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Dynamic Optimization of Emergency Logistics for Major Epidemic Considering Demand Urgency

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Abstract: In recent years, epidemic disasters broke through frequently around the world, posing a huge threat to economic and social development, as well as human health. A fair and accurate distribution of emergency supplies during an epidemic is vital for improving emergency rescue efficiency and reducing economic losses. However, traditional emergency material allocation models often focus on meeting the amount of materials requested, and ignore the differences in the importance of different emergency materials and the subjective urgency demand of the disaster victims. As a result, it is difficult for the system to fairly and reasonably match different scarce materials to the corresponding areas of greatest need. Consequently, this paper proposes a material shortage adjustment coefficient based on the entropy weight method, which includes indicators such as material consumption rate, material reproduction rate, durability, degree of danger to life, and degree of irreplaceability, to enlarge and narrow the actual shortage of material supply according to the demand urgency. Due to the fact that emergency materials are not dispatched in one go during epidemic periods, a multi-period integer programming model was established to minimize the adjusted total material shortage based on the above function. Taking the cases of Wuhan and Shanghai during the lockdown and static management period, the quantitative analysis based on material distribution reflected that the model established in this paper was effective in different scenarios where there were significant differences in the quantity and structure of material demand. At the same time, the model could significantly adjust the shortage of emergency materials with higher importance and improve the satisfaction rate.

Keywords: major epidemic; demand urgency; emergency logistics; material distribution optimization

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1. Introduction

The outbreak of COVID-19 caused huge disasters and heavy losses worldwide, which also triggered people's reflection and attention on the prevention and control of major epidemics and material support [1]. The issue of how to allocate scarce emergency materials reasonably has become a key concern for ensuring patient safety and reducing losses. Researchers [2–5] have addressed this issue from a variety of perspectives, primarily studying how to optimize the allocation of scarce emergency materials to reduce delivery times, reduce costs, and maximize demand satisfaction. The current research on emergency management material allocations still has limitations, as most models only focus on single-period allocations. However, for major public health events, as an epidemic develops, the demand for emergency materials will accordingly change dynamically [6]. Therefore, this study considered the demand characteristics of different periods of epidemic disasters and established a dynamic multi-period model to optimize material allocation.

During the outbreak of major epidemics, the supply of emergency materials often cannot meet the demand, and there is a serious of shortages of medical equipment, protective equipment, and daily necessities. The shortage of medical materials will lead to an increase in the spread of the epidemic. Therefore, this study took the shortage of materials as the optimization goal, aiming to improve the satisfaction rate of patients and further ensure their health.

Among the many shortages of emergency materials, different categories of materials have different demand characteristics. For example, consumables need to be delivered regularly to meet the needs of each person multiple times, but materials with high durability usually need to be delivered only once to each person [7]. Nevertheless, a low distribution efficiency will not only delay the delivery of emergency materials and increase the suffering of people affected, but for patients who rely on specific emergency materials, a shortage will directly endanger their lives, thus creating a greater social security risk [8]. However, research on the emergency material allocation of major public health events ignores the patients' subjective feelings. In this case, this study considered both the objective characteristics of scarce materials and the subjective urgency of patients' demand for materials and constructed an emergency material demand urgency index system to quantify and distinguish the urgency of different emergency materials.

To minimize casualties and property damage in disaster areas and to distribute emergency materials in the shortest time, emergency relief must simultaneously achieve the goal of efficiently, accurately, and equitably meeting the demand for emergency materials. Therefore, based on the proposed urgency of demand, this study designed a material shortage adjustment coefficient to adjust the amount of material shortage, reflecting not the traditional quantity of shortage, but taking into account the importance of materials, which is more in line with practical needs and achieving fair distribution.

Above all, this study took dynamic changes in emergency materials demand and differences in the urgency of emergency materials demand for various types of materials into consideration, to construct an index system indicating the urgency of emergency materials. Furthermore, this adjusted the goal of minimizing material shortage via the material shortage adjustment coefficient to develop a dynamic optimization model for emergency logistics with multi-period and multi-frequency distribution. This model ensured that high-importance emergency materials are distributed priority and that emergency materials are distributed fairly to improve emergency rescue.

This paper makes the following contributions:

(1) This paper proposes a dynamic optimization model for emergency logistics that takes multiple periods, frequencies, and types into account, in contrast to traditional emergency logistics, which only consider a single type of emergency material and a single period.
(2) Compared to the lack of research on patients' subjective feelings in the existing literature, this paper considers both the subjective feelings of patients towards the shortage of emergency materials, and the differences in the importance of different emergency materials, and establishes a demand urgency index system and numerical calculation method.
(3) Compared to existing models that focus on delivery time and cost as optimization objectives, the objective function of minimizing the total material shortage is improved by the material shortage adjustment coefficient, which is more in line with the fair distribution goal of balancing actual demand and material importance in reality.

The rest of this study is as follows. Section 2 presents the literature review. Section 3 introduces the assessment method of emergency material demand urgency. Section 4 constructs a dynamic distribution model of emergency materials that considers demand urgency. Section 5 presents an example analysis of two cities, Wuhan and Shanghai, at different stages of epidemic development. Section 6 presents the research conclusions and future research directions.

2. Literature Review

Generally, most researchers have studied emergency materials distribution by developing models and algorithms to provide decision-makers with solutions. Some researchers have focused on the improvement of emergency material distribution speed for vehicle routing problems. Xue et al. developed a multi-objective optimization model under capacity-constrained conditions, minimizing the shortest average waiting time for rescue at the affected point with access constraints [2]. Wang et al. proposed a scenario-specific emergency material distribution model with time windows to minimize emergency material loading and unloading time and distribution time [3]. Wang et al. developed a dual-objective mixed-integer programming model based on state–space–time networks with the minimum cost and the maximum emergency response speed to meet demands [9]. Wu et al. presented an emergency material dispatching model with a time window to satisfy the objective of minimum vehicle cost [10]. The above research shows that vehicle routing optimization is relatively rich for traditional emergency logistics in natural disasters.

Furthermore, to meet emergency relief needs more quickly, many researchers have studied the location problem of pre-disaster emergency facilities and post-disaster emergency facilities, as well as that of the emergency medical center. Boonmee and Kasemset proposed a decision model for locating, stocking, and distributing pre-disaster materials, which minimized response time as well as budget costs [4]. Ghasemi and Khalili-Damghani proposed a robust simulation optimization method to optimize the selection of emergency facility locations and material inventory during the planning stage [11]. Zhang et al. proposed a scenario-based stochastic planning method that integrated decisions on facility location, material inventory, and material distribution under different scenarios [12]. However, most of the models outlined above are single-period allocation models, which cannot be applied to the multi-period problem, where the demand amount changes dynamically over time. Only a few studies have explored multi-period models. Yang et al. proposed a robust optimization model, with a static pre-disaster phase and a dynamic post-disaster phase, for prepositioning the distribution of emergency supplies over multiple periods [13]. Wang et al. developed an optimization decision model for the dynamic distribution of emergency materials under fuzzy information conditions to minimize system loss and delay time [14]. While most of these studies focused on developing multi-period emergency logistics optimization under natural disasters, it was difficult to find emergency logistics studies that took into account how material demand changes with the spread of epidemics. Therefore, this paper focuses on the multi-period and multi-frequency allocation problem of emergency materials for major epidemics.

