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Authors:

Yanyan Wang

Date Submitted: 2023-02-21

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Record Type: Published Article

Submitted To: LAPSE (Living Archive for Process Systems Engineering)

Citation (overall record, always the latest version): LAPSE:2023.0845
Citation (this specific file, latest version): LAPSE:2023.0845-1
Citation (this specific file, this version): LAPSE:2023.0845-1v1

DOI of Published Version: https://doi.org/10.3390/pr10112317 processes

Article

An Optimization Method for Distributing Emergency Materials Which Balances Multiple Decision Criteria

Yanyan Wang

School of Humanities, Social Sciences and Law, Harbin Institute of Technology, Harbin 150001, China; wyy@hit.edu.cn

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Citation: Wang, Y. An Optimization Method for Distributing Emergency Materials Which Balances Multiple Decision Criteria. *Processes* **2022**, *10*, 2317. https://doi.org/10.3390/pr10112317

Academic Editors: Chia-Nan Wang, Thanh-Tuan Dang and Ngoc Ai Thy Nguyen

Received: 18 October 2022
Accepted: 4 November 2022
Published: 7 November 2022

1. Introduction

In recent years, various large-scale emergencies, such as earthquakes, floods and infectious diseases, have occurred frequently, causing huge casualties and social and economic losses. Therefore, how to make and choose scientific emergency rescue decisions has attracted great attention [1–5]. The distribution of emergency materials is an important guarantee for emergency response and post-disaster recovery, which has an important impact on the success of the overall emergency relief work [6–9]. However, there are many decision criteria such as efficiency, equity, economy and effectiveness in the distribution of relief materials in large-scale emergencies. The selection of different decision criteria has an important and different impact on the actual distribution of emergency materials [10,11]. In addition, the information related to the distribution of relief materials in emergency situations is usually uncertain, incomplete or inaccurate [12,13]. During major outbreaks of infectious diseases, for example, in the process of emergency rescue, a large number of emergency materials such as masks, protective clothing, disinfectants and medicines are needed, but during the rescue process, problems such as insufficient initial supply, lagging demand information acquisition, dynamic changes of demand with the epidemic trend, and limited distribution capacity are often faced, which seriously affects the rescue work. Therefore, how to maximize the balance of multiple decision indicators to obtain a scientific and reasonable emergency material allocation plan under the condition of uncertain disaster information is an important practical problem to be solved in the decision field of large-scale emergency rescue. Based on the above background, this study proposes a multi-period distribution optimization model of emergency materials based on multiple decision criteria under uncertain information. The purpose of this study is to provide new ideas and decision-making basis for emergency material distribution operations under major public health emergencies to improve the efficiency and effectiveness of emergency material rescue, and reduce the emergency rescue costs and losses caused by public health emergencies.

2. Literature Review

There is a growing literature that explores emergency material distribution in humanitarian logistics in recent years due to the increased frequency of disasters and the severity of the consequences [14–19]. Meanwhile, the issue of different decision criteria/objectives for the distribution of emergency materials has also received more attention, mainly focusing on the efficiency criterion (the shortest total time) [20–22], economic criterion (the lowest total cost) [23–28], and equity criterion (the lowest total loss) [29,30]. For example, Yan and Shih [20] proposed an optimization model for disaster emergency material allocation with the goal of minimizing the total allocation time, including path transportation time and road repair time. Tang and Ye [22] developed an emergency medical material allocation model facing multiple distribution centers and multiple demand points with the goal of minimizing the total time of loading, unloading and transportation. Zhu et al. [26] took the social cost of emergency rescue scheduling as the optimization objective, and presented an optimization model of post-disaster emergency materials dynamic scheduling considering heterogeneous behavior. Liu et al. [27] established a real-time dispatching and distribution model of emergency materials for epidemic relief based on the data-driven idea with the goal of minimizing emergency costs. Ge et al. [29] proposed an equity distribution model of emergency materials with the optimization objective of minimizing the loss of victims on the basis of considering the severity of disasters, demand points and attributes of emergency materials. Pang et al. [30] constructed an allocation optimization decision model based on a three-level emergency material transportation network with the goal of minimizing system loss.

There are also studies that combine different decision criteria/objectives to put forward corresponding emergency material allocation models [31–36]. For example, Tzeng et al. [31] developed a multi-stage emergency material distribution model with the goal of minimizing the total distribution time, minimizing the total cost and maximizing the satisfaction of victims. Liu et al. [33] took minimizing the overall loss comparison effect and distribution time comparison effect as the goal and constructed a double-layer cooperative optimization emergency material distribution model considering the irrational comparison psychology of victims. Zahedi et al. [35] proposed a multi-objective optimization decision model for emergency material allocation with the goal of minimizing unmet demand and minimizing the total cost, including vehicle costs and goods costs. Xue et al. [36] presented a multi-objective decision model for emergency material allocation based on capacity limitation, taking the minimum total network cost and the shortest average waiting time as the optimization objectives. However, it should be noted that the above studies are based on deterministic disaster information in the model construction.

With the continuous deepening of research, some studies on emergency material distribution began to gradually consider relevant uncertain factors [37–40]. For example, Gao [37] proposed a multi-commodity allocation rebalancing stochastic optimization model for earthquake relief considering uncertain transportation network and demand, aiming at minimizing the overall unmet level and expected transportation time. Zhang et al. [39] developed a two-stage emergency material distribution model combining disaster preparedness and disaster relief with the goal of minimizing the total cost on the basis of considering demand uncertainty.

In summary, a brief review of related research shows that it is crucial to consider multiple decision criteria and uncertain disaster information in emergency material distribution. However, there are still gaps in the existing research.

- Firstly, previous research on emergency material distribution mostly focused on a single decision criterion; although some studies began to consider the combination of the different decision criteria, most of them focused on deterministic disaster information, ignoring the large amount of uncertain information in rescue and its impact on material distribution.

- Secondly, in the relevant studies of emergency material distribution considering uncertain information, the consideration and trade-off of multiple decision criteria are usually ignored.

Therefore, this study attempts to develop an optimization model of emergency material distribution that balances multiple decision criteria under uncertain conditions. Compared with most existing works, four different decision criteria in the case of emergency material distribution—efficiency, economy, effectiveness and equity—are simultaneously considered and balanced in this paper. We also discussed the overall and periodization effects of different decision criteria on the distribution strategy of emergency materials to help obtain high-quality or optimal material distribution plan and provide support and reference for the decision of emergency material distribution in actual large-scale disaster relief responses.

3. Model and Methods

3.1. Model Formulation

3.1.1. Notation

The selection of sets, parameters and variables in this study is related to the reality of emergency material distribution.

