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Optimization of Warehouse Location and Supplies Allocation for Emergency Rescue under Joint Government–Enterprise Cooperation Considering Disaster Victims' Distress Perception

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Abstract: The location and allocation of emergency supplies are an important part of emergency rescue work. The existing emergency location and allocation process is inefficient, costly, and neglects the psychology of victims. To improve the emergency relief work and solve the current problems, this paper introduces the victims' pain perception cost into the model, takes the lowest cost of the whole emergency rescue system as the goal, constructs a government–enterprise joint emergency material location–allocation model, and uses the simulated annealing algorithm to solve the model. This paper takes the 2008 Wenchuan earthquake in Sichuan Province as the background and verifies the validity and rationality of the model through a comparative analysis of case simulations. The results show that the model and algorithm can effectively solve the emergency supplies location–allocation problem considering the victims' pain perception, reflecting the idea of human-centered sustainable development and providing support for building a sustainable emergency relief system.

Keywords: joint government–enterprise cooperation; victims' suffering perception; emergency supplies location–allocation problem

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1. Introduction

China is often affected by natural disasters. According to the statistics of the Ministry of Emergency Management of China, 138 million people were affected by various natural disasters in 2020, resulting in a direct economic loss of CNY 370.15 billion [1]. The severity of natural disasters has brought great challenges to emergency rescue work. Bad planning not only wastes many resources but also causes more severe casualties.

Traditional research on emergency logistics in rescue work mainly focuses on the optimization of a single link. Some scholars pay attention to optimizing the location of emergency supplies storage [2,3], and some scholars focus on the allocation of emergency relief supplies [4,5]. This paper integrates and optimizes the location of emergency supplies storage and the allocation of emergency supplies to avoid any disconnection. In addition, existing research usually treats the government as the entity responsible for the entire emergency logistics rescue system, which brings a huge financial burden and causes a massive waste of resources [6]. Therefore, this paper innovatively considers cooperation between the government and enterprises and brings the supplies warehouses of enterprises into the set of national emergency supplies warehouses to jointly carry out emergency rescue work, which improves work efficiency and reduces the cost of the entire emergency rescue system. Finally, this paper introduces the concept of human-centered sustainable development into the emergency relief work, focuses on the influence of the "human" factor along with the "material" factor, quantifies the victims' suffering perception function, considers its impact on the location–allocation process, and uses the suffering perception cost to reflect the delay of supplies, which is more in line with the actual situation. The purpose of this study is to minimize the total cost of the entire emergency logistics system by constructing a location–allocation model of joint government–enterprise emergency supplies provision considering the suffering perception of disaster victims.

This article is organized as follows. The second section briefly introduces the most relevant literature. The problem description and basic model formulation are defined in Section 3. Then, in Section 4, we design a solution algorithm. In Section 5, a numerical example is designed to verify the validity of the model in the context of the 2008 Wenchuan earthquake. Section 6 summarizes this paper and proposes directions for future research.

2. Literature Review

Location problems [7] and allocation problems [8] are classical problems in the field of operations research, and with the application of operations research theory in the field of emergency logistics, single-link research on the location of emergency warehouses and the allocation of emergency supplies has been a hot topic in academia. For the planned layout of emergency material warehouses, different scholars consider different factors and construct different location models with different objectives [9]. Feng [10] et al. established a mathematical model for the location of emergency supplies depots based on realistic factors, aiming at the lowest total cost and the shortest transportation time and considering different weighting factors. Paul [11] constructed a maximum coverage location model based on the existing emergency rescue network to maximize the satisfaction rate of victims' needs. Yu et al. [12] built a model to improve the serviceability and risk resistance ability of emergency supplies warehouses. For the distribution of emergency supplies, early scholars focused on maximizing the efficiency of supplies distribution. For example, Erfan et al. [13] constructed a supplies allocation model to minimize the total completion time of rescue operations and the total delay of rescue operations. On this basis, scholars began to consider the impact of victims' psychology on the formulation of rescue plans and introduce the factor of fairness into the study of emergency supplies allocation. Tzeng et al. [14] consider fairness and efficiency simultaneously and use a multi-objective programming method to construct a supplies allocation model. Qu [15] aimed at maximizing the minimum satisfaction of emergency supplies to ensure the fairness of emergency supplies allocation. With the development of humanitarian thought [16,17], scholars began to pay attention to the psychological impact on disaster victims on emergency rescue work. Yi [18] et al. considered the psychological status of the victims after a disaster and quantified it with a specific model. Song [19] used the waiting effect and shortage effect to measure the psychological impact of disaster victims on the allocation of emergency supplies from a multi-dimensional perspective. The above study did not consider the location of emergency supplies and the allocation of emergency supplies together, but the two are closely linked and influence each other. It is challenging to solve the emergency rescue problem if we only consider it from a single perspective.