The main goal of the above studies was to design emergency logistics optimization strategies to improve the speed of material distribution and the efficiency of the allocation of relief facilities. However, it is also important to focus on the subjective perceptions of affected people regarding the effectiveness of humanitarian emergency relief, in addition to ensuring the efficiency of rescue [15]. Wang et al. designed a distress function to portray affected people's perceived distress costs using a numerical rating scale (NRS) and incorporated these factors into decision-making for the total costs of emergency response [16]. Zhu et al. measured psychological distress as an economic loss and developed a mathematical model to minimize total cost [17]. Sakiani et al. developed a mathematical model to minimize deprivation costs, fleet operation costs, and decision costs, solving a two-stage inventory routing problem [7]. Song et al. proposed an optimization model for the fair distribution of emergency supplies, which considered differentiated disaster classification, and aimed to minimize dispatching time and maximize fairness in emergency supplies distribution [18]. Zhan et al. designed a loss cost function to quantify the psychological tolerance of patients in case of a shortage of personal protective equipment; they then developed a location–allocation optimization model for emergency material distribution centers with the dual objective of minimizing loss cost and logistics cost [19]. According to the above research, the subjective feelings of disaster victims are usually quantified as costs to be modeled, but the internal connection between different materials shortages and the feelings of disaster victims is not taken into account, nor is the degree to which the materials affect their feelings.

Material allocation accuracy and fairness in emergency logistics optimization have been extensively studied [20–22]. When the pandemic occurs, the COVID-19 spreads very quickly. Accordingly, some scholars have introduced the concept of demand urgency to reduce the impact of different demand amounts on the fair distribution among different demand points. Hu et al. proposed a dynamic distribution model of emergency medical materials based on the demand urgency of materials, with the maximization of the weighted demand satisfaction rate as the main goal [5]. Zhao et al. constructed an evaluation index system for demand urgency and then developed a dual-objective model that minimizes distribution costs and prioritizes the distribution of demand points with the higher demand urgency [23]. Wang et al. developed a multi-objective optimization model that maximizes the satisfaction of affected people, minimizes the cost, and distributes fairly based on the demand urgency [24]. Liu et al. improved the index system for evaluating demand urgency and constructed a multi-objective model that maximizes both demand urgency and full load rate while minimizing the total cost of vehicle distribution [25]. Li et al. introduced the time penalty cost function to characterize the urgency of emergency material demand and proposed an uncertain location–allocation model for the emergency facility that minimizes time penalty cost, distribution cost, and carbon dioxide emissions [26]. Most studies suggest that introducing emergency material demand urgency can effectively improve material allocation fairness and accuracy. However, the urgency considerations for emergency material demand are not comprehensive. Therefore, this paper further improves the demand urgency indicator system.

The existing studies have laid a solid foundation for the research on the emergency material allocation problem. However, existing studies still have several gaps:

(1) There has been a lack of consideration for the dynamic change of emergency material demand during major epidemics. Currently, most research focuses on single-period material allocation models, which cannot be applied to the multi-period emergency material allocation problem.
(2) The relationship between the shortage of different types of materials and patients' pain perception was not fully considered in the modeling. It is not practical that regarding different types of materials as equally important.
(3) Current research on the urgency of emergency materials demand during major epidemics is not sufficient. In addition, the evaluation factors of demand urgency are not comprehensive.

The following contributions have been made to bridge the above research gap:

(1) Based on patients' subjective feelings towards different emergency materials and the differences in the importance of emergency materials, a more comprehensive demand urgency evaluation system was developed and the calculation of demand urgency was proposed accordingly.
(2) Integrating the urgency of material demand into dynamic emergency material allocation, a dynamic optimization model for emergency logistics was established, which minimizes the total amount of emergency material shortage over multi-period and multi-frequency distributions.
(3) Based on the demand urgency, the concept of material shortage adjustment coefficient was proposed for major epidemic emergency logistics. The objective of minimizing the total material shortage was adjusted by the material shortage adjustment coefficient to enhance the fairness of material allocation.

3. Demand Urgency Assessment of Emergency Material

In the context of emergency supply, demand urgency refers to the priority of satisfaction after the occurrence of demand. In the existing research, the demand urgency mainly has two connotations. The first connotation focuses on the categorization of the affected degree of the disaster areas, giving weights to different areas according to the severity of the disaster, such as increasing the priority of areas with greater weight and reducing the priority of areas with a smaller weight. The second connotation is to categorize the importance of different emergency materials, giving weights to different materials based on the importance of material; for example, increasing the priority of materials with high importance. The urgency of demand in this paper is consistent with the second connotation.

3.1. Index Selection and Description

During the outbreak of epidemics, on the demand side, the greater the rate of emergency material consumption, the greater the need for such materials in the same period, and the corresponding urgency [5,27]. On the supply side, the smaller the reproduction rate, the easier it is to increase the shortage of materials for the same demand, and therefore, the greater the urgency [23,27,28]. The sooner durable emergency materials arrive, the better the chances are of reducing the risk of delays in emergency rescue and improving emergency rescue efficiency [29]. If life-threatening or irreplaceable emergency supplies are not provided in a timely manner, it will increase the threat to the safety of the personnel [30]. Based on the above theoretical analysis and literature review, this paper summarizes the five main factors that affect the urgency of emergency material demand, as shown in Table 1.

Table 1. Urgency index system of emergency materials.

Indicator	Symbol	Indicator Description	Indicator Type	Relationship to Demand Urgency	Supporting Literature References
Material consumption rate	u_1	Average consumption per patient per unit of time	Exact real number	Positive correlation	[5,27,31]
Material reproduction rate	u_2	Supply volume per unit of time	Exact real number	Negative correlation	[23,25,27,28,32–34]
Durability	u_3	Whether it is a durable material	Binary	Positive correlation	[5,27,31,34,35]
Degree of danger to life	u_4	The degree to which the patient's risk of death increases in the absence of	Fuzzy number	Positive correlation	[30,35]
Degree of irreplaceability	u_5	Functional uniqueness and quantity of substitutable material	Fuzzy number	Positive correlation	[30,34,35]

The two indicators of *Material consumption rate* and *Material reproduction rate* are exact real numbers; that is, they measure the real situation of material use and supply. *Durability* means that the material can be repeatedly used. This variable is a binary variable, which is 1 when the material is durable and 0 otherwise. The *Degree of danger to life* and *Degree of irreplaceability* are fuzzy numerical variables that need to rely on subjective judgment. The two indicators are divided into five levels, and each level is scored 1–5, from low to high. The higher the score, the higher the importance of emergency material.