First of all, regarding the selection of the sets, emergency material distribution generally refers to a logistics activity that distributes various types of emergency materials (such as medicines, daily necessities and rescue equipment) from supply centers to affected sites within the emergency response time period [41]. Therefore, this study chooses supply centers M, affected sites N, emergency materials I and emergency periods T as the sets for model building.

Secondly, the selection of parameters, especially the selection of uncertain parameters, can be input into the model in the form of fuzzy numbers to make them obey certain distribution rules. The reason is that the sudden and destructive nature of the disaster makes it impossible to obtain completely accurate information during the emergency rescue process. The demand and supply of materials, as well as transportation costs, are highly uncertain. This uncertain information can be input into the model as fuzzy numbers and this has been successfully done by previous researchers [42]. Therefore, this paper chooses to use the uncertain parameters with disturbance coefficient to represent the incompleteness of material demand information acquisition and the fuzzy uncertainty of transportation cost in emergency situations and uses the normal distribution to represent the uncertainty of material supply caused by inaccurate or delayed information in emergency contexts. Thirdly, for the selection of variables, the ultimate purpose of model construction and solution is to obtain the optimal emergency material distribution scheme, including whether to conduct distribution, the quantity of material distribution, the quantity of shortage, the quantity of inventory, the satisfaction of distribution, etc. Therefore, these variables are selected for model building in this paper.

The sets and indices, decision variables and parameters used in the model formulation are shown in Table 1.

Table 1. Notations.

Notations	Description
Sets and Indices	
I	Set of types of emergency materials, $i \in I$
T	Set of emergency periods for material distribution, $t \in T$
N	Set of all affected sites, $n \in N$
M	Set of all supply centers, $m \in M$
Decision Variables	
O_{mn}^t	Binary variable indicating whether materials are distributed to affected site $n \in N$ from supply center $m \in M$ during time period $t \in T$. If so, the value is 1; otherwise, it is 0
S_{ni}^t	Shortfalls of material $i \in I$ at affected site $n \in N$ at the end of each time period $t \in T$
x_{mni}^t	Amount of material $i \in I$ allocated to affected site $n \in N$ from supply center $m \in M$ during time period $t \in T$
J_{mi}^t	Inventory of material $i \in I$ at supply center $m \in M$ at the end of each time period $t \in T$
η_{ni}^t	Satisfaction rate of emergency material $i \in I$ at affected site $n \in N$ during time period $t \in T$
Parameters	
D_{mn}	Shortest distance from supply center $m \in M$ to affected site $n \in N$
V_{mn}^t	Vehicle traveling speed from supply center $m \in M$ to affected site $n \in N$ during time period $t \in T$
L_{mni}^t	Loading and uploading time of unit material $i \in I$ from supply center $m \in M$ to affected site $n \in N$ during time period $t \in T$
∂_{ni}^t	Urgency of affected site $n \in N$ for emergency material $i \in I$ during time period $t \in T$. The higher the value, the more urgent the affected site's demand for such materials
β_n^t	Vulnerability of affected site $n \in N$ during time period $t \in T$, and it can be comprehensively determined according to disaster intensity, disaster degree, characteristics of victims and disaster carrying capability. The greater the vulnerability value is, the greater the possible loss caused by disasters at the affected site
ρ	Confidence level that makes constraints hold
a_i	Space required to store per unit of material $i \in I$
U_m^t	Available inventory capacity at supply center $m \in M$ during period $t \in T$
$\Pr\{\cdot\}$	Probability that constraint conditions in $\{\cdot\}$ hold
C_i^t	Unit purchase cost of material $i \in I$ during time period $t \in T$
H_{mni}^t	Unit cost of loading and uploading material $i \in I$ from supply center $m \in M$ to affected site $n \in N$ during time period $t \in T$
G_{mn}^t	Fixed cost of transportation from supply center $m \in M$ to affected site $n \in N$ during time period $t \in T$
$\widetilde{R}_{ni}^t$	New forecast demand of emergency material $i \in I$ at affected site $n \in N$ during time period $t \in T$ expressed by uncertain parameters with disturbance coefficient μ. $\widetilde{R}_{ni}^t = \left[\hat{r}_{ni}^t,\ \hat{r}_{ni}^t + \mu \cdot \hat{r}_{ni}^t\right]$, where $\hat{r}_{ni}^t$ represents the minimum nominal amount of new forecast demand, $\mu \cdot \hat{r}_{ni}^t$ represents the maximum disturbance value of the new forecast demand, and the disturbance coefficient μ can be determined according to the actual emergency situation
$\widetilde{Q}_{mi}^t$	Fuzzy quantity of the new raised of emergency material $i \in I$ at the supply center $m \in M$ during time period $t \in T$. It obeys a normal distribution with mean $E_{Q_{mi}^t}$ and variance $Var_{Q_{mi}^t}{}^2$, $\widetilde{Q}_{mi}^t \sim N\left(E_{Q_{mi}^t}, Var_{Q_{mi}^t}{}^2\right)$
$\widetilde{K}_{mni}^t$	Unit mileage transportation cost of per unit of material $i \in I$ from supply center $m \in M$ to affected site $n \in N$ during time period $t \in T$. $\widetilde{K}_{mni}^t = \left[\hat{k}_{mni}^t,\ \hat{k}_{mni}^t + \mu \cdot \hat{k}_{mni}^t\right]$, where $\hat{k}_{mni}^t$ represents the lowest nominal unit mileage transportation cost, $\mu \cdot \hat{r}_{ni}^t$ represents the maximum disturbance value of the unit mileage transportation cost, and the disturbance co-efficient μ can be determined according to the actual emergency objective conditions
Q_{mi}^t	Actual supply of material $i \in I$ at supply center $m \in M$ during time period $t \in T$
R_{ni}^t	Actual demand for material $i \in I$ at affected site $n \in N$ during time period $t \in T$
Y_{mn}^t	Maximum total amount of material $i \in I$ that can go from supply center $m \in M$ to affected site $n \in N$ during time period $t \in T$

3.1.2. Mathematical Model

This paper constructs an optimization model of emergency material distribution that balances efficiency, economy, effectiveness and equity. The objective Function (1) minimizes the total time of material distribution in all emergency periods to pursue the efficiency criterion. The objective Function (2) minimizes the total costs for distributing materials in all emergency periods to pursue the economic criterion. The objective Function (3) maximizes the overall satisfaction rate at each affected site in all emergency periods to pursue the effectiveness criterion. The objective Function (4) minimizes the total losses caused by unmet demand at each affected site in all emergency periods to pursue the equity criterion. Constraint (5) represents the inventory capacity constraints of the supply center. Constraints (6) and (7) show demand and supply constraints, respectively. Constraint (8) indicates transportation capacity constraints. Constraint (9) is the constraint to satisfying as much demand as possible. Constraint (10) is a binary variable indicating whether the connection from the supply center to the affected site is used during time period t. Constraints (11) and (12) are, respectively, the expressions of actual demand and actual supply. Constraints (13) and (14) are, respectively, the expressions of shortfalls and satisfaction rate of materials. Constraint (15) is the value constraint of binary variables, and constraint (16) is a nonnegative constraint of decision variables. The objective functions and constraints of the proposed model are as follows.

