with split delivery problem involves three decisions, i.e., (1) how to decide the optimal packaging scheduling of fresh agri-products with multiple categories, (2) how to minimize the number of vehicles by split delivery, (3) how to arrange time-efficient vehicle routings.

### 3.2. Objective function

In this study, three different objectives related to the fresh agri-product emergency supply at large-scale epidemic disease context are formulated: average response time, infectious risk possibility and transportation resource utilization.

#### (1) The average response time

To characterize the response efficiency of fresh agri-product emergency supply, it is unrepresentative to calculate the total delivery time. In this formulation, the arrival time of each demand node is used to describe the response time, which could intuitively reflect the rescue equality. Let  $N = \{i, j | 0, 1, 2, \dots, \text{cnum}\}$  denote the collection of nodes including one emergency distribution center and multiple communities, where  $i = 0$  denotes the emergency distribution center, and  $\text{cnum}$  denotes the number of communities. According,  $N' = N / \{0\}$  denotes the collection of community nodes. Let  $K = \{k | 1, 2, \dots, \text{knum}\}$  represent the collection of refrigerated vehicles, where  $\text{knum}$  is the number of vehicles.  $t_i^k$  denotes the arrival time of vehicle  $k$  at community  $i$ , and  $t_0^k = 0$ . The average response time objective function can be represented as Eq. (1)

$$\text{obj}_1 = \sum_{i \in N'} \max\{t_i^k\} / \text{cnum} \quad (1)$$

In the objective, we would minimize  $\text{obj}_1$ .

#### (2) The infectious risk possibility

The contact frequency is most relevant to epidemic disease spread. Although multiple deliveries could improve the efficiency of fresh agri-product emergency supply, frequent vehicle visit numbers of each community would increase the contact frequency between transportation staff and community service staff. At large-scale epidemic disease context, these may greatly increase the infection possibility. Therefore, reducing the split delivery appropriately is conducive to epidemic containment. In this study, the contact frequency between vehicle and community is formulated to characterize the infectious risk possibility. Let  $A = \{(i, j) | i, j \in N, i \neq j\}$  denote the arc set of the vehicle routing network. Let  $x_{ij}^k \in \{0, 1\}$  be a decision variable. If  $x_{ij}^k = 1$ , the arc  $(i, j)$  belongs to the delivery routing of vehicle  $k$ . That is, the vehicle  $k$  continuously serves community  $i$  and community  $j$ . The infectious risk possibility objective function can be represented as Eq. (2)

$$\text{obj}_2 = \sum_{j \in N'} \sum_{k \in K} \sum_{i \in N} x_{ij}^k \quad (2)$$

In the objective, we would minimize  $\text{obj}_2$ .

#### (3) The transportation resource utilization

Due to the large-scale quarantine intervention and transport network interruption of COVID-19, many logistics enterprises are closed, and transportation resources are extremely scarce. The available transportation resources are usually prioritized to deliver medical resources, which imposes more restrictions on the vehicle arrangement of fresh agri-product emergency supply (Pu and Zhong, 2020). In this context, conserving limited transportation resources is another focus of this study. That is to say, how to minimize the vehicle number to complete the fresh agri-product emergency supply is a crucial optimization strategy at large-scale epidemic disease context. To describe the transportation resource utilization, a decision variable  $y_k \in \{0, 1\}$  is introduced. The vehicle  $k$  is used to deliver fresh agri-products if  $y_k = 1$ . The total number of vehicles used is formulated to represent the transportation resource utilization, which can be expressed as Eq. (3)

$$\text{obj}_3 = \sum_{k \in K} y_k \quad (3)$$

In the objective, we would minimize  $\text{obj}_3$ .

### 3.3. Constraints

To model the fresh agri-product emergency supply at large-scale epidemic disease context, the multi-item packaging and vehicle routing with split delivery are integrated to improve rescue efficiency. Let  $P = \{p | 1, 2, \dots, \text{pnun}\}$  represent the collection of fresh agri-product category, where  $\text{pnun}$  is the number of categories. Let  $q_{ip}^k$  denote the category  $p$  quantity of community  $i$  delivered by vehicle  $k$ .  $z_{ip}^k \in \{0, 1\}$  is a decision variable, and the category  $p$  of community  $i$  is loaded in vehicle  $k$  if  $z_{ip}^k = 1$ .  $d_i^p$  is the demand quantity of category  $p$  of community  $i$ . Constraints are given as follows.



$$\sum_{i \in N'} \sum_{p \in P} q_{ip}^k \leq w_k y_k \quad \forall k \in K \quad (4)$$

$$\sum_{k \in K} z_{ip}^k \geq 1 \quad \forall i \in N', p \in P \quad (5)$$

$$\sum_{k \in K} q_{ip}^k = d_i^p \quad \forall i \in N', p \in P \quad (6)$$

$$z_{ip}^k + z_{ip'}^k \leq y_k \quad \forall i \in N', p, p' \in P, k \in K, \lambda_{pp'} = 1 \quad (7)$$

$$\sum_{i \in N} \sum_{k \in K} x_{ij}^k \geq 1 \quad \forall j \in N' \quad (8)$$

$$\sum_{i \in N} x_{ij}^k = \sum_{i \in N} x_{ji}^k \quad \forall j \in N, k \in K \quad (9)$$