The above five indexes constitute the index system for measuring the urgency of different emergency materials.

3.2. Measurement of Demand Urgency

In order to ensure the objectivity of the calculation results, and that the weight of each factor is between 0 and 1 and the sum of the weights is equal to 1, this paper uses the entropy weight method to calculate the demand urgency. The entropy weight method is more objective than the Analytic Hierarchy Process (AHP) for the research problems in this paper. This is because the AHP quantifies the weight of the index according to the subjective analysis of the evaluator, but the entropy weight method determines weight using the discrete degree of the index value, which avoids human factors interfering with the weight calculation and is more objective. Furthermore, it is simpler and easier to understand than the TOPSIS method. In addition, many related studies [30,34,36] have also used the entropy weight method.

Step 1: Build the Normalized Matrix

From the above description, there are m types of materials and scores for each indicator. The score for a certain material on a certain indicator can be expressed as u_{mi}, wherein, i is the index of the indicator, m is the index of materials, and a two-dimensional list is formed by the scores for different materials on the above five indicators, which are expressed in the form of a matrix as follows:

$$A = \begin{pmatrix} u_{11} & u_{12} & \cdots & u_{15} \\ u_{21} & u_{22} & \cdots & u_{25} \\ \vdots & \vdots & \ddots & \vdots \\ u_{m1} & u_{m2} & \cdots & u_{m5} \end{pmatrix} \quad (1)$$

However, since the initial data for each index are inconsistent in dimension and unit, there is no comparability among the indexes, and the data cannot be directly compared. Therefore, the data need to be standardized. The specific formula is shown in Formula (2):

$$u^*_{mi} = \frac{u_{mi} - min\{u_{1i}, u_{2i}, \cdots, u_{mi}\}}{max\{u_{1i}, u_{2i}, \cdots, u_{mi}\} - min\{u_{1i}, u_{2i}, \cdots, u_{mi}\}} \ (m = 1, 2, \cdots, M;\ i = 1, 2, \cdots, 5) \quad (2)$$

Thus, a normalized matrix is obtained $A = \begin{pmatrix} u^*_{11} & u^*_{12} & \cdots & u^*_{15} \\ u^*_{21} & u^*_{22} & \cdots & u^*_{25} \\ \vdots & \vdots & \ddots & \vdots \\ u^*_{m1} & u^*_{m2} & \cdots & u^*_{m5} \end{pmatrix}$. In this matrix, for the ith indicator, the greater the difference in the value u^*_{mi}, the greater the role of program evaluation, and the greater the weight of the index will be.

The normalized matrix is then normalized, and the specific formula is as shown in Formula (3):

$$u^{**}_{mi} = \frac{u^*_{mi}}{\sum_{m=1}^{M} u^*_{mi}}, m = 1, 2, \cdots, M; i = 1, 2, \cdots, 5 \quad (3)$$

Finally, the normalized matrix is obtained $A^{**} = \begin{pmatrix} u^{**}_{11} & u^{**}_{12} & \cdots & u^{**}_{15} \\ u^{**}_{21} & u^{**}_{22} & \cdots & u^{**}_{25} \\ \vdots & \vdots & \ddots & \vdots \\ u^{**}_{m1} & u^{**}_{m2} & \cdots & u^{**}_{m5} \end{pmatrix}$.

Step 2: Calculate the weight of each index l_m.

Based on the calculation of information entropy using the formula below, the entropy value of the ith index can be calculated:

$$o_i = \frac{\sum_{m=1}^{M} u^{**}_{mi} \cdot ln\left(u^{**}_{mi}\right)}{ln(M)}, i = 1, 2, \cdots, 5 \quad (4)$$

If $u^{**}_{mi} = 0$, then define $\lim\limits_{u^{**}_{mi} \to 0} \left(u^{**}_{mi} \cdot ln u^{**}_{mi}\right) = 0$.

Therefore, according to the calculated entropy value of each index, the weight of each index can be obtained by Formula (5):

$$l_i = \frac{1 - o_i}{5 - \sum_{i=1}^{5} o_i}, i = 1, 2, \cdots, 5 \quad (5)$$

Step 3: Determine the urgency of the demand for different materials

After the weight of each index is calculated in Step 2, the general weighted summation method is used to determine the calculation method of the comprehensive score of the demand urgency, as shown in Formula (6):

$$\varepsilon_m = l_1 u^{**}_{m1} + l_2 u^{**}_{m2} + l_3 u^{**}_{m3} + l_4 u^{**}_{m4} + l_5 u^{**}_{m5}, m = 1, 2, \cdots, M \quad (6)$$

3.3. Material Gap Adjustment Function

In the process of emergency rescue, the importance of different materials is also different. Therefore, when the infected population needs different materials at the same time, due to the limitations of distribution time and transportation capacity, it is necessary to give priority to the distribution of materials with higher importance. When considering the shortage degree of different materials in demand areas, it is not enough to measure the actual shortage of materials; the shortage of materials with different importance needs to be enlarged and narrowed according to the demand urgency score. When two emergency materials with different demand urgency have the same degree of shortage, due to the different importance, the material with high demand urgency will have a more severe impact on the epidemic.

Therefore, in order to achieve the goal of minimizing the total material shortage, it is necessary to adjust the shortage of different materials through certain methods, so that the higher the urgency of demand, the higher the priority of allocation. Based on the above discussion, this paper proposes the adjustment function of material shortage.

According to the demand urgency calculated above, the material shortage adjustment function is expressed in the following form:

$$\pi_m = e^{\varepsilon_m}, m = 1, 2, \cdots, M \tag{7}$$

where π_m is the shortage coefficient of emergency material m. Since the weight of each index is within 0–1, and the normalized value of each index is also within 0–1, the comprehensive score of demand urgency calculated by Formula (7) is also within 0–1. The relationship between the material shortage adjustment coefficient and the material demand urgency is shown in Figure 1.

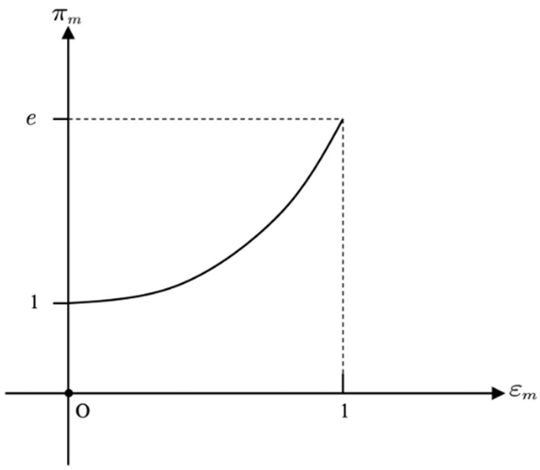

Figure 1. Adjustment function of material shortage.