- Objective Function

$$\min F_1 = \sum_{m\in M}\sum_{n\in N}\sum_{t\in T} D_{mn}/V_{mn}^t \cdot O_{mn}^t + \sum_{m\in M}\sum_{n\in N}\sum_{i\in T}\sum_{t\in T} L_{mni}^t \cdot x_{mni}^t \tag{1}$$

$$\min F_2 = \sum_{m\in M}\sum_{n\in N}\sum_{t\in T} G_{mn}^t \cdot O_{mn}^t + \sum_{m\in M}\sum_{n\in N}\sum_{i\in I}\sum_{t\in T} \left(C_i^t + H_{mni}^t\right)\cdot x_{mni}^t + \sum_{m\in M}\sum_{n\in N}\sum_{i\in I}\sum_{t\in T} \widetilde{K}_{mni}^t \cdot D_{mn}\cdot x_{mni}^t \tag{2}$$

$$\min F_3 = \sum_{n\in N}\sum_{i\in I}\sum_{t\in T} \eta_{ni}^t \tag{3}$$

$$\min F_4 = \sum_{n\in N}\sum_{i\in I}\sum_{t\in T} \frac{\left(S_{ni}^t\right)^{\partial_{ni}^t\cdot\beta_n^t}}{\sum\limits_{n\in N} R_{ni}^t} \tag{4}$$

- Constraints

$$\sum_{i\in I}\left(Q_{mi}^t - \sum_{n\in N} x_{mni}^t\right)\cdot a_i \le U_m^t \qquad \forall m\in M, t\in T \tag{5}$$

$$\sum_{m\in M} x_{mni}^t \le \widetilde{R}_{ni}^t + S_{ni}^{t-1} \qquad \forall n\in N, i\in I, t\in T \tag{6}$$

$$\Pr\left\{\sum_{n\in N} x_{mni}^t - J_{mi}^{t-1} \le \widetilde{Q}_{mi}^t\right\} \ge \rho \qquad \forall m\in M, i\in I, t\in T \tag{7}$$

$$\sum_{i\in I} x_{mni}^t \le Y_{mn}^t \qquad \forall m\in M, n\in N, t\in T \tag{8}$$

$$\sum_{m\in M}\sum_{n\in N} x_{mni}^t = \min\left\{\sum_{m\in M} Q_{mi}^t, \sum_{n\in N} R_{ni}^t\right\} \qquad \forall, i\in I, t\in T \tag{9}$$

$$x_{mni}^t\cdot\left(1 - O_{mn}^t\right) = 0 \qquad \forall m\in M, n\in N, i\in I, t\in T \tag{10}$$

$$R_{ni}^t = \widetilde{R}_{ni}^t + S_{ni}^{t-1} \qquad \forall n\in N, i\in I, t\in T \tag{11}$$

$$Q_{mi}^{t} = \widetilde{Q}_{mi}^{t} + J_{mi}^{t-1} \qquad \forall m \in M, i \in I, t \in T \tag{12}$$

$$S_{ni}^{t} = R_{ni}^{t} - \sum_{m \in M} x_{mni}^{t} \qquad \forall n \in N, i \in I, t \in T \tag{13}$$

$$\eta_{ni}^{t} = \sum_{m \in M} x_{mni}^{t} \Big/ R_{ni}^{t} \qquad \forall n \in N, i \in I, t \in T \tag{14}$$

$$O_{mn}^{t} \in \{0,\ 1\} \qquad \forall m \in M, n \in N, t \in T \tag{15}$$

$$x_{mni}^{t} \geq 0 \qquad \forall m \in M, n \in N, i \in I, t \in T \tag{16}$$

3.2. Solution Method

The solution method of the proposed model is divided into two steps: the first step is to transform the uncertain parameters in the model with certainty, and the second step is to convert the proposed multi-objective model into a single-objective form for solution.

- Step 1. Deterministic transformation of uncertain parameters.

According to relevant research [43], it is assumed that there is a disturbance parameter μ that changes around the nominal value E, $\widetilde{W}$ is the fuzzy uncertain parameter value, then introducing the optimization constraint level σ ($\sigma \in [0,1]$, which can be set according to the disaster situation, disaster area and rescue reality), and let $\sigma \geq \left(\widetilde{W} - E\right) \Big/ (E \times \mu)$, then $\widetilde{W} \leq E \times (\sigma \times \mu + 1)$.

Taking the uncertain parameter $\widetilde{K}_{mni}^{t}$ with disturbance coefficient in the constructed model as an example, $\widetilde{K}_{mni}^{t} \leq \sigma \cdot \overline{k}_{mni}^{t} + \hat{k}_{mni}^{t}$. The objective Function (2) can be transformed as follows:

$$\min F_2 = \sum_{m \in M} \sum_{n \in N} \sum_{t \in T} G_{mn}^{t} \cdot O_{mn}^{t} + \sum_{m \in M} \sum_{n \in N} \sum_{i \in I} \sum_{t \in T} \left(C_i^t + H_{mni}^{t}\right) \cdot x_{mni}^{t} + \sum_{m \in M} \sum_{n \in N} \sum_{i \in I} \sum_{t \in T} \left(\sigma \cdot \overline{k}_{mni}^{t} + \hat{k}_{mni}^{t}\right) \cdot D_{mn} \cdot x_{mni}^{t} \tag{17}$$

Similarly, other uncertain parameters with disturbance coefficients can be transformed into deterministic forms.

According to the chance constrained programming problem proposed by Charnes and Cooper [44], if the function $g(x, \psi) = h(x) - \psi$, then for any given confidence level ρ $(0 \leq \rho \leq 1)$, there must be a number $\ell_\rho = \Phi^{-1}(1-\rho)$ to make $\Pr\{\ell_\rho \leq \psi\} = \rho$, where Φ^{-1} is an inverse function of Φ. If and only if $h(x) \leq \ell_\rho$, then $\Pr\{h(x) \leq \psi\} \geq \rho$.