$$\sum_{j \in N'} x_{0j}^k = y_k \quad \forall k \in K \quad (10)$$

$$\sum_{i \in N'} x_{i0}^k = y_k \quad \forall k \in K \quad (11)$$

$$t_i^k + \tau_{ij} - (1 - x_{ij}^k)M \leq t_j^k \quad \forall i, j \in N, k \in K \quad (12)$$

$$Mz_{ip}^k \geq q_{ip}^k \quad \forall i \in N', p \in P, k \in K \quad (13)$$

$$y_k \geq z_{ip}^k \quad \forall i \in N', p \in P, k \in K \quad (14)$$

$$t_i^k \geq 0 \quad \forall i \in N, k \in K \quad (15)$$

$$q_{ip}^k \geq 0 \quad \forall i \in N', p \in P, k \in K \quad (16)$$

$$z_{ip}^k, y_k, x_{ij}^k \in \{0, 1\} \quad \forall i, j \in N, p \in P, k \in K \quad (17)$$

Constraints (4)–(7) indicate the rules of multi-item packaging. Constraint (4) is a packaging weight limit  $w_k$  of vehicle  $k$ . Constraint (5) states that each category fresh agri-product of community can be served by at least one vehicle. Constraint (6) ensures the fresh agri-product demand of community can be satisfied. Constraint (7) denotes the compatibility between multiple fresh agri-product categories. If categories  $p$  and  $p'$  of fresh agri-products are incompatible in food cold chain temperature,  $\lambda_{pp'} = 1$  and they cannot be loaded in one refrigerated vehicle. Constraints (8)–(12) are the rules of vehicle routing. Constraint (8) ensures that each community can be served by at least one vehicle. Constraint (9) describes the network flow balance of vehicles, that is, the vehicle arrives at a certain node and then must leave this node. Constraints (10) and (11) indicate that all vehicles can leave and return to the emergency distribution center at most once. Constraint (12) eliminates the sub-tours of vehicle  $k$ , and describes the time continuity of community  $i$  and  $j$ .  $M$  is defined as a large positive constant, and  $\tau_{ij}$  is defined as vehicle transport time between community  $i$  and  $j$ . If vehicle  $k$  delivers from community  $i$  to  $j$  ( $x_{ij}^k = 1$ ), the arrival time of community  $j$  satisfies  $t_j^k \geq t_i^k + \tau_{ij}$ , otherwise Constraint (12) is equivalent to  $t_i^k + \tau_{ij} - t_j^k \leq M$ . Constraints (13)–(17) define the properties of variables. Constraints (13) and (14) demonstrate the synchronization between variables  $z_{ip}^k$ ,  $q_{ip}^k$  and  $y_k$ . Constraint (13) relates the variables  $z_{ip}^k$  and  $q_{ip}^k$ . For example, if vehicle  $k$  does not distribute category  $p$  of fresh agri-products to community  $i$ ,

$z_{ip}^k = q_{ip}^k = 0$ ; otherwise,  $q_{ip}^k \leq M$ . Constraint (14) describes the relationship between the variables  $y_k$  and  $z_{ip}^k$ . If vehicle  $k$  is not used,  $y_k = z_{ip}^k = 0$ ; otherwise,  $z_{ip}^k \leq 1$ . Constraints (15) and (16) indicate value ranges of variables  $t_i^k$  and  $q_{ip}^k$ . Constraint (17) defines  $z_{ip}^k$ ,  $y_k$  and  $x_{ij}^k$  as binary decision variables.

### 3.4. Model formulation

According to the discussions in Subsections 3.2 and 3.3, the fresh agri-product emergency supply model is formulated as a split delivery vehicle routing problem with multi-item packaging. However, in the  $obj_1$  function, the response time of each community is defined as the maximum arrival time of multiple deliveries, which is not straightforward in the mathematical formulation. To linearize this objective function, a new defining variable  $\mu_i$  is introduced and a correspondent constraint is added as Eq. (18)

$$obj_1' = \sum_{i \in N'} \mu_i / cnum \quad (18)$$

$$\mu_i \geq t_i^k \quad \forall i \in N', k \in K \quad (19)$$

Eq. (18) is the simplified average response time function, where  $\mu_i = \max\{t_i^k\}$ . Constraint (19) indicates that  $\mu_i$  is greater than arrival times of all vehicles at community  $i$ . That is to say, variable  $\mu_i$  satisfies the maximum of  $t_i^k$ .

In addition, there are three objectives with different magnitudes in the optimization model. Considering the solution complexity and decision preference, the weighted sum method is adopted to integrate these three objectives and transform them into one equivalent objective function in this study (Zhang et al., 2020). The weighted sum method could specify weights to obtain more focused solutions (Kaddani et al., 2017). The weights of three objectives are set as a convex combination, i.e.,  $\lambda_1, \lambda_2, \lambda_3 \geq 0$  and  $\lambda_1 + \lambda_2 + \lambda_3 = 1$ . To solve the magnitude differences of  $obj_1'$ ,  $obj_2$ , and  $obj_3$ , the min-max normalization method is applied to transform the multiple objectives to a scalar optimization problem (Mausser, 2006; Sheu, 2007). Therefore, the integrated multi-item packaging and vehicle routing with split delivery model for fresh agri-product emergency supply can be described as Eqs. (20) and (21)