With the gradual progress of research, many scholars at home and abroad began to consider the government as the main body responsible for integrating the location and allocation of emergency supplies [20], aiming to solve the location–allocation problem (LAP) [21] of emergency supplies. Mahfuzur Rahman [22] considered the location of emergency facilities and the formulation of transportation plans from government planning of emergency rescue networks. Wang [23] comprehensively considered time, resources, transportation, and other factors and established a mixed-integer programming model considering both time and cost with the government as the main body. Zhou [24] constructed a location–allocation model of emergency facilities based on the traditional location–allocation model, considering insufficient government storage capacity limitation. With the development of LAP research, it has been realized that the emergency response system is not only set up to respond to a single disaster but as a sustainable system to respond to multiple disasters [25]. Therefore, more and more scholars have started to consider sustainability issues. For example, Cao [26–28] et al. have studied the construction of disaster response systems with sustainability and developed an improved genetic algorithm. However, the above studies are all based on the government as the single main body responsible for all aspects of the emergency rescue work. They do not consider the shortage of emergency supplies caused by the government's financial constraints and the waste of resources caused by a low probability of disasters.

To improve the multi-level emergency relief management system, the government considers establishing a partnership with enterprises and entrusting them to carry out storage based on holding part of the inventory [29,30]. In the event of a disaster, the allocation of supplies can be carried out by both the government and enterprises. Regarding joint government and enterprise emergency relief work, many scholars have taken a quantitative approach. Zhang [31] proposed an optimal stockpiling strategy for local governments and enterprises from the perspective of rapid response, considering different disaster types, probability of occurrence, the number of emergency supplies demanded, and the severity of the damage. Meanwhile, considering that emergency supplies have the characteristics of low probability of demand and high cost of out-of-stock penalties, Hu [32] studied the conditions for joint government–enterprise material stockpiling to ensure that temporary necessities are guaranteed for better emergency relief work in case of disasters.

Through the analysis of the above literature, we can find three shortcomings of the current study. Firstly, the current research focuses on constructing traditional location–allocation models of emergency supplies with the government as the main body, ignoring the lack of funds and waste of resources caused by the single-agent plan. Secondly, the research on joint government–enterprise rescue work focuses on how to store emergency supplies jointly and has not considered the location and allocation of emergency supplies, nor has it carried out integrated quantitative research. Thirdly, the psychology of disaster victims is only reflected in the research of emergency supplies allocation, and the existing location–allocation models do not consider the huge impact of disaster victims' psychology on emergency rescue work. Most of the models are built with the lowest cost and maximum efficiency as the goal. Based on this, the study seeks answers to the following research questions: (1) how to develop an economical and humanitarian program for emergency rescue work? (2) To what extent can the joint government–enterprise cooperation improve relief operations? (3) What method is used to represent the psychology of disaster victims? Therefore, this study constructs a multi-material and multi-level emergency location–allocation model to minimize overall system cost, which provides a new idea for the smooth development of emergency rescue work.

3. Problem Description

The purpose of setting up government and enterprise emergency supplies warehouses is to effectively provide supplies for victims in disaster areas when disasters occur, so the allocation of supplies can meet the needs of the residents in disaster areas to the greatest extent. At the same time, due to the low probability of earthquake disasters, the construction cost and storage cost of emergency facilities should also be considered while pursuing demand satisfaction. In the rescue process, the psychology of the victims is an essential factor that cannot be ignored, and relief supplies should be delivered to the disaster area as soon as possible to reduce the psychological distress of victims.

On the one hand, in order to avoid waste of resources, the government will choose to entrust some enterprises to store emergency supplies. On the other hand, the government still needs to hold some materials to prevent shortages in case of any enterprise inefficiency [33]. Therefore, the location–allocation model of emergency supplies built in this paper mainly considers the transportation of various types of supplies between two types of warehouses (of government emergency supplies and enterprises' emergency supplies), and vehicles depart from each warehouse site and transport the supplies to the disaster site according to the demand.

To ensure the lowest total cost of the system (as shown in Figure 1), the location of the disaster area, vehicle transportation capacity, emergency supplies warehouses, and psychology of the victims are integrated to determine the optimum locations of the government emergency supplies warehouses and the enterprise emergency supplies warehouses. Furthermore, according to the needs of residents in different disaster areas, a material allocation scheme from government and enterprise warehouses to the disaster area is formulated.

