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The Distribution of Emergency Logistics Centers under the COVID-19 Lockdown: The Case of Yangtze River Delta Area

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Abstract: The regular lockdown policy adopted in controlling the pandemic of COVID-19 has caused logistic disruptions in some areas that have a great impact on the living standards of residents and the production of enterprises. Given that the construction of emergency logistics centers is an effective solution, this paper takes the Yangtze River Delta Area (YRDA) of China as an example and discusses the site selection and material distribution of the emergency logistics centers in the region via a two-stage model. The first stage is the selection of candidate emergency logistics centers in the YRDA. A comprehensive evaluation index system is built with 4 primary and 15 secondary indexes to evaluate the logistic infrastructure capacity of the 41 cities in the YRDA. Further, through a principal component analysis, 12 cities are selected as candidate construction sites for emergency logistics centers. In the second stage, a biobjective site selection model with uncertain demand is established and calculated via the NSGA-II algorithm. According to the time sensitivity of emergency logistics, six cities are filtered from the optimal solution set, including Hefei, Hangzhou, Xuzhou, Wenzhou, Changzhou, and Shanghai, ensuring that all 41 cities are within their service scope.

Keywords: COVID-19; emergency logistics center; site selection

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1. Introduction

Due to the stronger spreading ability of COVID-19, many countries have adopted a lockdown or traffic control policy [1], which brought the entire community into a state of rapid standstill. This policy effectively blocked the community spread of the virus, but soon caused a shortage of living and production materials in social life since the supply chain operation was interrupted [2]. In China, for example, online shopping was completely stopped in some regions conducting the lockdown policy due to the closing of logistic channels. Enterprises that were still in operation could only be maintained by their inventories, which had a long-term and severe impact on the economy. In addition, the rising convenience and volume of human mobility aggravated the dispersion of COVID-19, leading to recurrent lockdowns in many regions.

For the accessibility and timeliness of material supply in such an emergent situation, both the government and enterprises have been considering solutions through emergency logistics. Emergency logistics is designed to control the impact of disasters and public crises, where the material distribution and facility location are of vital importance [3]. As early as 1984, Kemball-Cook and Stephenson first proposed that in the process of rescue activities, logistics management should be adopted to complete the distribution of relevant materials in order to improve transport efficiency [4]. Thomas et al. [5] classified the concept of emergency logistics in each stage and proposed that the components of emergency logistics were transport processes and methods. Duran et al. [6] argued that the most important issues in emergency disaster relief were the flexibility of mobilizing materials and the effectiveness of distribution.

Since the severe acute respiratory syndrome (SARS) virus (2003), China's emergency logistics system has been built for the sustainable development of the supply chain. However, it still has faced great challenges under the massive lockdown in megacities. To further diminish the effects of the pandemic, China is planning a corresponding emergency system at the national level, the government report [7] explicitly stating to strengthen the construction of an emergency logistics system. As the most developed economic zone and industrial base in China, it is necessary to establish an emergency logistics system in the Yangtze River Delta Area (YRDA), including the four provinces of Shanghai, Jiangsu, Zhejiang, and Anhui, where one-sixth of China's population lives (0.24 billion in 2021). Its economic volume accounts for over 25% of the national GDP (2021). As an important base for China's auto industry, 23% of cars are produced in the YRDA, and a disruption in the supply chain would have an impact on the car production of the whole country (e.g., Shanghai's lockdown during April 2022–June 2022). To support the control of COVID-19 and minimize the side effects of the lockdown policy, the establishment of an emergency logistics system in the YRDA has become a solution to encountering ever-emerging natural and artificial disasters.

The question remains of how to establish the emergency logistics network in the YRDA (e.g., how many and in which city should we locate the emergency logistics centers), and what kinds of factors should be considered to balance the social and economic benefits. As identified by Lau et al. [8], the key elements for the success of China's emergency logistics system are demand forecasting and planning, inventory management, distribution network, and systematic information management. However, as the situation of the YRDA becomes more complicated, the YRDA needs to consider the situation of intercity synergies. Most of the current studies in China are based on the provincial and municipal levels, and there is a lack of research on the siting of emergency logistics in cross-regional urban clusters, which requires the consideration of regional divergence. Therefore, this paper applies a two-stage model to present a framework for logistics center site selection in the YRDA. The first stage includes the determination of criteria through a literature review and interviews with experts. The second stage conducts a weight setting with the linear best–worst multicriteria decision-making method (BWM). Finally, the locations are ranked with the evaluation based on distance from average solution (EDAS).