$$\begin{aligned} \text{Minimize } obj = & \lambda_1 \left[ \frac{obj_1' - \underline{obj_1'}}{\overline{obj_1'} - \underline{obj_1'}} \right] + \lambda_2 \left[ \frac{obj_2 - \underline{obj_2}}{\overline{obj_2} - \underline{obj_2}} \right] \\ & + \lambda_3 \left[ \frac{obj_3 - \underline{obj_3}}{\overline{obj_3} - \underline{obj_3}} \right] \end{aligned} \quad (20)$$

$$\text{subject to Constraints (4) – (17) and (19)} \quad (21)$$

where  $\underline{obj_1'}$ ,  $\underline{obj_2}$  and  $\underline{obj_3}$  are the lower bounds of  $obj_1'$ ,  $obj_2$ , and  $obj_3$ , and  $\overline{obj_1'}$ ,  $\overline{obj_2}$  and  $\overline{obj_3}$  are the upper bounds of  $obj_1'$ ,  $obj_2$ , and  $obj_3$ . The lower and upper bounds are calculated by the box constraint (Mausser, 2006). For example,  $\underline{obj_1'}$ ,  $\underline{obj_2}$  and  $\underline{obj_3}$  could be set to 0 based on Constraints (15) and (17) in the model.  $\overline{obj_1'}$ ,  $\overline{obj_2}$  and  $\overline{obj_3}$  could be set according to Constraints (6), (7), (12) and demand information. In the integrated model, we could minimize  $obj$  with Constraints (4) – (17) and (19).

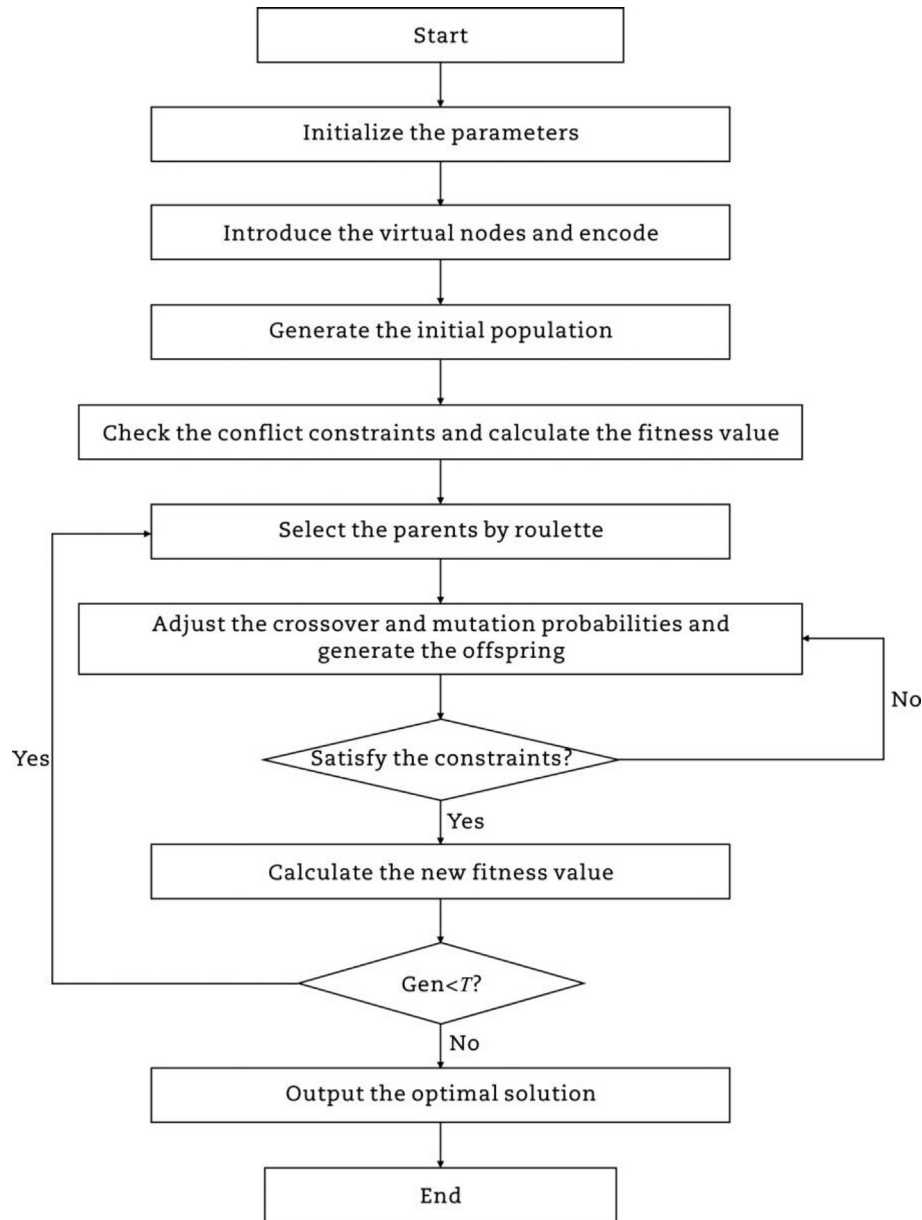


Fig. 2 – Flow chart of the improved genetic algorithm based on solution features.