If the demand urgency calculated by the method in Section 3.2 is 0, it is considered that the importance of the material is 0, so it is calculated by its actual shortage amount without adjustment; if the demand urgency is greater than 0, it is considered that the material has a certain importance, and its material shortage cannot be measured only by the actual amount, but it needs to be enlarged accordingly. When the demand urgency is greater than 0, the greater the value is, the more severe the impact of materials on epidemics and the higher the amplification ratio of the shortage, and the amplification trend becomes faster with the increase of the urgency value.

4. Dynamic Distribution Model of Emergency Materials Considering Demand Urgency

4.1. Problem Description and Model Assumptions

At the beginning of an outbreak, the virus spreads rapidly in a certain area, the number of infected people increases exponentially, and the emergency materials in stock in the area are consumed rapidly. In order to control the epidemic as soon as possible, the government will introduce strict quarantine measures and designate some medical institutions in the area as rescue centers. In order to meet the material needs of the rescue centers, it is necessary to transport materials from other areas to supplement the shortage. These transported materials are then stored in different temporary distribution centers, and the distribution centers accurately deliver the materials to the rescue centers according to demand. At the same time, considering the continuous development of the epidemic and in order to make distribution more accurate, the duration of the epidemic is divided into several equal periods, and distribution needs to be arranged according to the materials demand in each period

Figure 2 illustrates the problem graphically. In Figure 2, the large rectangle represents the area where the materials need to be distributed, and several irregular curves divide it into several independent areas with different shapes and sizes. Each region has a rescue center (represented by a small triangle), which is responsible for the treatment of infected patients in that area. There are also several distribution centers (represented by small squares) in the region, each with its own service area (represented by a dotted circle). Supplies are delivered from external areas (represented by solid circles) to temporary distribution centers, and then distributed from the temporary distribution centers to the rescue centers within the scope, according to their demands.

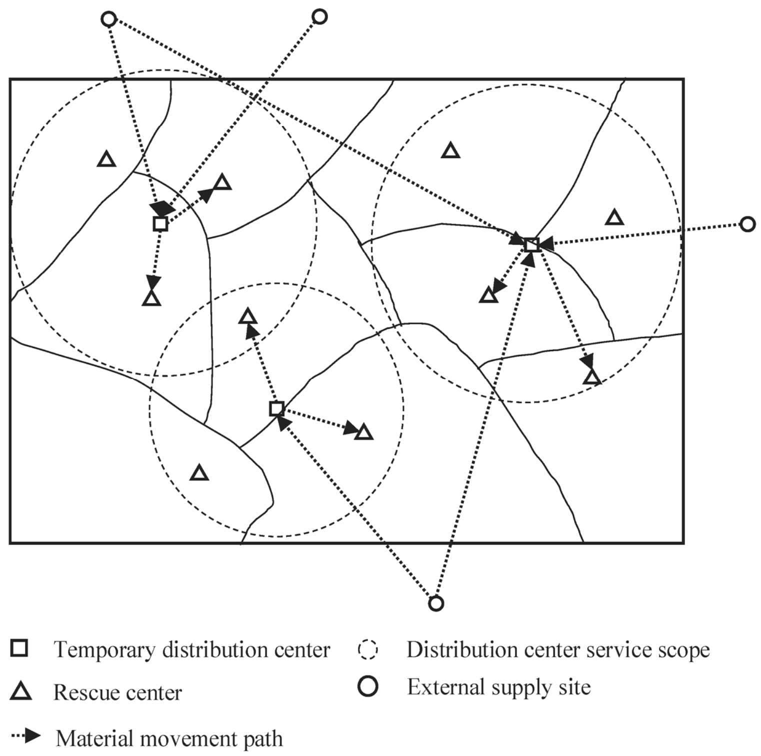

Figure 2. Emergency material distribution network diagram.

Some assumptions of this system are made as follows:

(1) Each rescue center is responsible for the treatment of infected patients in a certain scope, and there is no overlapping of the scopes of the rescue centers. Once the infected person is diagnosed, they will be sent to the nearest rescue center.

(2) The external supply sites are a kind of virtual node, which essentially have several possible channels for materials to enter the area. External emergency supply sites have no actual coordinates, but there are parameters such as supply volume, price, and so on. Accordingly, only the distribution of materials within the affected area is considered while the distribution of materials outside the affected area and the distance factor are not considered.

(3) The materials for each rescue center in one delivery can be provided by multiple distribution centers, and one distribution center can provide materials for different rescue centers in one delivery.
(4) Only the purchase cost of external material input (from the supply site to the distribution center) is considered, and the transportation cost of internal and external material (from the distribution center to the rescue center) and the storage cost in the distribution center are not considered.
(5) The volume difference is not considered, different materials can be loaded together, and the damage to road facilities and the limitations of road conditions are ignored.

4.2. Symbol Definition

(1) Sets

M: Set of emergency materials m = 1, 2, ..., M
T: Set of rescue periods t = 1, 2, ..., T
W: Set of emergency supply sites w = 1, 2, ..., W
J: Set of temporary distribution centers j = 1, 2, ..., J
K: Set of rescue centers k = 1, 2, ..., K

(2) Parameters

D_{jt}^m, D_{kt}^m: The volume of material m demanded by the temporary distribution center j and rescue center k in Period t, respectively.
ns_{wt}^m: The volume of the material m supplied from emergency supply site w in Period t.
c_{wt}^m: The price of the material m supplied from emergency supply site w in Period t.
Ω: Total budget during the epidemic.
P_{jt}^m: The volume of material m supplied by temporary distribution center j in Period t.
V_{jt}^m: The inventory of material m of temporary distribution center j in Period t.
V_{j0}^m: The initial inventory of material m of temporary distribution center j.
V_j^m: The maximal inventory volume of material m of temporary distribution center j.
v_j^m: The safety inventory volume of material m of temporary distribution center j.
V_j: The total inventory capacity of temporary distribution center j.
ω_{kt}^m: The shortage volume of material m of rescue center k in Period t.
π^m: The shortage adjustment coefficient of material m.

4.3. Model Construction

The decision variables of the dynamic distribution model are:
x_{wjt}^m: The volume of material m transported from emergency supply site w to temporary distribution center j in Period t.
x_{jkt}^m: The volume of material m transported from temporary distribution center j to rescue center k in Period t.
p_{jkt}: Whether there is any material transported from temporary distribution center j to rescue center k in Period t.
p_{wjt}: Whether there is any material transported from emergency supply point w to temporary distribution center j in Period t.
In which, p_{jkt} and p_{wjt} are 0-1 variables, and when the event occurs, the variable is 1, otherwise 0.