The rest of this paper is constructed as follows: Section 2 reviews the literature on location selection and allocation problems of emergency logistics systems. Sections 3 and 4 introduce the two stages including the establishment of the index system, the process of data collection, methodology introduction, etc. Section 5 presents the empirical analysis. Section 6 concludes this paper.

2. Literature Review

Literally, location selection and allocation problems can be solved through criteria assessment and mathematical programming. Methodologies such as analytic hierarchy process (AHP), analytic network process (ANP), technique for order preference by similarity to ideal solution (TOPSIS), axiomatic fuzzy set (AFS), decision-making trial and evaluation laboratory (DEMATEL) are well developed in dealing with such problems [9]. Compared with the general distribution issues, the selection of an emergency logistics center considers more factors, such as response time, emergency demand, transport cost, etc. Most of the literature focuses on site selection and transport planning, which are also the two issues that need to be addressed in the emergency logistics center planning of the YRDA. Thus, the site selection of emergency logistics centers can be divided into continuous and discrete problems. For example, Xiong et al. [10] used the gravity model to calculate the layout of independent facilities of logistics centers, as it is easier to establish a coordinate system by determining the relative distance between each site. A discrete solution, however, refers to the selection of the optimized point among several alternative locations by certain mathematical methods, such as P-center, P-median, maximum coverage, two-stage, integer planning, etc. Caunhye et al. [11] applied the two-stage model for risk management in disaster situations with an uncertain demand and infrastructure status. Wang et al. [12] discussed the application and extension of the discrete coverage-based emergency facility location problem. So far, there have been limitations in the research due to the uncertainty caused by emergencies, where static models are no longer applicable. To overcome the uncertainties, Rawls and Turnquist [13] introduced the application of a two-stage stochastic programming model and Shen et al. [14] solved the logistics center location and allocation problems with fuzzy linear programming models. Sun et al. [15] separated the location and allocation problem into three stages: suppliers, logistic centers, and customers. The carbon tax regulation was introduced to optimize the emission problem with the application of fuzzy set theory, which provided a crisp plan for the establishment of a green logistic network. The principles of these models require that the indicators are completely independent, but in reality, there are still certain dependencies. Moreover, the subjectivity in the establishment of indicators and weights can also lead to a limited range of indicator selection. Hong et al. [16] applied AHP to evaluate environmental and technical issues and found that time minimization was superior to cost minimization. Niroomand et al. [17] proposed a nonlinear model and applied the interval TOPSIS approach for determining the location of emergency centers in Firouzabad city. Jiang et al. [18] assessed the reliability of an emergency logistic system by developing a hybrid model using a DEMATEL–ANP.

In mathematical programming, scholars focus on stochastic programming models and heuristic algorithms to solve it. Zhou and Liu [19] proposed three models, an expected-value model, chance-constrained and dependent-chance programming to formulate the location selection problems, and the network simplex algorithm, stochastic simulation, and genetic algorithm were integrated to design a hybrid intelligent algorithm. Cheng and Wang [20] extended the chance-constrained programming model by taking the road condition into consideration. To optimize the service quality of emergency hubs, Geng et al. [21] considered the diversion of shelters from the perspective of humanitarian logistics and the needs of victims and proposed a multistandard constrained site-selection model Özmen and Aydoğan [22] applied a three-stage methodology for the location selection with criteria for establishing, weighting, and ranking. The criteria were weighted with a linear best–worst method, while the evaluation based on distance from average solution (EDAS) is adopted to rank the locations. Maharjan and Hanaoka [23] developed a multiobjective location-allocation model for the location sequencing of temporary logistics hubs under uncertainty, considering the imprecise and time-varying nature of different parameters. In considering limited transportation resources, Wang et al. [24] proposed a state–space–time network-based mixed-integer programming model. Multifacility collaboration provided a better solution for the operation of the emergency logistics network. Li et al. [25] developed an uncertain multiobjective model and generated the Pareto optimal solutions under uncertainty distribution.