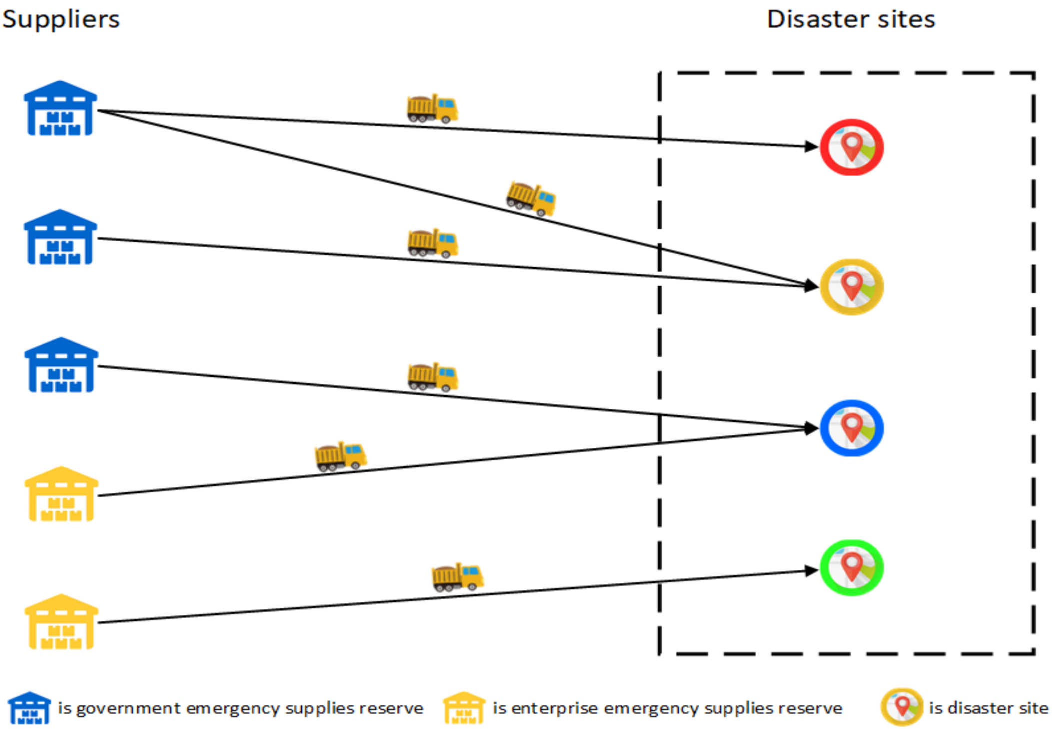

Figure 1. The supplies location–allocation system.

4. Model Formulation

4.1. Assumptions

1. Each vehicle only corresponds to one starting point and one endpoint, without considering the round-trip situation of vehicles;
2. The number of rescue vehicles is not limited, the vehicle type is consistent, and the carrying capacity of the vehicle is fixed and known;
3. The cost of wear and tear and the cost of obsolescence are not taken into account;
4. The demand of each disaster area is known.

4.2. Notation System

I	Set of candidate points for the government emergency supplies warehouses, $i \in I$;
J	Set of candidate points for the enterprise emergency supplies warehouses, $j \in J$;
W	Set of emergency supplies types, w ∈ W;
A_i	The construction cost of the government emergency supplies warehouses i;
B_j	The rental cost of the enterprise emergency supplies warehouses j;
h_{1i}^{w}	Unit storage cost of type w supplies in the government emergency supplies warehouses i;
h_{2j}^{w}	Unit storage cost of type w supplies in the enterprise emergency supplies warehouses j;
c	Transportation cost per distance per vehicle;
r_{1i}^{w}	Maximum capacity of the government emergency supplies warehouses i;
r_{2j}^{w}	Maximum capacity of the enterprise emergency supplies warehouses j;

s_{1im}	Distance from the government emergency supplies warehouses i to the disaster site m;
s_{2jm}	Distance from the enterprise emergency supplies warehouses j to the disaster site m;
v	The vehicle speed;
d_m^w	The demand of the disaster site m for the type of supplies w;
β^w	The penalty factor of type w supplies;
q	The unit vehicle capacity;
F	The suffering perception cost;
a_w,b_w	The suffering perception parameter;
e	The pain penalty factor;
M	A huge positive number;
f_{1im}^w	Suffering perception cost caused by undelivered supplies of type w from the government emergency supplies warehouses i to the disaster site m;
f_{2jm}^w	Suffering perception cost caused by undelivered supplies of type w from the enterprise emergency supplies warehouses j to the disaster site m;
p_{1im}^w	The amount of type w supplies transported from the government emergency supplies warehouses i to the disaster site m;
p_{2jm}^w	The amount of type w supplies transported from the enterprise emergency supplies warehouses j to the disaster site m;
k_{1im}	The number of vehicles from the government emergency supplies warehouses i to the disaster site m;
k_{2jm}	The number of vehicles from the enterprise emergency supplies warehouses j to the disaster site m;
x_{1im}, x_{2jm}	A 0–1 variable, 1 if the government/enterprise emergency supplies warehouses i/j dispatch supplies to the disaster area; otherwise, 0;
y_{1i}, y_{2j}	A 0–1 variable, 1 if government/enterprise emergency supplies warehouses chosen i/j; otherwise, 0.