Assume that the random distribution vector is $\psi = (k_1, k_2, \cdots, k_n, b)$, and the form of the random constraint function is $g(x, \psi) = k_1 x_1 + k_2 x_2 + \cdots + k_n x_n - b$. If k_ω and b follow a normal distribution and are independent of each other, then for any given confidence level $\rho (0 \leq \rho \leq 1)$, if and only if:

$$E[b] \ \geq \ \sum_{\omega=1}^{n} E[k_\omega] x_\omega + \Phi^{-1}(\rho) \sqrt{\sum_{\omega=1}^{n} Var[k_\omega] x_\omega^2 + Var[b]}, \text{ then } \Pr\{g(x,\psi) \leq 0\} \ \geq \ \rho,$$

where $E[k_\omega]$ is the expectation, and $Var[k_\omega]$ is the variance.

Based on the above analysis, the Constraint (7) of the proposed model can be transformed into the following deterministic form:

$$\sum_{n \in N} x_{mni}^{t} \leq \Phi^{-1}(1-\rho) \cdot Var_{Q_{mi}^{t}} + E_{Q_{mi}^{t}} + J_{mi}^{t-1} \quad \forall m \in M, i \in I, t \in T \tag{18}$$

- Step 2. Multi-objective transformation.

We first normalize the objective functions of benefit type and cost type, where $F_j^{\min}(x_{mni}^t)$ and $F_j^{max}(x_{mni}^t)$ are the minimum and maximum value of the objective function, respectively, and j is the number of objective functions.

$$f_{j\text{cost}}(x_{mni}^t) = \frac{F_j(x_{mni}^t) - F_j^{\min}(x_{mni}^t)}{F_j^{\max}(x_{mni}^t) - F_j^{\min}(x_{mni}^t)} \tag{19}$$

$$f_{jbenefit}(x_{mni}^t) = \frac{F_j^{\max}(x_{mni}^t) - F_j(x_{mni}^t)}{F_j^{\max}(x_{mni}^t) - F_j^{\min}(x_{mni}^t)} \tag{20}$$

Then we determine the weight coefficients of each objective function. In the case of emergency rescue, the importance of each decision objective in different rescue stages is different. The weight coefficient can be determined by relevant decision makers and emergency experts according to the degree of disaster, the vulnerability of victims, the urgency of demand, and should be satisfied $\sum_{j=1}^{\delta} \omega_j = 1$.

Finally, the following single-objective model is constructed.

$$\min F = \sum_{j=1}^{\delta} \omega_j \cdot f_j(x_{mni}^t) \tag{21}$$

4. Results and Discussion

4.1. Case Description

This part takes the distribution of emergency medical materials during the COVID-19 epidemic as the background to design a research case to verify the effectiveness and feasibility of the proposed model. Wuhan (WH), Xiaogan (XG), Huanggang (HG) and Jingzhou (JZ), which were seriously affected by the epidemic, are selected as the affected sites for emergency medical materials, and Changsha City (CS) and Hefei City (HF) were selected as supply centers. Disposable surgical masks (KZ) and medicine (Lianhua Qingwen capsules (YP)) were selected as the urgently needed materials in the epidemic area, and the units are the thousand pieces and the thousand boxes, respectively. As part of the data could not be accurately obtained in the emergency rescue phase of the epidemic, the relevant parameters were set by combining the actual data with some simulation data. The demand for emergency materials in each period can be estimated according to the daily usage per capita of various emergency materials, as shown in Table 2. The latest amount of emergency materials that can be raised in each period under the urgency of emergency rescue is estimated according to the epidemic situation, material production and mobilization capacity of emergency relief centers, as shown in Table 3. The average speed of highway transportation is set to be 100 km/h, the shortest distance from the supply center to the affected site is obtained by Baidu Maps, and the corresponding fixed transportation cost in the case of disasters is estimated, as shown in Table 4. The procurement cost, transportation cost, loading and unloading cost, loading and unloading time and required storage space per unit of emergency materials are shown in Table 5. The available inventory capacity at the supply center at the end of each time period is shown in Table 6. The maximum transportable volume of emergency materials from the supply center to the affected site during each time period is shown in Table 7, and the vulnerability of each affected site and the urgency of the demand for emergency material are shown in Table 8. This computational case was solved by using Lingo 11.0 on a computer with an Intel(R) Core(TM) 1.90 GHz processor with 16.0 GB of RAM, and the confidence level and constraint optimization level are, respectively, $\rho = 0.95$ and $\sigma = 0.9$.

Table 2. Demand for emergency materials at affected sites at the beginning of each time period.

Affected Sites	Emergency Materials	Period 1	Period 2	Period 3	Period 4
WH	KZ	(21, 0.3)	(23, 0.4)	(25, 0.5)	(30, 0.6)
	YP	(2, 0.3)	(1.2, 0.3)	(0.8, 0.2)	(0.6, 0.1)
XG	KZ	(2, 0.3)	(4, 0.3)	(8, 0.2)	(14, 0.1)
	YP	(1, 0.1)	(0.6, 0.2)	(0.3, 0.4)	(0.2, 0.1)
HG	KZ	(1.5, 0.1)	(3, 0.5)	(6, 0.2)	(12, 0.2)
	YP	(0.5, 0.3)	(0.3, 0.4)	(0.2, 0.1)	(0.1, 0.1)
JZ	KZ	(0.5, 0.3)	(1.5, 0.4)	(3.5, 0.2)	(6, 0.1)
	YP	(0.3, 0.1)	(0.2, 0.1)	(0.1, 0.1)	(0.05, 0.1)

Note: The data format in this table is (a, b), where a is the nominal value and b is the disturbance coefficient.

Table 3. Supply of emergency materials at the supply centers at the beginning of each time period.

Supply Centers	Emergency Materials	Period 1	Period 2	Period 3	Period 4
CS	KZ	N(12, 9)	N(28, 9)	N(35, 9)	N(46, 16)
	YP	N(5, 4)	N(6, 9)	N(5.2, 4)	N(5, 4)
HF	KZ	N(17, 9)	N(20, 9)	N(42, 16)	N(60, 9)
	YP	N(6.5, 9)	N(5.5, 4)	N(5.4, 9)	N(5, 4)

Note: The data format is N(A, B), and the demand obeys a normal distribution.

Table 4. Shortest distance and fixed transportation cost from supply center to affected site.

Supply Centers	Affected Sites			
	WH	XG	JZ	HG
CS	331, 2	371, 2.7	296, 1.8	380, 3
HF	367, 2.5	381, 3	580, 3.5	332, 2

Note: The data format in this table is (c, d), where c is the shortest distance (km) and d is the fixed transportation cost (10^4 CNY).