Above all, there are fruitful research results in terms of criteria assessment, but the index system is often complex, with some indexes being completely independent. Although verified by numerical experiments, such an index system is not suitable in reality. Furthermore, there is a certain subjectivity in the establishment and weighting of indicators, which could limit the scope of the indicator selection. In addition, it can be found that research topics on emergency logistics vary from disaster operations to terrorist attacks, while the consideration of disease is neglected [8]. Moreover, some traditional mathematical models are carried out under static conditions, focusing on the problems of a certain stage and ignoring the integrity of emergency logistics. Therefore, this study contributes to formulating a real-world problem of emergency logistic center location and allocation: (1) in the selection of the comprehensive evaluation method, the principal component analysis is applied to avoid the subjectivity of the scoring process; (2) uncertain factors are added to the mathematical model, including the characteristics of emergency logistics, such as suddenness, uncertainty, and irregularity; (3) empirical research in the YRDA solves the problem of location selection of interprovincial emergency logistics centers, and provides a reference for the logistics network under the background of regional divergence.

3. Stage 1: Candidate Center Selection

The first stage was mainly the selection of emergency logistics centers in the cities of the Yangtze River Delta Area with a strong logistics infrastructure capacity. In this step, the principal component analysis was applied to evaluate the candidate emergency logistics centers. The concept of the principal component analysis is to calculate independent indicators, also known as the main components, on the basis of retaining most of the information of the original indicators. At the same time, the weight was determined according to the contribution rate, which overcame the defects of other subjective evaluation methods.

3.1. Evaluation Index System

According to China Logistics Statistical Yearbook, and the Statistical Yearbook of each province (city), 4 aspects were set as the primary index: emergency demand and supply, logistics scale, economic development, and information technology development. Based on these indexes, 15 specific indicators were selected as the secondary index for the evaluation of the logistics capacity, as shown in Table 1.

Table 1. Evaluation System of Emergency Logistic Capacity.

Primary Index	Secondary Index	Symbol
Emergency demand and supply	Population	X1
	Number of employees in the transport industry	X2
	Number of medical and health institutions	X3
	General public budget expenditures (transportation)	X4
Logistics scale	Road freight volume	X5
	Road freight turnover	X6
	Road mileage	X7
	Civil motor vehicle ownership	X8
Economic development	GDP	X9
	Total investment in fixed assets	X10
	Total value of import and export	X11
	Total retail sales of social consumer goods	X12
Information technology development	Number of cell phone subscribers	X13
	Number of internet subscribers	X14
	Revenue of post and telecommunications business	X15

There were 4 secondary indexes under the emergency supply and demand: population, number of employees in the transport industry, number of medical and health institutions, and general public budget expenditures in the transport section. Since the scale of emergency relief can be roughly judged based on the number of urban residents, the population was adopted to reflect the level of emergency demand, while the other 3 indexes stood for the level of emergency supply. The number of employees determines the rescue force in the event of an emergency, and the staff and volunteers in the logistics and transportation companies have a certain reserve of expertise, in order to react in the shortest possible time under an emergency situation. The number of medical and health institutions is the combination of hospitals, health centers, disease control centers and other institutions in each city, which directly affects the level and efficiency of emergency rescue. The role of the general public budget expenditures on transportation is to guarantee people's living standards and ensure the normal functioning of society while reducing casualties and economic losses.

As for the logistics scale, road freight volume, road freight turnover, road mileage, and civil motor vehicle ownership were included. The road freight volume and the road freight turnover both directly reflect the city's road freight transport capacity, while the road mileage represents the degree of development of the city's road transportation network. Civil motor vehicle ownership is the number of registered civilian cars in the city. In addition to the existing special disaster relief vehicles, private vehicles can also be used as a second choice for emergency logistics transportation (as Wuhan did during the pandemic).