4.3. Human Suffering Function

The occurrence of disasters brings physical injury to the residents in the disaster area and causes huge psychological trauma. If the psychological distress of the victims is ignored in the emergency rescue work, the victims may behave irrationally and cause more severe losses [34]. Therefore, while completing the rescue work efficiently, we should also pay attention to the people-oriented idea, consider the mental health of the victims, and provide a strong guarantee for the victims in both material and spiritual aspects.

Psychological theories, such as prospect theory [35,36] and exploitation theory [37,38], are generally used to quantify the suffering of victims. This paper refers to the research of Wang Xihui [39]. On the one hand, the urgency of each type of supply is different, and the degree of distress caused by the shortage of different supplies is also different. On the other hand, the longer the victims wait for supplies, the greater the degree of psychological distress. Therefore, this paper considers the impact of supply type and provision delay on the psychological distress of victims and quantifies it with the suffering perception cost function. The specific function refers to the research of Wang Xihui [39]:

$$f^w = a_{w*} t^{b^w} . \forall w \in W$$

Due to financial constraints, reserve supplies cannot fully meet the needs of victims, and victims will suffer from the fact that their needs cannot be fully met. Wang Xihui's study does not consider this factor and only considers the suffering caused by the supplies that can meet the needs of the victims that have not yet been delivered. Therefore, this paper extends the current study by improving the original function and considering both government and enterprise emergency supplies warehouses, and the improved function is:

$$\begin{aligned} F &= \sum_w \sum_m \left[\sum_i a_w (s_{1im}/v)^{b_w} p_{1im}^w + \sum_j a_w (s_{2jm}/v)^{b_w} p_{2jm}^w \right] \\ &+ \sum_i \sum_j \sum_m \sum_w (d_m^w - x_{1im} p_{1im}^w - x_{2jm} p_{2jm}^w) e \end{aligned}$$

Among them, the first item represents the suffering perception cost caused by the fact that the supplies have not been delivered; the second item represents the suffering perception cost caused by the number of supplies that cannot meet the needs of the disaster area.

4.4. Mathematical Model

The location–allocation model is as follows:

$$\begin{aligned} \mathrm{Min} Z_1 &= \sum_i A_i y_{1i} + \sum_i \sum_w \sum_m p_{1im}^w h_1^w y_{1i} + \sum_i B_j y_{2j} + \sum_j \sum_w \sum_m p_{2jm}^w h_2^w y_{2j} \\ &+ c \sum_i \sum_m \sum_w s_{1im} k_{1im} x_{1im} + c \sum_j \sum_w \sum_m s_{2jm} k_{2jm} x_{2jm} \\ &+ \sum_i \sum_j \sum_m \sum_w (d_m^w - x_{1im} p_{1im}^w - x_{2jm} p_{2jm}^w) \beta^w + \mathrm{F} \end{aligned} \tag{1}$$

$$\sum_i x_{1im} p_{1im}^w + \sum_j x_{2jm} p_{2jm}^w \le d_m^w \tag{2}$$

$$x_{1im} \le y_{1i}, x_{2jm} \le y_{2j} \tag{3}$$

$$x_{1im} + x_{2jm} \ge 1 \tag{4}$$

$$\sum_m p_{1im}^w \le r_1^w, \sum_m p_{2jm}^w \le r_2^w \tag{5}$$

$$\sum_w p_{1im}^w \le q k_{1im}, \sum_w p_{2jm}^w \le q k_{2jm} \tag{6}$$

$$\begin{aligned} F = & \sum_w \sum_m \left[\sum_i a_w (s_{1im}/v)^{b_w} p_{1im}^w + \sum_j a_w (s_{2jm}/v)^{b_w} p_{2jm}^w \right] \\ & + \sum_i \sum_j \sum_m \sum_w (d_m^w - x_{1im} p_{1im}^w - x_{2jm} p_{2jm}^w) e \end{aligned} \tag{7}$$

$$k_{1im} = \left\lceil \sum_w p_{1im}^w / q \right\rceil, k_{2jm} = \left\lceil \sum_w p_{2jm}^w / q \right\rceil \tag{8}$$

$$k_{1im}, k_{2im}, p_{1im}^w, p_{2jm}^w \in Z^+, x_{1im}, x_{2jm}, y_{1i}, y_{2j} \in \{0, 1\} \tag{9}$$