Table 5. Attribute parameters of per unit of emergency materials.

Emergency Materials	Purchase Cost (10^4 CNY)	Transportation Cost per Unit Mileage (10^4 CNY)	Loading and Uploading Cost (10^4 CNY)	Loading and Uploading Time t (h)	Required Storage Space (m^3)
KZ	1	(0.03, 0.1)	0.1	0.2	0.3
YP	20	(0.04, 0.25)	0.2	0.4	3.3

Table 6. Available inventory capacity of each supply center at the end of each time period (m^3).

Supply Centers	Period 1	Period 2	Period 3	Period 4
CS	15,000	20,000	22,000	25,000
HF	18,000	26,000	27,000	30,000

Table 7. Maximum transportable amount of emergency materials from supply centers to affected sites in each time period (m^3).

Periods	Supply Centers	Affected Sites			
		WH	XG	HG	JZ
1	CS	70	80	80	100
	HF	80	80	90	120
2	CS	90	110	120	130
	HF	110	120	140	150
3	CS	120	140	160	180
	HF	130	140	150	180
4	CS	130	160	190	240
	HF	140	150	180	220

Table 8. Vulnerability and demand urgency coefficient of each affected site in each time period.

Affected Sites	Period 1	Period 2	Period 3	Period 4
WH	1.8; 1.9	1.6; 1.8	1.3; 1.5	1.1; 1.3
XG	1.5; 1.8	1.3; 1.6	1.2; 1.5	1.1; 1.3
HG	1.4; 1.7	1.2; 1.5	1.1; 1.3	1.1; 1.2
JZ	1.3; 1.7	1.2; 1.5	1.1; 1.3	1; 1.1

4.2. Result Analysis and Discussion

4.2.1. Influence of Different Decision Criteria on Overall Emergency Material Distribution

The influence of different decision criteria on the overall strategy of emergency material distribution was explored by calculating the value of objective functions under the five decision criteria, as shown in Figure 1. The five decision criteria are as follows: the efficiency criterion $W_1 = (w_1, w_2, w_3, w_4) = (1, 0, 0, 0)$, that is, the decision weights of the four objective functions under the efficiency criterion are $(1, 0, 0, 0)$ respectively, denoted as $W_1 = (1, 0, 0, 0)$. By analogy, the economic criterion is denoted as $W_2 = (0, 1, 0, 0)$, the effectiveness criterion is denoted as $W_3 = (0, 0, 1, 0)$, the equity criterion is denoted as $W_4 = (0, 0, 0, 1)$, the balance-criterion (considering four objectives simultaneously) is denoted as $W^* = (0.25, 0.25, 0.25, 0.25)$.

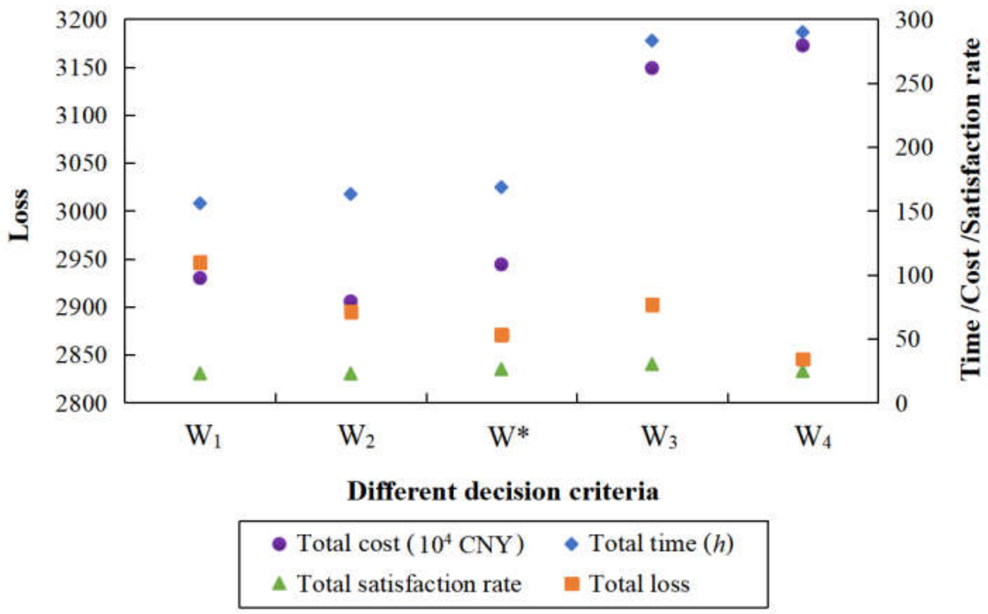

Figure 1. Total time, total cost, total satisfaction rate and total loss of emergency material distribution under different decision criteria.

As can be seen from Figure 1, the total time, total allocation cost, total satisfaction rate and total loss of emergency material distribution are significantly different under different decision criteria, indicating that different decision criteria have an important impact on the overall strategy selection of emergency material distribution. We can find that balance-criterion has advantages in the process of large-scale multi-period emergency material distribution. As shown in Figure 1, compared with other decision criteria, under balance-criterion (W*), the distributing time, cost, satisfaction rate and loss of emergency materials allocation are above the medium level, indicating that the decision scheme formed based on the balance-criteria can properly balance and take into account various indicators in combination with the specific disaster situation and rescue information of different emergency periods in the material distribution process, thus avoiding more extreme distribution situations as much as possible.

4.2.2. Influence of Different Decision Criteria on Multi-Period Emergency Material Distribution

The time, distribution cost, satisfaction rate and loss of emergency material distribution, as well as the evolution trend in each time period under the condition of adhering to the efficiency criterion (W_1), economic criterion (W_2), effectiveness criterion (W_3), equity criterion (W_4) and balance-criterion (W^*), are shown in Figures 2–5, respectively.

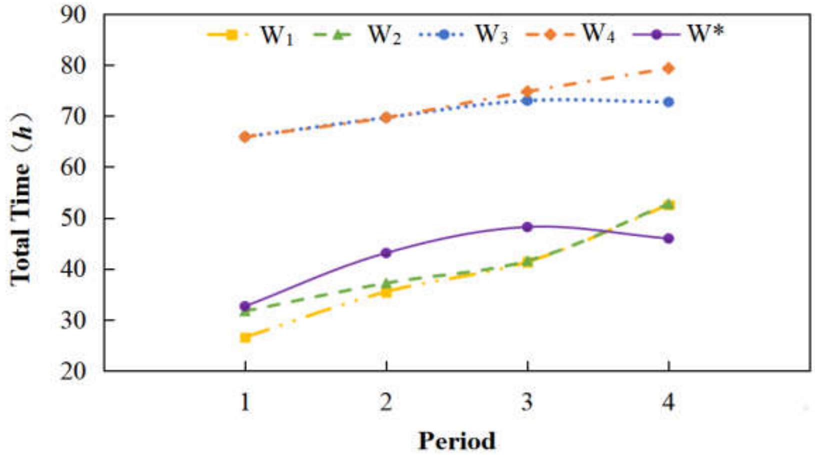

Figure 2. Distribution time of emergency materials in each time period under different decision criteria.