Under the economic development, there were GDP, total investment (in fixed assets), the total value of imports and exports, and the total retail sales of social consumer goods. GDP refers to the total output of production activities of each unit in the region. The overall economic and social development level, side-by-side, can show the logistics requirements. The total investment in fixed assets is a monetary representation of the costs associated with the acquisition of fixed assets and the amount of work involved. The total value of imports and exports is the total amount of actual goods entering the city. The total retail sales of social consumer goods refer to the number of goods obtained through enterprises, where some essential goods are important parts of emergency supplies.

With regard to information technology development, the number of cell phone subscribers, number of internet subscribers, and revenue from post and telecommunications business were chosen as the three secondary indices. These indices measure the degree of communication development, which affects the timeliness of information transmission in case of emergencies.

3.2. Principal Component Analysis

Since a single indicator does not reflect the problem comprehensively, the principal component analysis (PCA) was introduced. The penal data involved in the research process were obtained from the Statistical Yearbook of each selected province and city, the official website of each municipal government, the Big Data Development Authority, and the open data platform from 2016 to 2020.

Further, although all the indicators selected in this paper were moderate and positive indicators, the dimensions of each indicator varied from each other. To ensure the accuracy of the results, we took the 5-year average of the extracted indicators, then standardized and calculated them with SPSS Statistics 25.

According to the SPSS calculation, the Kaiser–Meyer–Olkin (KMO) value of the original index in this paper was 0.835, greater than 0.7, and Bartlett's sphericity test significance was less than 0.05, which further indicated that the factors could be extracted for explaining most of the information of the original indicators (see Table 2).

Table 2. KMO and Bartlett's Test.

KMO Measure of Sampling Adequacy		0.835
Bartlett's test of sphericity	Approx. Chi-square	1342.724
	df.	105.000
	Sig.	0.000

The mean standardized data of 15 indicators were input to obtain the corresponding eigenvalues, variance contribution rate (% of variance) and cumulative contribution rate (cumulative %). Table 3 shows that the eigenvalues of the first 3 components were 10.519, 1.972, and 1.132, with variance contributions at 70.126%, 13.147%, and 7.546%, and cumulative variance contributions are 70.126%, 83.273%, and 90.819%, respectively. Since the cumulative variance contribution rate of the first three components was higher than 85%, we used them as principal components for the subsequent analysis and evaluation, and the overall evaluation FG was the linear combination of the principal components.

The equation for calculating the principal components can be derived as follows:

$$F_1 = 0.081{x^*}_1 + 0.255{x^*}_2 - 0.157{x^*}_3 + \ldots + 0.129{x^*}_{15}$$

$$F_2 = 0.013{x^*}_1 - 0.258{x^*}_2 + 0.372{x^*}_3 + \ldots - 0.019{x^*}_{15}$$

$$F_3 = 0.091{x^*}_1 + 0.043{x^*}_2 + 0.020{x^*}_3 + \ldots - 0.022{x^*}_{15}$$

Table 3. Total Variance Explained.

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotated Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	Variance %	Accumulation %
1	10.519	70.126	70.126	10.519	70.126	70.126	7.628	50.856	50.856
2	1.972	13.147	83.273	1.972	13.147	83.273	3.794	25.296	76.153
3	1.132	7.546	90.819	1.132	7.546	90.819	2.200	14.666	90.819
4	0.607	4.044	94.862						
5	0.316	2.104	96.966						
6	0.199	1.329	98.295						
7	0.111	0.741	99.036						
8	0.058	0.388	99.424						
9	0.029	0.193	99.617						
10	0.023	0.156	99.773						
11	0.016	0.107	99.880						
12	0.008	0.055	99.935						
13	0.007	0.044	99.979						
14	0.002	0.011	99.990						
15	0.001	0.010	100.000						

The weight of the principal components F_1, F_2 and F_3 were calculated as 0.7722, 0.1448, and 0.0831, respectively. After further substituting the principal component scores, the overall evaluation scores of 41 cities were obtained (see Table 4).

Table 4. Principal Component Scores of Each City.