#### 4. An improved genetic algorithm based on solution features

In this study, the fresh agri-product emergency supply problem is formulated as an integrated multi-item packaging and vehicle routing with split delivery problem, and decision variables can be divided into two parts, i.e., multi-item packaging variables ( $z_{ip}^k, q_{ip}^k$ ) and vehicle routing variables ( $x_{ij}^k, y_k$ ). As the number of decision variables increases, the solution complexity and computation time will increase accordingly. An IGA-SF is designed to obtain the optimal solution in a short time for medium-to-largescale cases.

##### 4.1. Coding strategy based on solution feature

Due to the conflict between massive demands and limited transportation resources at large-scale epidemic disease context, the split delivery of communities is inevitable. In this model, a balance between the time efficiency and delivery frequency is needed to simultaneously optimize the average response time, contact frequency and the number of vehicles used. Assume that each category of fresh agri-products in one community demand order will not exceed the vehicle maximum capacity, otherwise the demand could be split into two parts, i.e., the vehicle capacity and remaining quantity. Then, the virtual points are introduced to replace the real

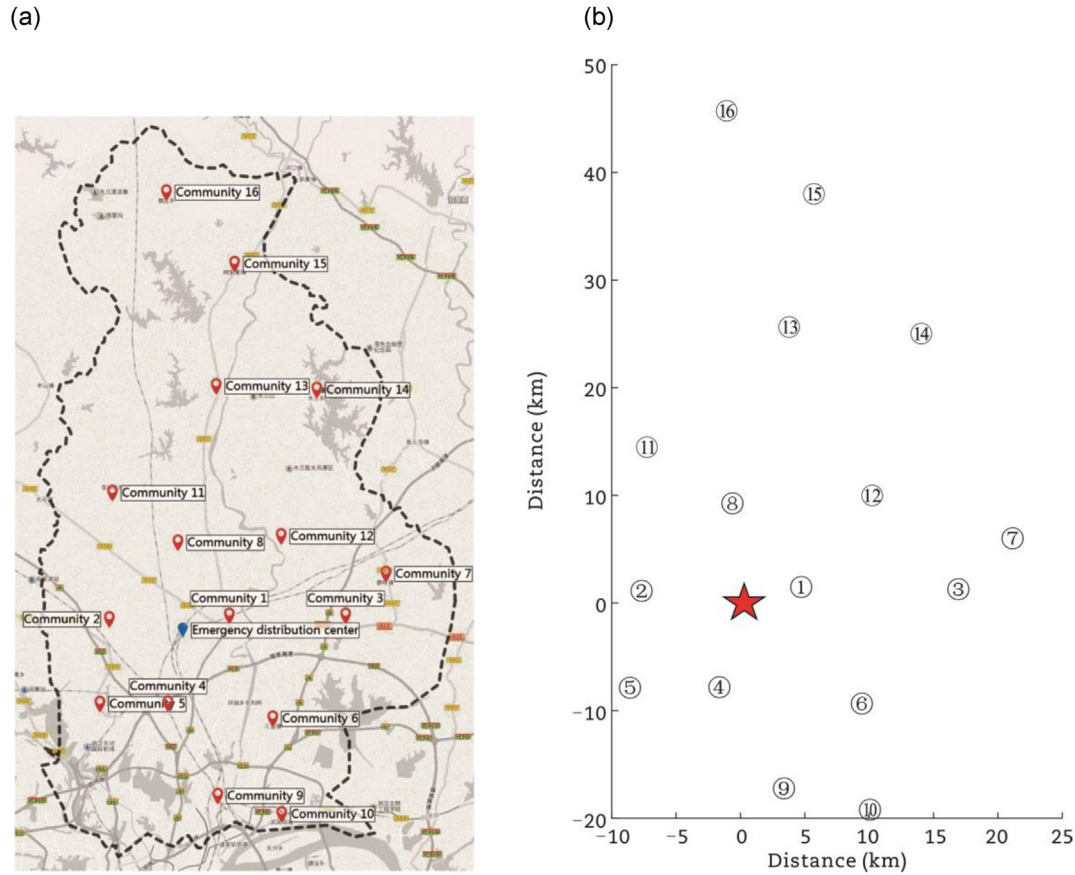


Fig. 3 – Schematic diagram of spatial coordinates. (a) Geographic location on the map. (b) Position in the coordinate.

community nodes, which could describe the single category of community. Set the individual codes according to the number of virtual points, and the code length is  $(\text{cnum} \times \text{pnum} + \text{knum} - 1)$ , where  $\text{cnum}$ ,  $\text{pnum}$  and  $\text{knum}$  represent the number of communities, fresh agri-product categories and refrigerated vehicles.

#### 4.2. Self-adaptive genetic operator probability

To improve the exploratory ability, a nonlinear curve is introduced to adjust the crossover and mutation operator probabilities. The crossover probability  $p_c$  and mutation probability  $p_m$  can be adaptively adjusted according to the fitness value, which is conducive to leaving out the local optimal solution.  $p_c$  and  $p_m$  are calculated as Eqs. (22) and (23)

$$p_c = \frac{e^{k_1 f_{\max}}}{e^{k_1 f_{\max}} + e^{k_1 f_{\text{avg}}}} \quad (22)$$

$$p_m = \frac{e^{k_2 f_{\max}}}{e^{k_2 f_{\max}} + e^{k_2 f_{\text{avg}}}} \quad (23)$$

where  $f_{\max}$  and  $f_{\text{avg}}$  are the optimal and average individual fitnesses, respectively. Set  $0 \leq k_1, k_2 \leq 1$ ,  $0.5 \leq p_c \leq 1$  and  $0 \leq p_m \leq 0.5$ . When the gap between  $f_{\text{avg}}$  and  $f_{\max}$  is small, the values of  $p_c$  and  $p_m$  would increase, which is conducive to preserving excellent individuals. When the gap between  $f_{\text{avg}}$  and  $f_{\max}$  increases, the value of  $p_c$  and  $p_m$  are small, which could eliminate poor individuals.