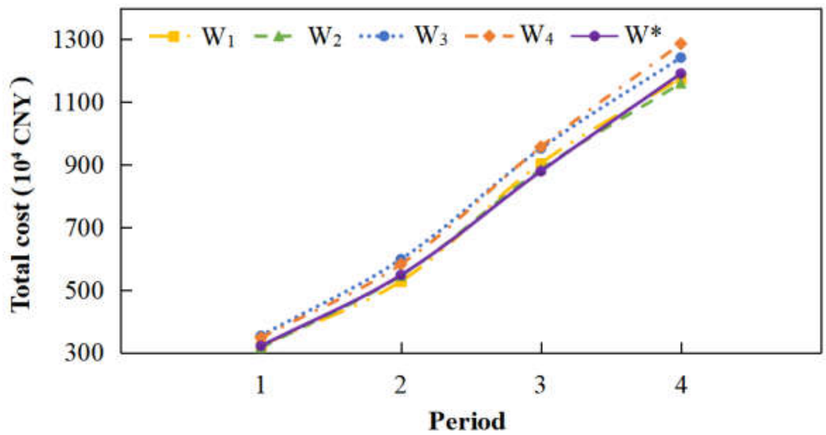

Figure 3. Distribution cost of emergency materials in each time period under different decision criteria.

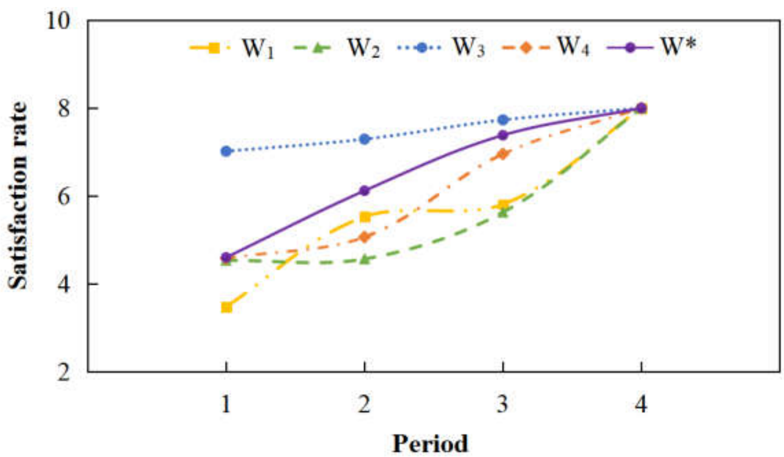

Figure 4. Satisfaction rate of emergency material distribution in each time period under different decision criteria.

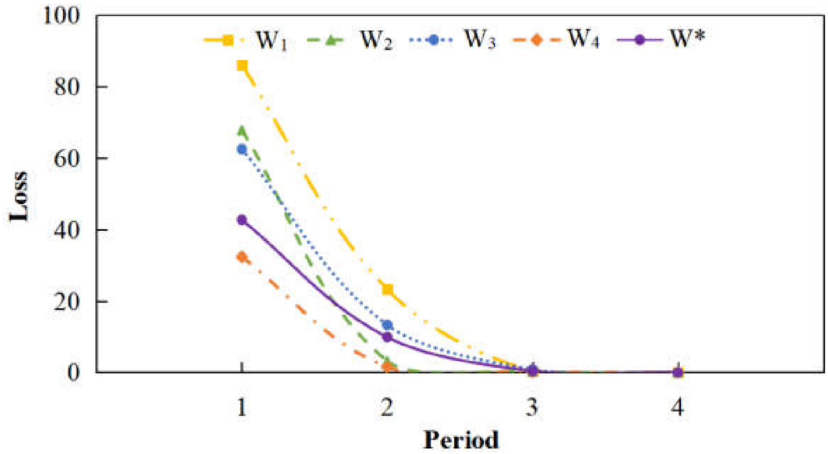

Figure 5. Loss due to shortages of emergency materials in each time period under different decision criteria.

It can be seen from Figures 2–5 that the five decision criteria all reflect the following trends: with the passage of time period, the time, cost and satisfaction rate of emergency material distribution in each time period gradually increase, and the system loss of material distribution gradually decreases until it reaches zero. The main reasons are as follows: At the beginning of emergency rescue, the supply centers are able to provide limited emergency materials, and the time and cost required to distribute the limited materials to affected sites are relatively low. However, at this time, all the affected sites tend to need a large number of rescue materials. Due to only a small amount of materials being obtained, the satisfaction rate of material distribution in the early period of rescue is low, which leads to large system losses. In the middle period of emergency rescue, with the continuous supply of all types of emergency materials, the quantity of materials needed to be distributed in each time period gradually increases, the time, cost and the satisfaction rate gradually increase, and the system loss gradually decreases. In the later period of emergency rescue, when the supply of materials is greater than or equal to the demand, the demand at all affected sites can be met, and the satisfaction rate reaches the maximum value, while the system loss decreases to the minimum; that is, when the demand is fully met, there is no loss caused by material shortage.

Further analysis of Figures 2–5 shows that the time of material distribution in each period is the shortest under adherence to the efficiency criterion, but the system loss is the largest and the coverage satisfaction rate is almost the lowest. The cost of distribution per period is the lowest based on the economic criterion, but the satisfaction rate is very low. Under the effectiveness criterion, the satisfaction rate of material distribution in each period is the highest, but the distribution time and cost are higher. Under the criterion of equity, the loss of material distribution in each period is the least, but it has the longest time and the highest cost. However, compared with other decision criteria, under adherence to the balance-criterion, the time, cost, satisfaction rate and loss of emergency material distribution in each time period have obvious advantages and meet the requirements of multi-period sustainable material distribution.

4.2.3. Multi-period Distribution Scheme of Emergency Materials under the Balance-Criterion of "Efficiency-Economy-Effectiveness-Equity"

Through calculation, the multi-period distribution scheme of emergency materials under balance-criterion is obtained, as shown in Table 9. The multi-objective evolution trend of multi-period distribution of emergency materials is shown in Figure 6. The time and cost required by each affected site to obtain emergency materials in each time period, the satisfaction rate obtained and the system loss generated are shown in Figures 7–10, respectively.