Considering the importance of different materials, the total material shortage is characterized as an adjusted weighted shortage based on the material shortage adjustment coefficient. Taking the minimum total material shortage as the objective of the model, the corresponding integer linear programming model was established as follows:

$$min \sum_{t=1}^{T} \sum_{k=1}^{K} \sum_{m=1}^{M} \pi^m \omega_{kt}^m \tag{8}$$

s.t.

$$D_{kt}^m \geq \sum_{j=1}^{J} p_{jkt} x_{jkt}^m, t \in T, k \in K, m \in M \tag{9}$$

$$P_{jt}^{m} \leq \sum_{k=1}^{K} p_{jkt} x_{jkt}^{m}, t \in T, j \in J, m \in M \tag{10}$$

$$P_{jt}^{m} \leq V_{j(t-1)}^{m}, t \in T, j \in J, m \in M \tag{11}$$

$$V_{jt}^{m} = V_{j(t-1)}^{m} - P_{jt}^{m} + \sum_{w=1}^{W} p_{wjt} x_{wjt}^{m}, t \in T, j \in J, m \in M \tag{12}$$

$$D_{jt}^{m} = V_{j}^{m} - V_{j(t-1)}^{m} + P_{jt}^{m}, t \in T, j \in J, m \in M \tag{13}$$

$$D_{jt}^{m} \geq \sum_{w=1}^{W} p_{wjt} x_{wjt}^{m}, t \in T, j \in J, m \in M \tag{14}$$

$$\sum_{j=1}^{J} p_{wjt} x_{wjt}^{m} \leq ns_{w(t-1)}^{m}, t \in T, w \in W, m \in M \tag{15}$$

$$V_{jt}^{m} \geq v_{j}^{m}, t \in T, j \in J, m \in M \tag{16}$$

$$V_{jt}^{m} \leq V_{j}^{m}, t \in T, j \in J, m \in M \tag{17}$$

$$\sum_{m=1}^{M} V_{jt}^{m} \leq V_{j}, t \in T, j \in J \tag{18}$$

$$\omega_{kt}^{m} = D_{kt}^{m} - \sum_{j=1}^{J} p_{jkt} x_{jkt}^{m}, t \in T, k \in K, m \in M \tag{19}$$

In the above Formulas (8)–(19), Formula (8) is the objective function of the model, which minimizes the material shortage after adjustment. Formula (9) reflects that during the rapid development of the epidemic, emergency materials are in short supply, so the total volume of supplies received by a single rescue center from the temporary distribution center in each period may not be able to meet all the needs, resulting in a certain material shortage.

Formulas (10) and (11) show that the goods shipped from a single distribution center are equal to the sum of the materials distributed to all the rescue centers and are less than the current inventory of the material. Formula (12) shows that the inventory of a certain material at the end of the current cycle is equal to the inventory at the end of the previous period minus the volume of materials transported in the current period plus those transported from the emergency supply site in the current period. Formulas (13)–(15) show that the demand of the temporary distribution center for a certain material is equal to the difference between the maximum storage capacity of the temporary distribution center and the current inventory, and is the same as the demand of the treatment center. The materials volume transported from the emergency supply site may not be able to meet the needs of the temporary distribution center, but it must not be larger than the total materials volume supplied by the supply site. Formulas (16)–(18) show that the inventory of materials should be less than the inventory capacity and greater than the safety inventory. Formula (19) defines the calculation method of the material shortage quantity of a single period in a certain rescue center.

5. Example Analysis

In order to verify the effectiveness of the model, this paper presents an example analysis of Wuhan and Shanghai under the background of city-wide lockdown and control at different stages of epidemic development. The computing environment was based on a personal computer (Intel Core I5 10210U 1.6 GHz CPU, 16 GB RAM, Windows 11 operating system), and Lingo 16 ExS was applied as the computing software. The parameters involved in the model were then adjusted, sensitivity analysis was carried out, and the impact of different parameter settings on the model results was compared. The details are as follows:

5.1. Relevant Background

At the end of 2019, the COVID-19 virus began to spread in Wuhan. In order to cut off the transmission of the virus and control the epidemic in a smaller range, Wuhan announced the "Lockdown" on 23 January 2020. In March 2022, the mutant strain of COVID-19, Omikron, began to break out in Shanghai, and the Shanghai Municipal Government executed the measure of "static management" on 1 April 2022.

5.2. Data Preparation

There are 13 and 16 administrative districts respectively in Wuhan and Shanghai, which are greatly different from each other. In order to improve the comparability of the solution results, the two cities were divided into five regions, respectively, according to the area and geographical location, as shown in Table 2.

Table 2. Regional division of cities.

Region	Wuhan		Shanghai	
	Contained Administrative Districts	Population Density (Person/km^2)	Contained Administrative Districts	Population Density (Person/km^2)
Region 1	Jiangan District, Jianghan District, Qiaokou District, Hanyang District, Wuchang District, Qingshan District, Hongshan District	7076	Huangpu District, Xuhui District, Changning District, Jing 'an District, Putuo District, Hongkou District, Yangpu District, Minhang District	14,161
Region 2	Dongxihu District, Hannan District, Caidian District	812	Pudong New Area, Fengxian District	3598
Region 3	Jiangxia District	489	Jiading District, Baoshan District	5531
Region 4	Huangpi District	456	Jinshan District, Songjiang District, Qingpu District	2148
Region 5	Xinzhou District	626	Chongming District	539

According to the existing literature, during the rapid development of the epidemic, Hubei Province designated five logistics parks as temporary transit stations for emergency materials, three of which were in Wuhan, located in Dongxihu District, Huangpi District, and Hannan District. In addition, according to the public data on the official website of the Hubei Provincial Health and Health Commission, during the epidemic period, all districts in Wuhan designated one or more hospitals to treat infected people. Therefore, after the re-division of the city, each region contained at least one designated rescue center. Shanghai has not released the information on the designated distribution centers.

This paper assumes that there were three different distribution centers (j_1, j_2, j_3) in the two cities and two emergency supply sites (w_1, w_2), which represented various ways for materials to enter the affected area. At the same time, each region had a corresponding rescue center, represented by $(k_1, k_2, k_3, k_4, k_5)$.

All kinds of materials used during the epidemic can be divided into medical materials, protective materials, and living materials, according to the use classification. In addition, they can be divided into consumptive materials and durable materials, according to the consumption classification. In reality, during the outbreak of the epidemic in Wuhan, people paid more attention to the distribution of medical and protective materials, while in Shanghai, the distribution of living materials was a more important topic. Therefore, this study selected medicine, medical alcohol, ventilator, and pork as representative materials. Of these, medicines, medical alcohol, and pork are consumptive materials, and ventilators are durable materials. The time period unit in this study was days. Indeed, according to the actual situation, the time period can be taken from any other unit.

Based on the population density data in Table 2, according to epidemic development law, the material demand data for the two cities in the first 10 periods were set as shown in Tables 3 and 4 respectively.

Table 3. Demand data for emergency materials in Wuhan (unit: piece).