#### 4.3. Implementation of the solution algorithm

The implementation of IGA-SF is demonstrated as follows.

- Step 1: Initialize the parameters of the population size  $N$ , iteration number  $T$ , crossover and mutation probabilities  $p_c$ ,  $p_m$ .
- Step 2: Introduce the virtual points to encode by analyzing the features of demands.
- Step 3: Generate the initial population  $P$  according to constraints Eqs. (4)–(14).
- Step 4: Check the conflict constraints and calculate the fitness value according to Eq. (20).
- Step 5: Select the parents  $P_1$  through roulette selection from the current population.
- Step 6: Generate the offspring  $P_2$  according to Step 6.1–6.2.
- Step 6.1: Adjust the crossover and mutation probabilities adaptively based on Eqs. (22) and (23).
- Step 6.2: Determine whether the offspring  $P_2$  satisfies the constraints.
- Step 7: Calculate the new fitness value again.
- Step 8: Check the current iteration number  $\text{Gen}$ . If  $\text{Gen} < T$ , then return to Step 5; otherwise, output the optimal solution.

The flow chart of proposed solution algorithm is shown in Fig. 2.



**Table 1 – Coordinates and fresh agri-product demands of communities in Huangpi District, Wuhan.**

Number of community	Coordinate (km)	Demand <sup>a</sup> (kg)
1	(4.9, 1.4)	[7799, 6463, 5834, 2394]
2	(−7.7, 1.0)	[3533, 2928, 2643, 1085]
3	(17.1, 1.3)	[3458, 2865, 2587, 1061]
4	(−1.6, −7.9)	[2306, 1911, 1725, 708]
5	(−8.6, −7.9)	[295, 244, 220, 90]
6	(9.5, −9.5)	[211, 175, 158, 65]
7	(21.3, 5.8)	[1093, 906, 817, 335]
8	(−0.6, 9.1)	[2369, 1964, 1772, 727]
9	(3.5, −17.5)	[679, 563, 508, 208]
10	(10.2, −19.6)	[523, 434, 391, 161]
11	(−7.3, 14.4)	[3179, 2635, 2378, 976]
12	(10.4, 9.8)	[2295, 1902, 1717, 705]
13	(3.8, 25.5)	[1500, 1243, 1122, 460]
14	(14.2, 25.2)	[1341, 1111, 1003, 412]
15	(5.7, 38)	[1612, 1336, 1206, 495]
16	(−1.1, 45.7)	[1330, 1102, 995, 408]

Note: Demand<sup>a</sup> represents the demand quantity of four categories of fresh agri-products, i.e., [vegetable demand quantity, fruit demand quantity, meat demand quantity, fish demand quantity].

## 5. Numerical experiments

The numerical results are reported in this section. Subsection 5.1 presents the community information of Huangpi District in Wuhan and gives the optimal emergency supply scheduling. Subsection 5.2 verifies the feasibility of different application scenarios by varying the weight of objectives. Subsection 5.3 examines the performance of the proposed algorithm from aspects of iteration number and CPU time. The numerical experiments in this section are performed on an Intel Core i3-8100 3.60 GHz processor with 16 GB RAM and the optimization routines are conducted on the MATLAB 2017.

### 5.1. A case on the Corona Virus Disease 2019 (COVID-19)

To verify the practical application of the model, this study carries out a typical case on fresh agri-product emergency supply of Huangpi District, Wuhan in the context of the Corona Virus Disease 2019 (COVID-19). All the data information is derived from government statistics and official news. Huangpi District is the most populous area in Wuhan, which has 15 streets and a township. The geographic locations are calculated from the Google Maps in Fig. 3(a). In this case, 15 streets and a township are formulated as 16 community nodes. The logistics park in this district is defined as an emergency distribution center, and set as the origin of coordinates. In Fig. 3(b), the red star represents the emergency distribution center, and circles 1 to 16 represent the community nodes.

For simplicity without loss of generality, four main categories of fresh agri-products are considered in this case according to the resident daily diet, i.e., vegetable, fruit, meat

and fish (Adekomaya et al., 2016). The temperature ranges in the food cold chain are mainly divided into four intervals, i.e., frozen (approximately  $-18^{\circ}\text{C}$ ), cold chill ( $0^{\circ}\text{C}$ – $1^{\circ}\text{C}$ ), medium chill (approximately  $5^{\circ}\text{C}$ ) and exotic chill ( $10^{\circ}\text{C}$ – $15^{\circ}\text{C}$ ) (Ndraha et al., 2018). Cold chill food includes fish and meat (Gao et al., 2020; Hassoun et al., 2019). Exotic-chilled food includes vegetable and fruit (Duan et al., 2020; Zubeldia et al., 2016). Therefore, the compatibility between these four fresh agri-product categories is defined according to the temperature of food cold chain, i.e., vegetable and fruit are compatible, and fish and meat are compatible. That is to say, the multi-item packaging rule requires that the fruit and vegetable cannot be transported together with meat and fish. The demand quantities of each community node are calculated by multiplying the population of Huangpi District and fresh agri-product annual purchases of households per capita in Hubei Province (Hubei Provincial Bureau of Statistics, 2019). According to estimates, the purchase demands of vegetable, fruit, meat and fish per meal are 50, 41, 37 and 15 g/person, respectively. Table 1 gives the detailed coordinates and four category demands of each community.