Table 9. Multi-period distribution scheme of emergency materials based on balance-criterion.

Emergency Materials	Distribution Scheme			
	Period 1	Period 2	Period 3	Period 4
KZ	(CS-WH, 6.43) (HF-WH, 12.065) (CS-JZ, 0.635)	(CS-WH, 17.987) (HF-WH, 13.025) (CS-HG, 5.078) (HF-JZ, 2.04)	(CS-WH, 22.078) (HF-WH, 20.29) (HF-XG, 11) (CS-HG, 7.987) (HF-JZ, 4.13)	(HF-WH, 48.525) (CS-XG, 21.32) (CS-HG, 14.16) (HF-JZ, 6.54)
YP	(CS-WH, 0.748) (HF-WH, 1.565) (CS-HG, 0.635) (CS-JZ, 0.327)	(CS-WH, 0.657) (HF-WH, 0.194) (HF-XG, 1.798) (CS-HG, 0.408) (HF-JZ, 0.218)	(CS-WH, 1.692) (HF-XG, 0.356) (CS-HG, 0.218) (HF-JZ, 0.109)	(HF-WH, 0.806) (CS-XG, 0.27) (CS-HG, 0.109) (HF-JZ, 0.0545)

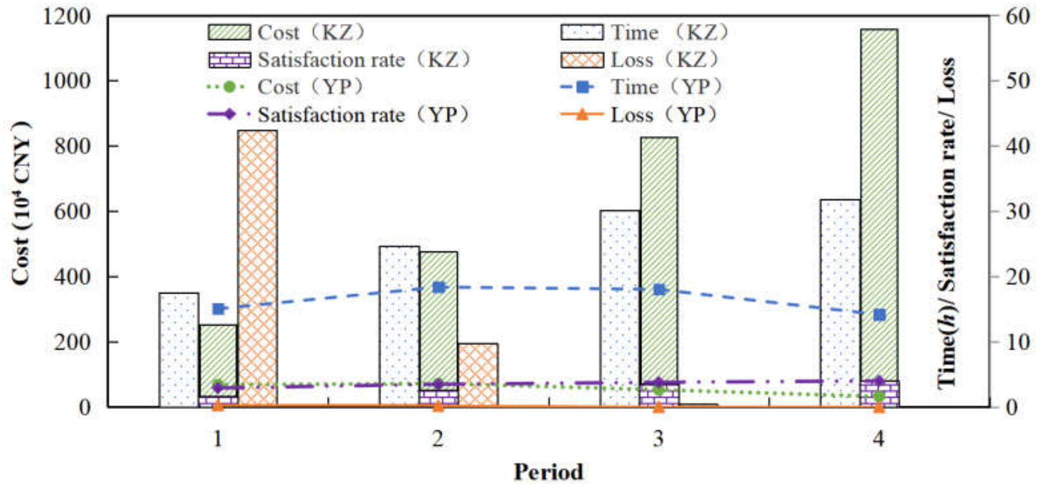

Figure 6. The multi-objective evolution trend of multi-period distribution of emergency materials based on the balance-criterion.

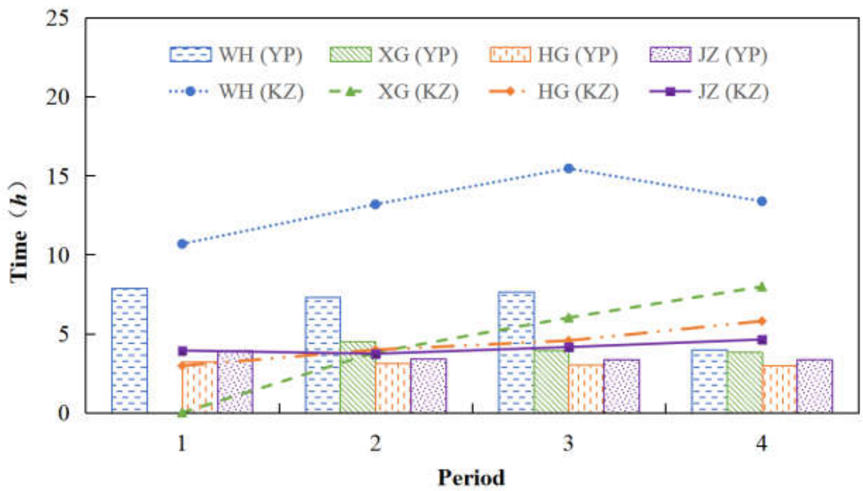

Figure 7. Time required to obtain emergency materials at each affected site in each time period based on the balance-criterion.

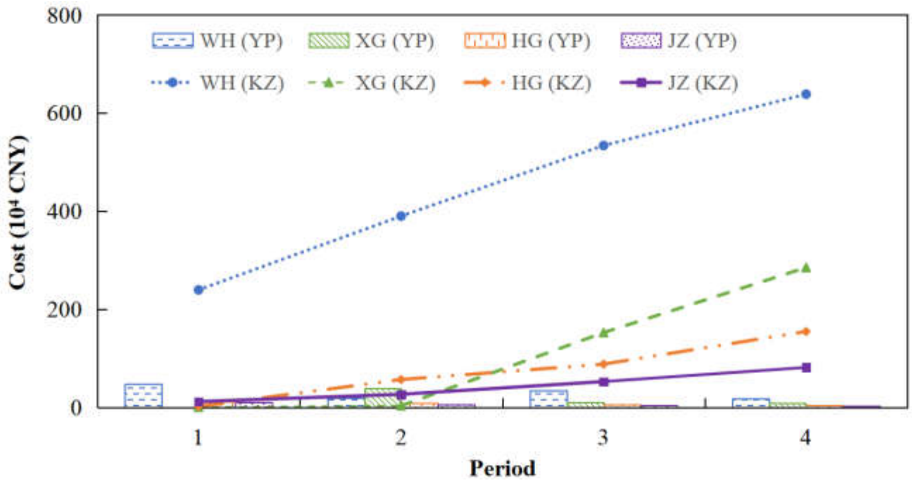

Figure 8. Cost of obtaining emergency materials at each affected site in each time period based on the balance-criterion.