	Period	1	2	3	4	5	6	7	8	9	10
k = 1	Medicine	1218	1416	1836	2358	2910	3450	3948	4404	4806	5160
	Medical alcohol	406	472	612	786	970	1150	1316	1468	1602	1720
	Ventilator	174	174	194	214	227	231	227	218	204	188
	Pork	102	118	153	197	243	288	329	367	401	430
k = 2	Medicine	264	294	366	456	552	642	726	798	858	906
	Medical alcohol	88	98	122	152	184	214	242	266	286	302
	Ventilator	38	36	38	41	43	43	42	40	37	34
	Pork	22	25	31	38	46	54	61	67	72	76
k = 3	Medicine	174	192	234	294	354	414	462	510	546	582
	Medical alcohol	58	64	78	98	118	138	154	170	182	194
	Ventilator	25	24	25	27	28	28	27	26	24	22
	Pork	15	16	20	25	30	35	39	43	46	49
k = 4	Medicine	180	198	246	306	366	426	480	528	570	600
	Medical alcohol	60	66	82	102	122	142	160	176	190	200
	Ventilator	26	25	27	29	30	30	29	27	25	23
	Pork	15	17	21	26	31	36	40	44	48	50
k = 5	Medicine	162	180	222	276	330	384	432	480	516	546
	Medical alcohol	54	60	74	92	110	128	144	160	172	182
	Ventilator	23	22	23	25	26	26	25	24	22	20
	Pork	14	15	19	23	28	32	36	40	43	46

Table 4. Demand data for emergency materials in Shanghai (unit: piece).

	Period	1	2	3	4	5	6	7	8	9	10
k = 1	Medicine	5785	11,230	16,472	21,582	26,625	31,660	36,744	41,929	47,267	52,805
	Medical alcohol	1928	3743	5491	7194	8875	10,553	12,248	13,976	15,756	17,602
	Ventilator	48	47	34	22	14	8	5	3	2	1
	Pork	482	936	1373	1798	2219	2638	3062	3494	3939	4400
k = 2	Medicine	3317	6298	9022	11,520	13,826	15,966	17,967	19,850	21,635	23,339
	Medical alcohol	1106	2099	3007	3840	4609	5322	5989	6617	7212	7780
	Ventilator	28	27	19	12	7	4	2	1	1	1
	Pork	276	525	752	960	1152	1330	1497	1654	1803	1945
k = 3	Medicine	2040	3892	5599	7183	8663	10,059	11,385	12,656	13,884	15,081
	Medical alcohol	680	1297	1866	2394	2888	3353	3795	4219	4628	5027
	Ventilator	17	16	12	8	5	3	2	1	1	1
	Pork	170	324	467	599	722	838	949	1055	1157	1257
k = 4	Medicine	1842	3485	4973	6326	7562	8698	9748	10,727	11,645	12,512
	Medical alcohol	614	1162	1658	2109	2521	2899	3249	3576	3882	4171
	Ventilator	15	14	10	6	4	2	1	1	1	1
	Pork	154	290	414	527	630	725	812	894	970	1043
k = 5	Medicine	283	531	752	951	1131	1294	1443	1580	1706	1823
	Medical alcohol	94	177	251	317	377	431	481	527	569	608
	Ventilator	2	2	1	1	1	1	1	1	1	1
	Pork	24	44	63	79	94	108	120	132	142	152

The data for various urgency indexes of the given emergency materials are shown in Table 5.

Table 5. Score of each material in each indicator.

Name of Material	Symbol	Material Consumption Rate u_1	Material Reproduction Rate u_2	Whether It Is Durable Material u_3	Degree of Irreplaceability u_4	Insufficient Supply Endangers Life Level u_5
Medicine	m = 1	6	4	0	4	5
Medical alcohol	m = 2	2	1.5	0	2	1
Ventilator	m = 3	1	1	1	5	3
Pork	m = 4	0.5	3	0	1	2

5.3. Calculation and Result Analysis

According to the methods of calculating demand urgency and adjusting material shortage introduced in Section 3.3, the demand urgency and shortage adjustment coefficient of each material was obtained as shown in Table 6.

Table 6. Material demand urgency and material shortage adjustment coefficient.

Material m	Medicine m = 1	Medical Alcohol m = 2	Ventilator m = 3	Pork m = 4
Demand urgency ε_m	0.333	0.067	0.540	0.061
Material shortage adjustment coefficient π_m	1.395	1.069	1.716	1.062

After obtaining the shortage adjustment coefficient of each material, the solution for the model was obtained based on Lingo 16 software. The results of the materials accumulated in the first 10 periods from Wuhan emergency supply sites to temporary distribution centers are shown in Table 7, and those from Wuhan temporary distribution centers to various rescue centers are shown in Table 8. The results of the materials accumulated in the first 10 periods from Shanghai emergency supply sites to temporary distribution centers are shown in Table 9, and those from Shanghai temporary distribution centers to various rescue centers are shown in Table 10. Based on the model results, it was found that:

Table 7. Distribution results for emergency supply sites to temporary distribution centers in Wuhan (unit: piece).

Temporary Distribution Center	Emergency Materials	Emergency Supply Site	
		w = 1	w = 2
j = 1	Medicine	7410	3000
	Medical alcohol	4322	1780
	Ventilator	100	104
	Pork	958	136
j = 2	Medicine	10,548	4400
	Medical alcohol	2864	830
	Ventilator	187	15
	Pork	733	46
j = 3	Medicine	11,942	2300
	Medical alcohol	4064	850
	Ventilator	355	0
	Pork	1399	56

Based on the Shanghai data, the optimal value of the model was 111,794.9, and the transferred actual shortage was 88,636 pieces; therefore, the overall shortage rate was 10.18%. The specific shortage of different materials varies, and the specific shortage of each type of material is shown in Figure 3.

Table 8. Distribution results for temporary distribution centers to rescue centers in Wuhan (unit: piece).

Rescue Center	Emergency Materials	Temporary Distribution Center		
		j = 1	j = 2	j = 3
k = 1	Medicine	7726	9624	11,396
	Medical alcohol	4700	2172	3364
	Ventilator	304	300	394
	Pork	769	496	1155
k = 2	Medicine	1392	2754	798
	Medical alcohol	650	398	784
	Ventilator	0	2	37
	Pork	158	105	130
k = 3	Medicine	1482	684	696
	Medical alcohol	376	402	320
	Ventilator	0	0	24
	Pork	114	62	29
k = 4	Medicine	426	1314	1434
	Medical alcohol	162	508	426
	Ventilator	0	0	0
	Pork	44	88	112
k = 5	Medicine	384	1572	918
	Medical alcohol	414	414	220
	Ventilator	0	0	0
	Pork	59	78	79

Table 9. Distribution results for emergency supply sites to temporary distribution centers in Shanghai (unit: piece).

Temporary Distribution Center	Emergency Materials	Emergency Supply Site	
		w = 1	w = 2
j = 1	Medicine	3953	90,000
	Medical alcohol	39,000	22,600
	Ventilator	0	0
	Pork	6765	7300
j = 2	Medicine	54,405	13,000
	Medical alcohol	17,100	8000
	Ventilator	0	0
	Pork	3500	2400
j = 3	Medicine	130,047	0
	Medical alcohol	56,400	4000
	Ventilator	0	0
	Pork	19,635	0

Based on the Wuhan data, the results of the model show that the optimal value of the objective was 10,532.15, and the transferred actual average shortage of materials was 7805 pieces; therefore, the actual average shortage rate of materials was 10.84%. The shortage of different types of materials is shown in Figure 4.