The large-sized refrigerated vehicles are used for delivery according to the publicly available news at large-scale epidemic disease context. The vehicle speed in the city is set to 50 km/h and the capacity is set to 17.2 t (Adekomaya et al., 2017; Castelein et al., 2020). To show the joint optimization of model proposed in this study, the weights of three objective functions are assumed as  $\lambda_1 = \lambda_2 = \lambda_3 = 1/3$ . The IGA-SF parameters are set as follows:  $N = 100$ ,  $T = 1000$ ,  $p_c = 0.9$ , and  $p_m = 0.05$ . The Huangpi District case is tested 10 times, and the optimal fresh agri-product emergency supply scheduling is shown in Table 2 and Fig. 4.

Eight vehicles are used to deliver the fresh agri-products to 16 communities. For example, vehicle 1 delivers 3533 kg vegetable and 2928 kg fruit to community 2, then delivers 523 kg vegetable and 434 kg fruit to community 10, and returns to the distribution center. Note that, due to the incompatibility and capacity constraints, the community 1 would be served 4 times (bold font in Table 2). For community 1, vehicle 4 delivers 7799 kg vegetable and 1983 kg fruit, vehicle 5 delivers 4480 kg fruit, vehicle 6 delivers 5834 kg meat and 1721 kg fish, and vehicle 7 delivers 673 kg fish, respectively. The average response time is 63 min, and the contact frequency between vehicle and community in this supply scheduling is 35.

### 5.2. Numerical analysis of application scenarios

In Subsection 5.1, the weights  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  are set as  $1/3$  to equalize the importance of average response time, infectious risk possibility and transportation resource utilization objectives. However, the different severity and evolutionary of epidemic disease will affect the aims of decision-making. For example, in the early stage of the epidemic disease, the time-effectiveness is the primary consideration for government due to the large-scale quarantine and massive fresh agri-product demands. In this case, increasing the

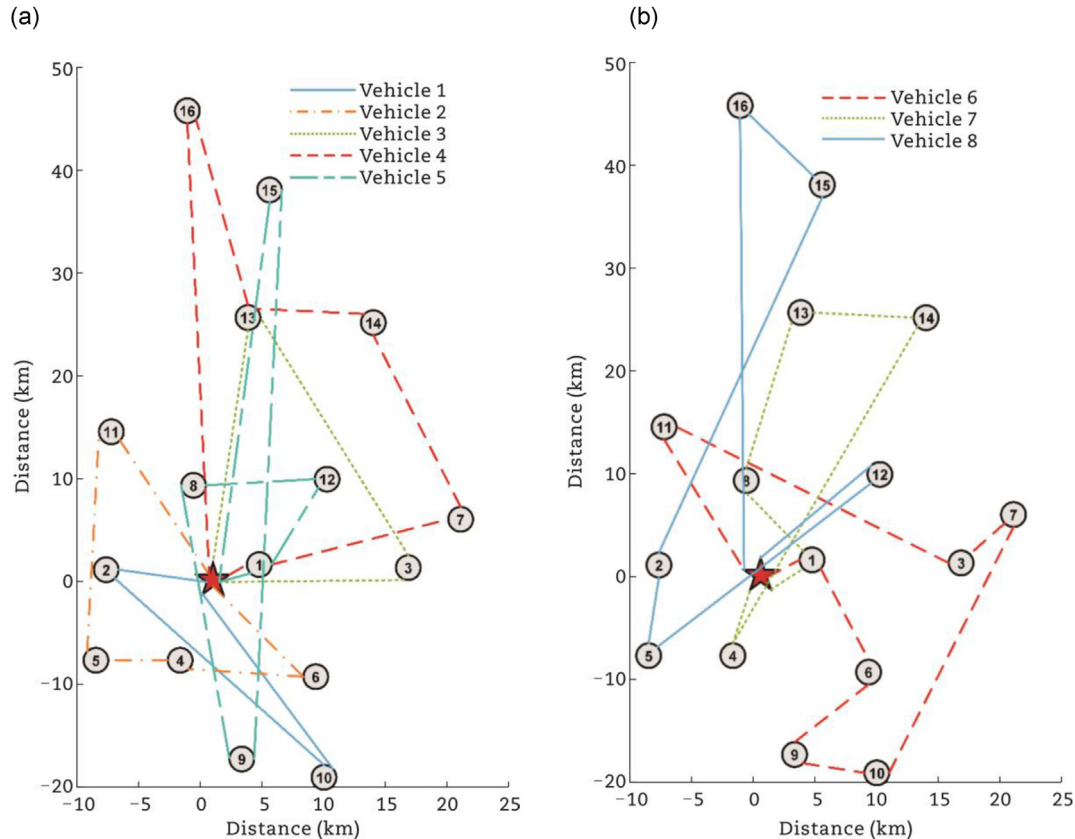
**Table 2 – Optimal fresh agri-product emergency supply scheduling.**