Equation (1) represents the objective function of the model, which aims to minimize the total cost of the logistics system. Among them, the first and second items represent the construction cost, and storage cost of the government emergency supplies warehouses, the third and fourth items represent the rental cost and storage cost of the enterprise emergency supplies warehouses, the fourth and fifth items represent the transportation cost from the government emergency supplies warehouses and the enterprise emergency supplies storage, and the sixth item is the punishment cost that the supplies cannot meet the needs of the victims. The seventh item represents the suffering perception cost of the disaster victims. Equation (2) ensures the quantity of each type of supply dispatched from the government emergency supplies warehouses and the enterprise emergency supplies warehouses does not exceed the demand of the disaster area. Equation (3) denotes that the supplies can be allocated to the disaster area only when the alternative point is selected as a government or enterprise emergency supplies warehouse. Equation (4) shows that every disaster area can receive supplies. Equation (5) indicates that the supplies delivered from the storage depot to the disaster area shall not exceed the maximum capacity of the storage depot. Equation (6) states that the actual supplies transportation volume does not exceed the maximum carrying capacity of the vehicle. Equation (7) describes the suffering function of lack of w type of supplies for victims at disaster area m. Equation (8) expresses the number of vehicles transporting supplies. Equation (9) defines decision variables.

5. Solution Methods

Authors should discuss the results and how they can be interpreted from previous studies and the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

The government–enterprise joint location–allocation model of emergency supplies constructed in this paper is a mixed-integer problem with many constraints and variables, and the traditional precise algorithm cannot find the optimal solution, so the simulated annealing algorithm is used to solve it [40]. The simulated annealing algorithm is a common heuristic algorithm. Its principle is similar to solid annealing in thermodynamics, starting from the initial solution, repeating the iteration of "generating a new solution → calculating the difference between the initial objective function and the current objective function → choosing to accept the new solution or abandon it", and gradually attenuating the initial parameters to find the optimal global solution of the objective function. Compared with the traditional heuristic algorithm, the simulated annealing algorithm is widely used in solving optimization problems because of its fewer restrictions on initial conditions and its ability to jump out of local optima. This paper uses the simulated annealing algorithm to solve the location–allocation model of emergency supplies based on the government–enterprise alliance.

5.1. Initialization

Set the initial solution X_0 as well as the initial temperature *TS*. The initial solution X_0 is randomly generated. Meanwhile, the initial temperature *TS* should be set to a suitable value. If the initial temperature is low, the calculation time is short, but sometimes the iteration will stop after the locally optimal solution is obtained. If the initial temperature is high, the number of iterations is large, and it is easier to find the optimal global solution, but the corresponding calculation time will be longer. Therefore, this paper introduces a conversion factor *Pr* to calculate the initial temperature by the cost difference of different siting options in the initial solution set. Since there may not be an optimal solution in the initial solution set, the value of *Pr* should be less than 1 to ensure a sufficient number of iterations. In this paper, $Pr = 0.5$ is chosen. The annealing rate is also an important parameter, which controls the speed of the annealing process and sets the temperature to 98% of the current temperature every time a better solution is generated.

5.2. Generation and Determination of the New Solution

A new location–allocation scheme is obtained by selecting government or enterprise warehouses through random perturbation, and a new objective function value is generated according to the scheme. If the solution reaches the condition of inner loop termination, that is, a plurality of invalid new solutions is generated, the fourth step is carried out; otherwise, another feasible solution is randomly selected from the set of feasible solutions, and the value of the objective function is compared, that is, the total cost of the new and old location–allocation schemes is compared. If the new objective function value is smaller than the original objective function value, that is, the cost of the new location–allocation scheme is lower, the new feasible solution is taken as the current solution; if the new objective function value is larger than the original objective function, the probability $\exp(-\Delta f/T)$ is used to accept the new feasible solution as the current solution. In this way, the deviation solution can be accepted with a certain probability, and the problem of falling into the local optimum can be alleviated to find the global optimum solution.

5.3. Termination Conditions

If the solution satisfies the final abort condition, the algorithm is ended with the current solution as the optimal solution. Generally, there are three ways to end the algorithm: (1) set the end temperature and end the algorithm when the current temperature is less than the end temperature; (2) set the maximum number of iterations and stop the loop when the number of iterations is reached; (3) end the algorithm when several new solutions are not accepted. In this paper, methods (1) and (2) are used to set the termination temperature and the maximum number of iterations. If any condition is satisfied, the annealing will be terminated, and the current result will be the optimal solution.

6. Case Study

6.1. Case Illustration

Sichuan Province is located in the Longmenshan seismic belt in Sichuan Province, a high-incidence area of earthquake disasters in China. According to the official website of the State Seismological Bureau, since 2012, 26 earthquakes of magnitude 5.0 or above have occurred in Sichuan Province, causing substantial property losses and casualties. In this paper, the 2008 Wenchuan earthquake in Sichuan Province is used to design the example.