In Figures 3 and 4, the blue rectangles represent the ideal shortage rates, that is, the shortage rate when all materials are used, while the orange rectangles represent the actual shortage rates, which is the result optimized by the model. It can be seen that although there was a significant difference in the absolute amount of material shortage between Shanghai and Wuhan, the overall shortage level was similar, as well as the shortage of each material, which indicates that the situation in the two cities is comparable.

Table 10. Distribution results for temporary distribution centers to rescue centers in Shanghai (unit: piece).

Rescue Center	Emergency Materials	Temporary Distribution Center		
		j = 1	j = 2	j = 3
k = 1	Medicine	99,263	76,054	105,552
	Medical alcohol	17,972	12,001	67,393
	Ventilator	40	45	44
	Pork	7882	1113	14,864
k = 2	Medicine	22,848	19,283	17,818
	Medical alcohol	20,981	6595	3007
	Ventilator	7	0	1
	Pork	3499	752	3288
k = 3	Medicine	0	2068	20,680
	Medical alcohol	21,651	5925	0
	Ventilator	0	5	4
	Pork	1257	1157	2483
k = 4	Medicine	1842	0	15,997
	Medical alcohol	10,996	10,052	0
	Ventilator	2	0	1
	Pork	2427	3878	0
k = 5	Medicine	0	0	0
	Medical alcohol	0	527	0
	Ventilator	1	0	0
	Pork	0	0	0

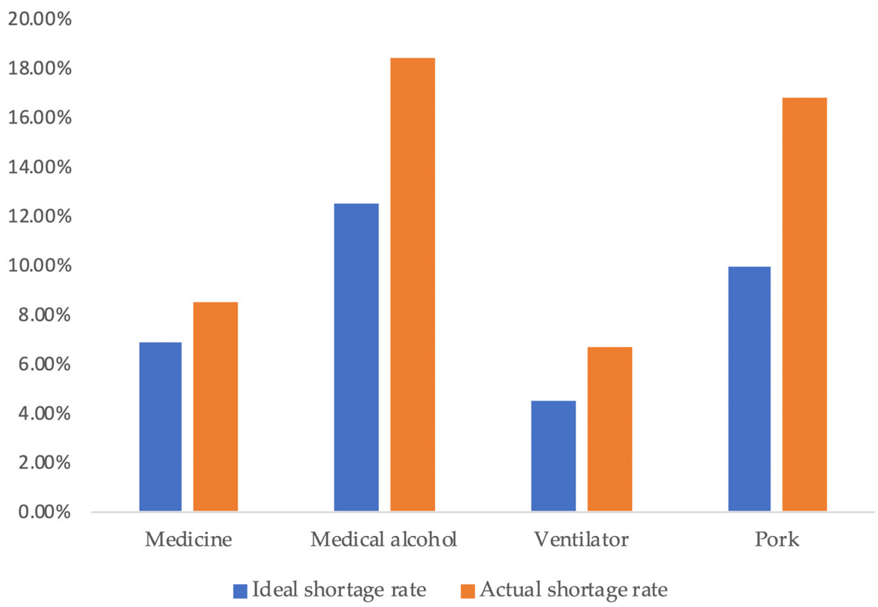

Figure 3. Material shortage of each type of material in Shanghai.

According to the demand urgency score for each material listed in Table 6, it can be seen that among the four materials, the importance of medicines and ventilators is higher, while the importance of the other two items is relatively lower. Figures 3 and 4 show that the actual shortage rate of medicines and ventilators was closer to the ideal shortage rate than the other two materials. These results show that the model established in this paper obviously adjusted the material distribution with higher importance, so the satisfaction of the more important materials reached a more ideal state. For the two kinds of materials, medicines belong to consumptive materials, while ventilators belong to durable materials. For the two types of materials, there was no significant difference in the optimization process.

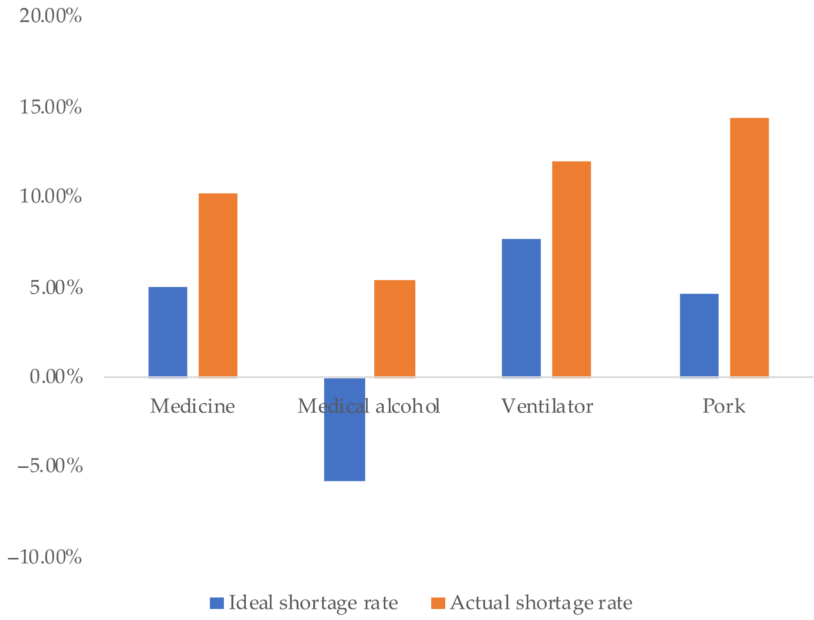

Figure 4. The shortage of each material in Wuhan.

5.4. Impact of Budget Funds

Based on the effective model established above, this section examines the impact of budget funds.

In reality, whether it is commercial logistics or emergency logistics, funds are always limited. Even for the emergency logistics led by the government, it is necessary to consider cutting costs and use limited funds as much as possible. The government needs to respond to emergency material demands in case of a shortage. Some of these materials are donated by society, while the majority come from government procurement. Government procurement is not unlimited, and the cost of purchasing emergency materials needs to be within a budget. This means that there is the following budget constraint in the model:

$$\sum_{t=1}^{T}\sum_{\omega=1}^{W}\sum_{j=1}^{J}\sum_{m=1}^{M} p_{wjt}c_{wt}^{m}x_{wjt}^{m} \leq \Omega \tag{20}$$

where c_{wt}^{m} is the price of the material, and Ω is the government budget.

In Formula (20), the cost of emergency logistics is defined as the cost incurred in purchasing materials from suppliers, which must not be over budget. This paper divides budget funds into three grades: 10 million yuan, 50 million yuan, and 100 million yuan, which were substituted into the model, respectively, for a solution. The final results were analyzed based on the single objective solution without budget constraints, as shown in Table 11 and Figure 5.