Fresh agri-product category	Vehicle	The optimal vehicle routing <sup>a</sup>	
Vegetable & fruit <sup>a</sup>	1	0 → 2 (3533, 2928) → 10 (523, 434) → 0	
	2	0 → 6 (211, 175) → 4 (2306, 1911) → 5 (295, 244) → 11 (3179, 2635) → 0	
	3	0 → 3 (3458, 2865) → 13 (1500, 708) → 0	
	4	0 → <b>1 (7799, 1983)</b> → 7 (1093, 906) → 14 (1341, 1111) → 13 (0, 535) → 16 (1330, 1102) → 0	
	5	0 → <b>1 (0,4480)</b> → 12 (2295, 1902) → 8 (2369, 1964) → 9 (679, 563) → 15 (1612, 1336) → 0	
Meat & fish <sup>b</sup>	6	0 → <b>1 (5834, 1721)</b> → 6 (158, 65) → 9 (508, 208) → 10 (391, 161) → 7 (817, 335) → 3 (2587, 1061) → 11 (2378, 976) → 0	
	7	0 → <b>1 (0, 673)</b> → 8 (1772, 727) → 13 (1122, 460) → 14 (1003, 412) → 4 (1725, 708) → 0	
	8	0 → 12 (1717, 705) → 5 (220, 90) → 2 (2643, 1085) → 15 (1206, 495) → 16 (995, 408) → 0	
Experimental result	Average response time (min)	Contact frequency	Number of vehicle
	63	35	8
Note: <sup>a</sup> The optimal routing in vegetable & fruit row are represented as: Emergency distribution center → Community i (deliver vegetable quantity, deliver fruit quantity) → Community j (deliver vegetable quantity, deliver fruit quantity) → Emergency distribution center. <sup>b</sup> The optimal routing in meat & fish row are represented as: Emergency distribution center → Community i (deliver meat quantity, deliver fish quantity) → Community j (deliver meat quantity, deliver fish quantity) → Emergency distribution center.			

value of  $\lambda_1$  is an effective method to highlight the importance of average response time objective. When the epidemic disease is gradually controllable, the delivery cost could be considered properly by increasing the value of  $\lambda_3$ . Therefore, to verify the impact of weights  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  in determining

optimal fresh agri-product supply schemes, three typical scenarios are set which only consider  $obj_1$ ,  $obj_2$ ,  $obj_3$ , respectively. The optimal results are shown in Table 3.

Case 1 only considers the average response time objective ( $obj_1$ ) and obtains the minimum average response time with



**Fig. 4 – Schematic diagrams of the optimal vehicle routing. (a) Routing for delivering vegetable and fruit. (b) Routing for delivering meat and fish.**

**Table 3 – Optimal scheduling in three application scenarios.**

Application scenario	Weight setting	Experimental result		
		obj <sub>1</sub> (min)	obj <sub>2</sub>	obj <sub>3</sub>
Case 1	$\lambda_1 = 1, \lambda_2 = 0, \lambda_3 = 0$	48	34	15
Case 2	$\lambda_1 = 0, \lambda_2 = 1, \lambda_3 = 0$	69	32	15
Case 3	$\lambda_1 = 0, \lambda_2 = 0, \lambda_3 = 1$	87	36	7

48 min. In order to pursue the maximum time efficiency, the government needs to assign all available vehicles to deliver the fresh agri-products. Case 2 only considers the infectious risk possibility objective (obj<sub>2</sub>) and the minimum contact frequency is 32. Due to the incompatibility of fresh agri-product categories, it is inevitable to serve each community node at least twice. Although it may have little practical significance for common disasters, controlling the contact frequency is an effective method to reduce the infectious risk at the epidemic disease context. In addition, considering contact frequency is conducive to reducing the cost of multi-temperature joint distribution mode. Case 3 only considers the transportation resource utilization objective (obj<sub>3</sub>) and the minimum number of vehicles used is 7. Reducing the number of vehicles would increase the delivery time and contact frequency. For the scenario with insufficient transportation resource, this decision could maximize the utilization of limited vehicles. Similarly, it can also reduce the rescue costs.

In general, these three cases provide the possibility for the government to make decisions flexibly. In the practice of fresh

agri-product emergency supply, the government could adjust the values of  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  to make the optimal scheduling according to different rescue requirements.

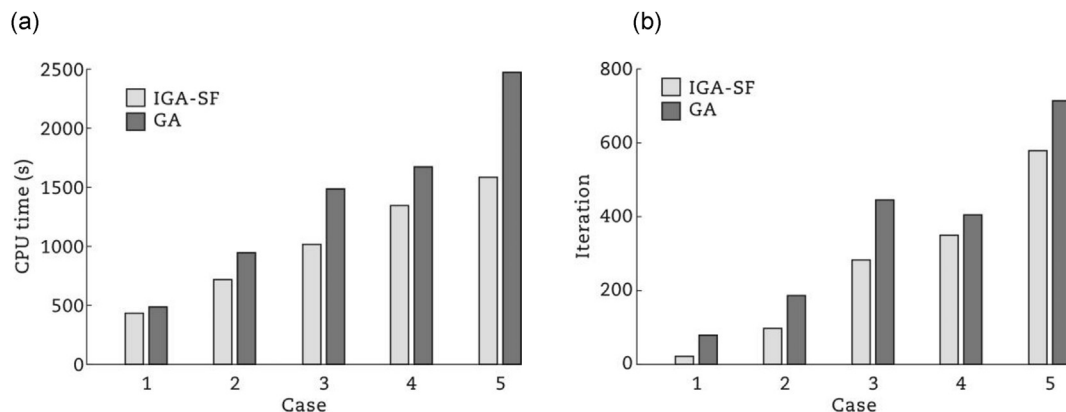
### 5.3. Medium-to-large scale numerical experiment