The food and tents are considered. The food is in the form of a fixed combination package, each package weighs 4 kg, and the tent is 3 m × 4 m × 2.5 m and can accommodate 6 people. The distribution of emergency warehouses and disaster areas is shown in Figure 2. Qingshen, Mianyang, Dujiangyan, Guanghan, Meishan, and Jiange were selected as candidate sites for the government emergency supplies warehouses, and Chengdu, Deyang, Ya'an, and Ziyang were selected as candidate sites for the enterprise emergency supplies warehouses. The storage capacity and storage cost of each type of warehouse are shown in Table 1. Jiangyou, Chongzhou, Shifang, Zhongjiang, Qingchuan, Beichuan, Renshou, Jinyang, Wenchuan, Maoxian, and Lixian were selected as the disaster areas, and the demand of each disaster area is shown in Table 2. A Baidu map was used to obtain the transportation distance between each area. The transportation cost per unit distance of the unit vehicle is CNY15/km. The carrying capacity of the vehicle is 8 t, and the speed is 50 km/h. The penalty factors for food and tent non-delivery are 0.15 and 0.25, and the pain penalty factor is 6. The suffering perception parameters are shown in Table 3.

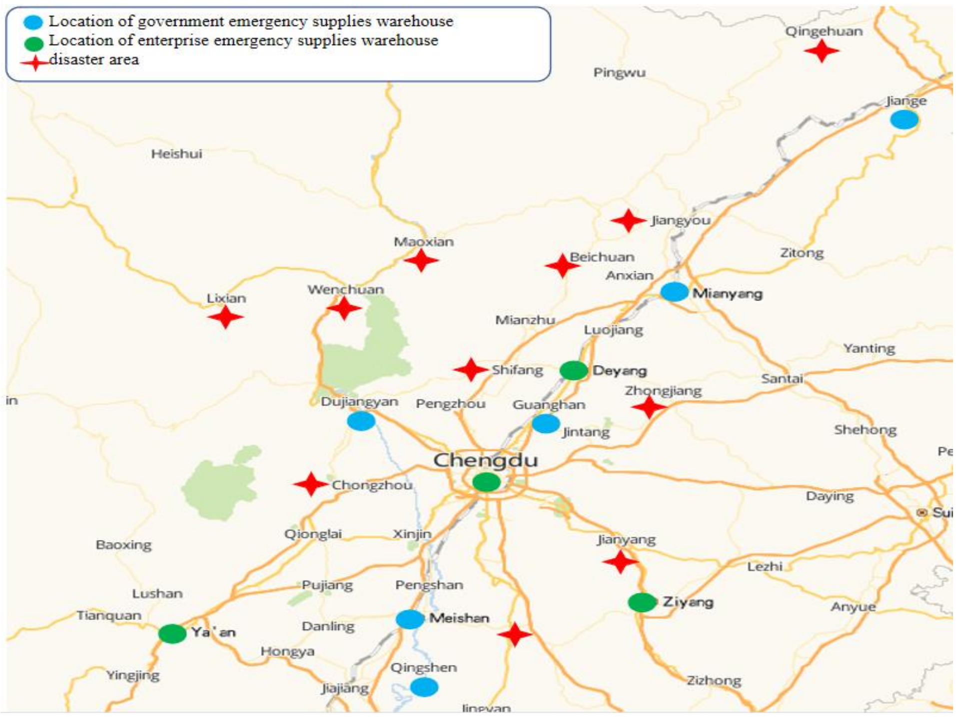

Figure 2. Distribution of emergency warehouses and disaster areas.

Table 1. Storage capacity and cost of various supplies in each type of warehouse.

Type	Location	Food Storage Capacity /(Million Pieces)	Tent Storage Capacity /(Million Pieces)	Construction Cost /(Million Yuan)	Food Storage Cost /(Yuan/Piece)	Tent Storage Cost /(Yuan/Piece)
Government emergency supplies warehouse	Qingshen	19.875	0.916	1754.810	0.03	0.05
	Mianyang	18.060	0.740	1754.084		
	Dujiangyan	19.295	0.856	1754.578		
	Guanghan	17.805	0.774	1753.982		
	Meishan	16.615	0.724	1753.506		
	Jiange	15.115	0.846	1752.906		
Enterprise emergency supplies warehouse	Chengdu	14.130	0.702	25.0714	0.04	0.06
	Deyang	12.265	0.666	25.0352		
	Yaan	14.375	0.764	25.0598		
	Ziyang	14.715	0.772	25.0300		

Table 2. Supplies demand of each disaster area.

Disaster Area	Food Demand/(Million Pieces)	Tent Demand/(Million Pieces)
Jiangyou	12.75	0.616
Chongzhou	7.20	0.700
Shifang	8.40	0.536
Zhongjiang	6.00	0.600
Qingchuan	9.10	0.736
Beichuan	7.50	0.560
Renshou	5.00	0.400
Jianyang	6.30	0.500
Wenchuan	16.00	0.880
Maoxian	6.30	0.440

Table 3. The suffering perception parameters.