As illustrated by Table 11 and Figure 5, when the budget funds were only 10 million yuan, the actual shortage of materials was 26,466 pieces, with a shortage rate of materials of up to 38.95%. With the increase of budget funds and the loosening of financial constraints, the shortage rate of materials gradually decreased. When the budget funds were 50 million yuan, the decrease in the shortage rate was the largest, with a decrease of over 14 percentage. This fully demonstrates that funds play an important role in the entire logistics, and if insufficient funds are invested, emergency logistics will not have a significant effect.

The shortage of three types of medical materials is shown in Figure 6. When the budget was between 10 million yuan and 50 million yuan, the shortage of medicines decreased the most significantly. However, when the budget was between 50 million yuan and 100 million yuan, the shortage of ventilators saw the biggest drop, while the shortage of medical alcohol remained at the same level. There are several possible reasons for this situation:

1. The demand for medicines was the highest. When the funding was only 10 million yuan, the shortage of medicines was much larger compared to the other two types of materials. Therefore, when the budget increased slightly, a large number of medicines were purchased to reduce the shortage.
2. The demand for ventilators was the lowest, but ventilators were the most expensive. When the financial constraint was tight, the limited funds were not used to purchase ventilators but first met the other two lower-priced and greater-demand materials. However, when the budget funds were sufficient, the importance of ventilators began to show, and more funds were used to purchase ventilators to meet the demand and reduce the shortage of this more important material.

Table 11. Sensitivity analysis results for budget funds.

Budget Constraints (Yuan)	10 Million	50 Million	100 Million	Unlimited
Objective function value	40,025.08	24,724.95	21,270.65	20,130.66
Actual shortage amount (piece)	26,466	16,722	14,617	13,830
Shortage rate	38.95%	24.61%	21.51%	20.35%

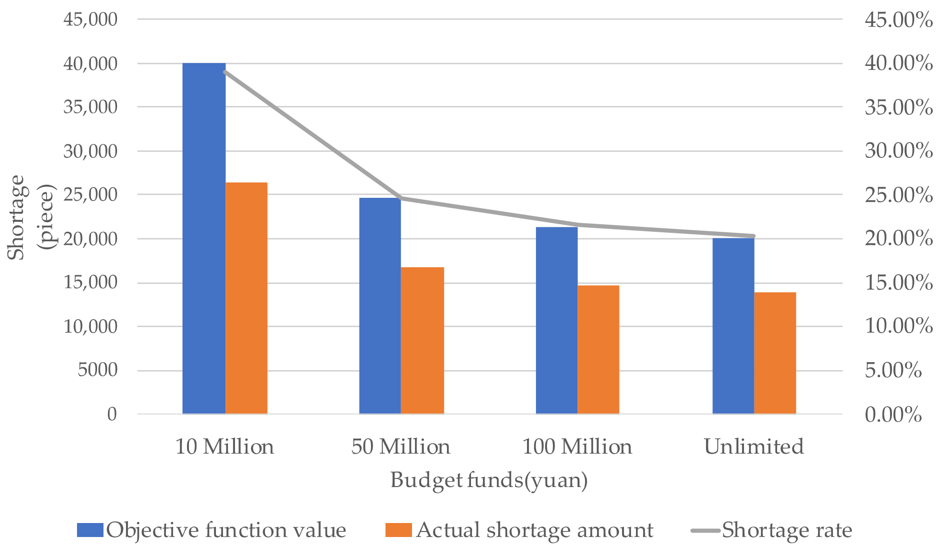

Figure 5. Sensitivity analysis results for budget funds.

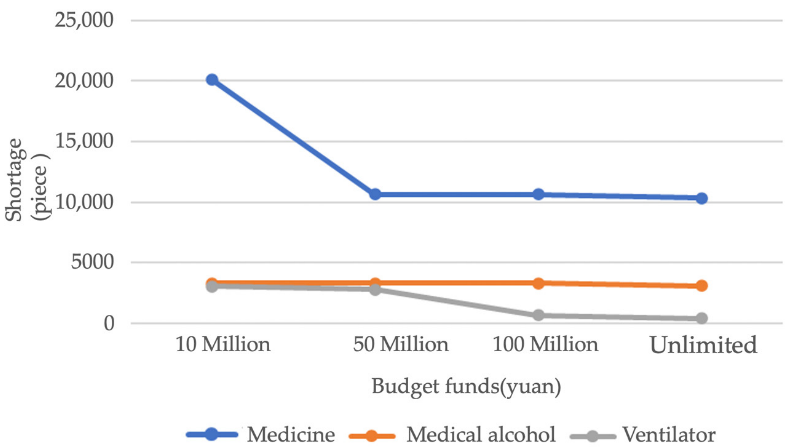

Figure 6. Material shortages under different budget constraints.

6. Conclusions

In the process of epidemic prevention and control, a perfect emergency logistics system is expected to be one the critical support to quickly control the epidemic and minimize casualties and losses. Emergency logistics not only needs to achieve the fastest distribution of materials, but it also needs to consider the accuracy and fairness of meeting the demand for materials in distribution. Therefore, in the context of the COVID-19 pandemic, this paper established a distribution model of emergency materials. In this model, the concept of demand urgency is introduced, and the importance of each material is measured through the demand urgency index system, to calculate the shortage adjustment coefficient of each material; furthermore, the shortage of the material is enlarged accordingly in the objective function, so that the material with higher importance is distributed more preferentially. Finally, the model was applied to study the cases of Wuhan and Shanghai, and it was found that, although there were differences in material demand volume and material demand structure between Shanghai and Wuhan, there were similar results for the two cities, indicating that the model can be applied to the emergency material distribution of major epidemics in a variety of situations.

Furthermore, there are some managerial implications:

(1) Medicines and ventilators were the two materials with higher demand urgency in this example, and the actual shortage rate was closer to the ideal state, which reflects the effectiveness of the model to some extent. Therefore, this proves that the shortage adjustment coefficient based on the demand urgency (material classification) had a more obvious adjustment effect on the distribution of more important materials.
(2) The effectiveness of emergency logistics increased with the increase of budget funds. When the budget funds were very limited, it resulted in a great shortage of emergency materials and a high shortage rate, regardless of the demand urgency. On the other hand, with the increase in budget funds, the demand urgency was clearly reflected in the allocation of funds. The more urgent materials received a larger share of finance, which means that increasing funds appropriately and conducting scientific allocation is an important strategy to improve the effectiveness of emergency rescue.

The considerations for follow-up studies are as follows:

(1) Although this paper considered multi-period emergency logistics dynamic planning, it simply divided the time into several equal small periods and gave a reasonable explanation for how to divide the periods. Therefore, in a follow-up study, we could carry out corresponding research on the reasonable division of the period, such as whether it is necessary to change the period into a random length, or the relationship between the division of the period and the development of the epidemic.
(2) In this paper, materials are divided into durable and consumable materials, but this division was too general to distinguish the differences between hundreds of materials in emergency logistics. Therefore, it is necessary to continue to study the division of emergency materials.

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