To further verify the efficiency of proposed algorithm, five medium-to-largescale cases are tested with 20, 30, 40, 50 and 60 communities, respectively. For each case, suppose the fresh agri-product category is 4 (i.e., vegetable, fruit, meat, fish). The delivery times between two nodes are generated randomly from an integer within [0, 60]. The fresh agri-product demands are generated randomly from [400, 5000]. The weights of objectives are set to  $\lambda_1 = \lambda_2 = \lambda_3 = 1/3$ . The max iteration number is 1000. To obtain more convincing results, each case is tested five times and the average values are selected to demonstrate the performances of proposed model and algorithm. The numerical results are shown in Table 4, which contains the number of communities (abbreviated as No. comm.), average response time in minutes (abbreviated as Avg. res.), average number of vehicles (abbreviated as Avg. veh.), average CPU time in seconds (abbreviated as Avg. CPU) and average iteration number (abbreviated as Avg. iter.).

In case 1, the traditional distribution method without split delivery obtains the average response time of 65 min, and the vehicle number is 13. The integrated model proposed in this study has an average response time of 76 min and the vehicle number is 11. From case 2 to case 5, the integrated model could obtain a solution that achieves an optimal balance between the response time and delivery vehicle number

**Table 4 – Numerical results of medium-to-largescale cases.**

Case	No. comm.	Traditional model		Integrated model		GA		IGA-SF	
		Avg. res. (min)	Avg. veh.	Avg. res. (min)	Avg. veh.	Avg. CPU (s)	Avg. iter.	Avg. CPU (s)	Avg. iter.
1	20	65	13	76	11	479.63	77	432.73	21
2	30	81	22	83	17	941.38	186	718.32	96
3	40	88	26	86	23	1479.05	442	1020.05	284
4	50	101	34	97	28	1660.11	404	1344.67	350
5	60	119	41	112	32	2474.58	713	1583.11	579



**Fig. 5 – Comparison of computational performance between IGA-SF (genetic algorithm based on solution features) and GA (genetic algorithm). (a) Comparison of CPU time between IGA-SF and GA. (b) Comparison of iteration number between IGA-SF and GA.**

simultaneously, compared with traditional distribution method. As the community number increases, the superiority of the integrated model becomes more obvious. That is, the integrated model proposed in this study is an effective method to deliver massive and diverse fresh agri-products. Especially in addressing the scattering demands, the superiority of integrating multi-item packaging and vehicle routing with split delivery will be more prominent.

In addition, the computational performance results of IGA-SF and GA are reported in Table 4 and Fig. 5. The average CPU time and iteration number of IGA-SF are significantly less than these of GA. Compared with GA, the IGA-SF proposed in this study saves an average of 23.91% CPU time and reduces the iteration number by 37.80% on average. Especially for the largest case with 60 communities, the CPU time of IGA-SF is within half an hour, while CPU time of GA is more than 40 min. Generally, the proposed IGA-SF converges the optimal solution with few iterations and shorter time. The integrated model in this study could solve the medium-to-larges scale cases within a reasonable time, which is feasible for practical application.

## 6. Conclusions

In this study, a joint optimization model is proposed to address the fresh agri-product emergency supply issue at large-scale epidemic disease context. The model optimizes the average response time, infectious risk possibility and transportation resource utilization simultaneously. To solve the problem of massive and diverse agri-product demands, a multi-item packaging strategy is designed according to the food cold chain temperature. An optimization model is formulated by integrating the multi-item packaging and vehicle routing with split delivery to determine the optimal emergency supply scheduling. The proposed model in this study represents a feasible method to deal with the fresh agri-product supply chain disruption in emergency context. The objectives focus on rescue efficiency rather than economic costs, which is different from traditional freight supply. Moreover, numerical experiments demonstrate the superiority of IGA-SF computational performance, which could save CPU time and iteration number by 23.91% and 37.80% on average than GA. Generally, the joint optimization model proposed in this study could balance the conflict between time and resources, and satisfy different application scenarios by weight adjustment, which has promising applications for fresh agri-product emergency supply at large-scale epidemic disease context.

This study establishes new approaches for further research in fresh agri-product emergency supply. Firstly, the fresh agri-product emergency supply scheduling in this study is decided within a single period. With the expansion of rescue scale, considering the dynamic decision-making in multiple periods is a future research direction. Secondly, the delivery time is calculated to represent the response time, while the packaging time and community service time are not incorporated. Further research could characterize these processes in more detail. Thirdly, the fresh agri-product emergency supply scheduling is based on the known demand information. To

obtain more rescue time, forecasting the future demands of communities could satisfy more application scenarios.

## Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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