Type	a	b
food	0.999	0.976
tent	0.990	0.985

6.2. Results

Programmed in MATLAB R2019b, running on an AMD Ryzen 5 3600X 6-Core Processor with 16G RAM. The parameters of the simulated annealing algorithm were set as follows: $Pr = 0.5$, initial temperature $t_0 = 86$, initial solution $X_0 = 85462245$, annealing rate $\gamma = 0.98$, and iteration number $\alpha = 2000$. After several iterations, the computational results were stabilized, and Figure 3 shows the convergence of the algorithm, which indicates that the algorithm converges well.

According to the calculation results, a total of two government emergency supplies warehouses and four enterprise emergency supplies warehouses were selected, and the specific location–allocation scheme is shown in Table 4. The total cost of the system is CNY 475.8588 million, and the supplies satisfaction rate is 94.25%, which basically meets the needs of disaster victims.

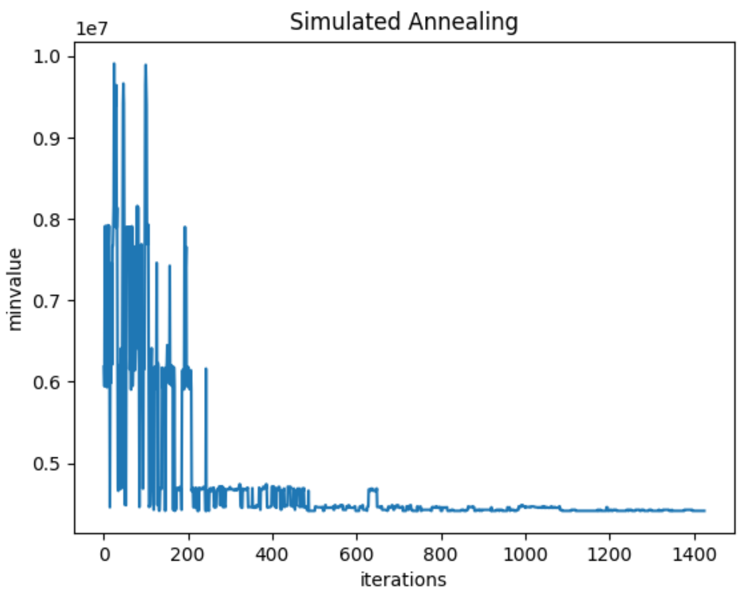

Figure 3. The evolution processes of the algorithm.

Table 4. Optimal location–allocation scheme.

Location	Type	Disaster Area	Allocation Supplies/Million Pieces
Dujiangyan	government	Wenchuan	food: 15.515 tent: 0.528
		Maoxian	food: 3.780 tent: 0.264
		Shifang	tent: 0.064
Jiange	government	Jiangyou	food: 6.015 tent: 0.3696
		Qingchuan	food: 9.100 tent: 0.4464
		Beichuan	tent: 0.03
Chengdu	government	Chongzhou	food: 2.075 tent: 0.436
		Shifang	food: 8.400 tent: 0.266
		Zhongjiang	food: 2.585
		Beichuan	food: 0.585
		Wenchuan	food: 0.485
Deyang	enterprise	Jiangyou	food: 5.350
		Beichuan	food: 6.915 tent: 0.306
		Zhongjiang	tent: 0.360
Yaan	enterprise	Chongzhou	food: 5.125 tent: 0.264
		Lixian	food: 9.250 tent: 0.500
Ziyang	enterprise	Zhongjiang	food: 3.415
		Renshou	food: 5.000 tent: 0.272
		Jianyang	food: 6.300 tent: 0.500

6.3. Analysis of the Results

To further illustrate the influence of this factor in the psychology of the victims, the pain penalty factor was changed, its effect on the demand satisfaction rate was analyzed, and the results are shown in Table 5.

Table 5. Suffering perception cost and demand satisfaction rate under different pain penalty factors.

e	Suffering Perception Cost/(Million Yuan)	Demand Satisfaction Rate
1	26.5,867	79.78%
3	60.6,863	81.35%
5	77.9,524	86.17%
7	26.9,225	97.07%
9	26.1,591	98.21%

It can be seen that as the pain penalty factor becomes larger, the suffering perception cost starts an increasing trend, which is due to the increase in the suffering perception cost caused by the number of supplies not meeting the needs of the disaster area and thus the increase in the total suffering perception cost. After the cost rises to a certain level, the suffering perception cost gradually decreases as the pain penalty factor becomes larger, which is because, in order to avoid a high suffering perception cost, more supplies are chosen to be transported to the disaster area, thus reducing the suffering perception of the victims. At the same time, as the pain penalty factor becomes larger, the supplies demand satisfaction rate also becomes larger, which indicates that as more attention is paid to victims' suffering perception, more supplies will be allocated to the disaster site, thus better satisfying victims' demand.