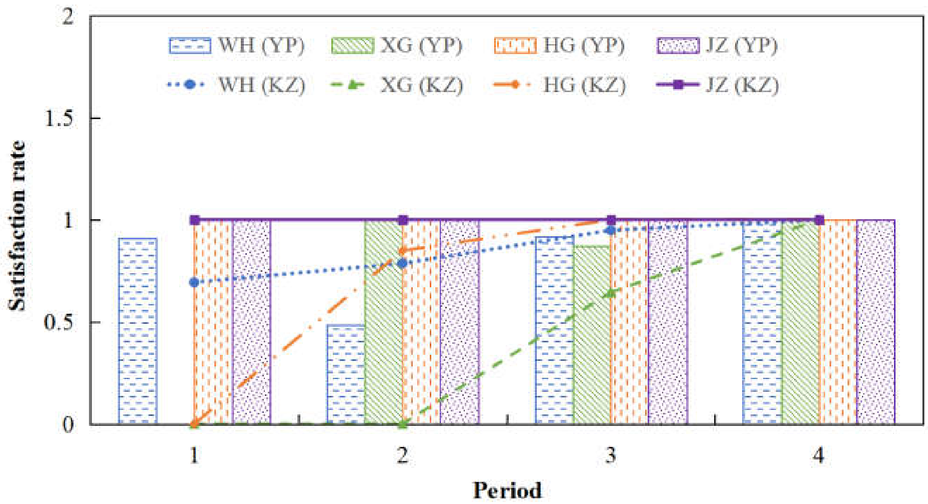

Figure 9. Satisfaction rate of emergency materials at each affected site in each time period based on the balance-criterion.

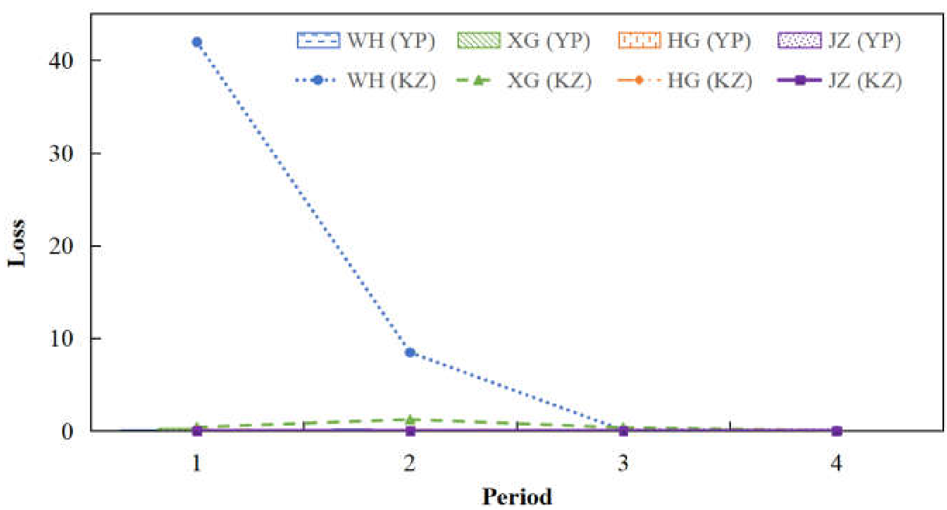

Figure 10. Losses due to shortages of emergency materials at each affected site in each time period based on the balance-criterion.

As can be seen from Figure 6, in general, the multi-period material distribution scheme formed based on the balance-criterion shows a trend of gradual increase in the total time, cost and satisfaction rate, and a trend of gradual decrease in the loss, which is in line with the reality of multi-period emergency materials distribution.

Figures 7–10 show that the distribution at each affected site is generally in line with the above trend. However, it should be noted that when the affected site for a type of emergency material decreases, the required distribution time is shortened accordingly, and the growth range of the required distribution cost is also slowed down. Meanwhile, the satisfaction rate gradually rises, and the system loss gradually decreases (e.g., WH (KZ) after the third period in Figures 7–10).

In addition, as can be seen from Figures 7–10, compared with the material distribution of other affected sites, the distribution of material KZ for affected site WH requires a longer time and higher cost, but its satisfaction is lower and its loss is greater in the early period of emergency. The main reason is that in the early period of emergency rescue, compared with the demand at other affected sites, the affected site WH has the largest demand for material KZ, so the supply centers distribute more materials to this affected site on the basis of weighing all decision indicators, resulting in longer distribution time and higher distribution cost. However, the amount of materials obtained could not completely cover all the demand of the affected site WH, and its vulnerability and demand urgency coefficient were the highest among all affected sites at the initial period of emergency relief, which resulted in relatively high system loss. It should be noted that this is already the best global distribution strategy under the condition of balancing all affected sites. Therefore, it is particularly necessary to scientifically weigh the decision criteria based on the multi-period global optimization perspective and consider the vulnerability and demand urgency of different affected sites for emergency material distribution under the condition that supply falls short of demand.

5. Conclusions and Directions for Future Research

This paper proposed an optimization model for emergency material distribution that balances multiple decision criteria—efficiency, economy, effectiveness and equity, which are simultaneously considered and balanced. A case study was conducted to validate the proposed model. Accordingly, the following conclusions were reached.

(1) In the initial period of emergency relief, when multiple affected sites are faced with emergency peak demand, paying attention to the effectiveness criterion and equity criterion can avoid the low coverage satisfaction rate and high system loss caused by material shortage as much as possible.
(2) When the initial rescue task is urgent and the time requirement is extremely high, the efficiency criterion can be concerned. In the case of sufficient supply of materials in the middle and later emergency periods, paying attention to economic criteria can improve the satisfaction rate and reduce system losses while completing the task of material distribution at a lower cost. However, from the perspective of long-term multi-period sustainable emergency rescue, the balance-criteria should be highly concerned and valued, and the weight selection of various decision criteria should be scientifically grasped.
(3) A decision scheme based on balance-criteria can trade-off the efficiency, economic, effectiveness and equity of emergency material distribution, achieving in a shorter time and lower cost for higher satisfaction rate and smaller system loss and thus avoiding the extreme or non-global optimization of distribution schemes caused by only paying attention to a certain decision criterion.

In the future, how to obtain real-time disaster information to distribute emergency materials more scientifically is a direction worthy of thinking and studying. Furthermore, as multi-period distribution of emergency supplies is a complex and systematic process, with the increase of the scale and complexity of the research problem, it is necessary to design more complex models and more effective model-solving methods with the increase of the scale and complexity of the research problem. Therefore, how to use big data technology to obtain real-time information, such as supply, demand and transportation capacity, and to design scientific and efficient solutions in the multi-time distribution process of large-scale disaster emergency relief operations still needs further discussion and consideration. In short, it is hoped that the proposed model can have certain reference and promotion values for large-scale disaster emergency material allocation under uncertain conditions.

Funding: This research was funded by the National Social Science Foundation of China, grant number 21CGL044.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this research are available within the article.

Conflicts of Interest: The author declares no conflict of interest.

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