To further verify the validity of the model, the candidate set of the enterprise emergency supplies warehouses is removed, and the government is used as a single subject to provide supplies to the affected sites. The same algorithm parameters are set for calculation. The obtained optimal location–allocation scheme is shown in Table 6.

Table 6. Optimal location–allocation scheme under the condition of no enterprise warehouses.

Location	Type	Disaster Area	Allocation Supplies/Million Pieces
Qingshen	government	Chongzhou	food: 7.2 tent: 0.42
		Renshou	food: 5.0 tent: 0.4
		Jianyang	food: 6.3 tent: 0.096
		Wenchuan	food: 1.375
Mianyang	government	Jiangyou	food: 6.735
		Beichuan	food: 7.5 tent: 0.336
		Maoxian	food: 3.825 tent: 0.236
		Zhongjiang	tent: 0.168
Dujiangyan	government	Wenchuan	food: 11.22 tent: 0.528
		Maoxian	food: 2.475 tent: 0.028
		Lixian	food: 5.6 tent: 0.3
Guanghan	government	Shifang	food: 8.4 tent 0.378
		Zhongjiang	food: 6.0 tent 0.192
		Wenchuan	food: 3.405
		Jianyang	tent: 0.204
Jiange	government	Jiangyou	food: 6.015 tent: 0.3696
		Qingchuan	food: 9.1 tent: 0.4764
		Jianyang	food: 6.300 tent: 0.500

Comparing the two solutions in Table 7, it can be seen that the total cost of the system is reduced by CNY 424.18 million, the satisfaction rate of food is increased by 0.73%, and the satisfaction rate of tents is increased by 6.33%, which shows that the reserve and distribution of supplies by two main bodies, the government, and enterprises, can improve the satisfaction rate of emergency supplies while effectively saving costs.

Table 7. Different results with/without enterprise warehouses.

With or without Enterprise Warehouse	Demand Satisfaction Rate		Total System Cost/(Million Yuan)	Suffering Perception Cost/(Million Yuan)
	Food	Tent		
No	96.10%	64.88%	900.0462	38.6487
Yes	96.83%	71.21%	475.8588	40.0591

It can be seen that the model proposed in this paper can effectively generate an optimal solution for the location–allocation of emergency supplies. Furthermore, it can meet the demand for supplies in the disaster area with a low total system cost, avoid a severe shortage of supplies at each disaster site, and deepen the distress of victims.

7. Conclusions

In this paper, considering the property losses and casualties caused by natural disasters, we comprehensively consider the location of emergency supplies warehouses and the allocation of emergency supplies, and introduce the disaster victims' suffering perception, based on the cooperation between the government and enterprises, and entrust enterprises to carry out storage on behalf of the government based on holding part of the inventory. We construct a multi-supply and multi-objective emergency location–allocation model and use the simulated annealing algorithm to solve it. The Wenchuan earthquake is used as the case background for analysis to thoroughly verify the model and algorithm's effectiveness. This paper provides strong data support for the emergency rescue system under the cooperation of government and enterprises and changes the status of separation between the theoretical framework and mathematical model, so that this model is no longer just a theoretical concept but can be applied to the practical field. Compared with the government as a single entity responsible for emergency supplies storage and distribution, cooperation between the government and enterprises to jointly store emergency supplies before a disaster and distribute them after a disaster can improve the sustainable performance of disaster response systems. Compared with the consideration of efficiency or cost in emergency relief work, this paper also considers the "human" factor while focusing on the "material" factor, focuses on the psychological impact of disaster victims on the construction of disaster response system, and meets the sustainable requirement of humanistic care for survivors. This paper also improves Wang's pain perception cost function to reflect the psychological pain of disaster victims more realistically. The method of this paper is universal and applicable to the construction of emergency response systems under different disasters in different regions, which can help countries or regions recover from the disaster state as soon as possible.

Although this paper provides a detailed study of warehouse location and supplies allocation in emergency relief work, some valuable issues deserve in-depth study in the future. Firstly, this paper describes the psychology of disaster victims through the Suffering perception cost, and in the subsequent research work, prospect theory and exploitation theory can also be introduced to portray disaster victims' perceptions of disasters. For example, the value function in prospect theory can be used to portray the degree of disaster victims' satisfaction with the distribution of goods [41]. Secondly, climate change is a hot issue, and future research can consider the impact of climate change on humanitarian relief. Thirdly, future research can consider the changing demand for supplies in disaster areas and construct a multi-cycle dynamic model of emergency supplies storage location and supplies allocation. In addition, the research in this paper has not considered the wear and tear and expiration of emergency supplies, and further discussion can be made to consider the reserve situation when emergency supplies are rotated [42,43] to bring the model closer to reality. Furthermore, the scenario of considering the importance of supplies based on the psychological distress of the victims to determine the priority of supply stockpiling and distribution would also be a meaningful research direction.

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