City	F_1	F_2	F_3	Overall Evaluation FG	Rank
Shanghai	5.803557	−0.2226	0.709274	4.508215	1
Suzhou (Jiangsu Province)	1.247087	1.606996	−0.71072	1.136633	2
Hangzhou	0.380162	2.120504	0.60648	0.651008	3
Nanjing	0.580743	1.208744	−0.47974	0.583609	4
Ningbo	0.280494	1.051578	0.75501	0.431607	5
Wuxi	0.34594	0.610957	−0.64792	0.301759	6
Hefei	−0.26461	1.181983	1.155259	0.062821	7
Wenzhou	−0.21669	1.773927	−0.73101	0.028786	8
Changzhou	0.089616	0.015198	−0.64307	0.017963	9
Jiaxing	0.092867	−0.17006	−0.58283	−0.00135	10
Fuyang	−0.25302	−0.87929	3.788309	−0.00789	11
Xuzhou	−0.50477	1.331821	1.109131	−0.10477	12
Zhoushan	0.255389	−1.67269	−0.74163	−0.10662	13
Shaoxing	−0.15336	0.295267	−0.5521	−0.12155	14
Bengbu	−0.09089	−1.26375	1.363799	−0.13984	15
Huzhou	−0.00847	−0.62561	−0.66282	−0.15221	16
Zhenjiang	0.016304	−0.69798	−0.81316	−0.15605	17
Yangzhou	−0.15082	0.04838	−0.71501	−0.16887	18
Jinhua	−0.38548	1.160942	−0.47463	−0.16901	19
Huaibei	0.097432	−1.52595	−0.31074	−0.17154	20
Taizhou	−0.33687	0.589845	0.03494	−0.17181	21
Haozhou	−0.26524	−1.02422	2.075239	−0.18068	22
Nantong	−0.54317	1.612954	−0.02392	−0.18786	23
Taizhou	−0.22818	0.191113	−1.04738	−0.23557	24
Huainan	−0.08421	−0.96473	−0.47653	−0.24432	25
Quzhou	−0.11026	−0.92736	−0.32836	−0.24671	26
Tongling	0.057433	−1.39079	−1.11543	−0.24973	27
Lianyungang	−0.34083	0.033151	−0.11587	−0.26802	28
Suzhou (Anhui Province)	−0.39915	−0.53194	1.350875	−0.27299	29
Wuhu	−0.25424	−0.19526	−0.62791	−0.27677	30
Maanshan	−0.12146	−0.85941	−0.82678	−0.28694	31
Suqian	−0.33919	0.007126	−0.52055	−0.30415	32
Huai'an	−0.41149	0.153796	−0.27476	−0.31831	33

Table 4. *Cont.*

City	F_1	F_2	F_3	Overall Evaluation FG	Rank
Huangshan	−0.13072	−1.19308	−0.7191	−0.33346	34
Chuzhou	−0.51165	−0.28813	0.837173	−0.36724	35
Yancheng	−0.72548	1.342764	−0.08476	−0.37283	36
Xuancheng	−0.3374	−0.62049	−0.27226	−0.37301	37
Chizhou	−0.21401	−1.04016	−0.79483	−0.38193	38
Lishui	−0.47213	−0.35822	−0.33652	−0.44441	39
Liuan	−0.72612	−0.03241	1.450991	−0.44483	40
Anqing	−0.66714	0.14709	0.393869	−0.46114	41

It can be seen that there are obvious gaps in the basic capacity of the 41 cities in the YRDA for emergency logistics, with Shanghai, Suzhou (Jiangsu Province) and Hangzhou at the top. Unlike single provinces and cities, an emergency system in the YRDA involves cross-provincial transportation, so under the constraints of reacting time, material reserves, and the range of cities served by emergency logistics centers, more alternative cities need to be considered to ensure that all regions are covered. In order to ensure that all cities of the YRDA were covered, we considered the 12 cities in the top 30% of the overall ranking as alternative locations for establishing logistics centers: Shanghai, Suzhou (Jiangsu Province), Hangzhou, Nanjing, Ningbo, Wuxi, Hefei, Wenzhou Changzhou, Jiaxing, Fuyang, and Xuzhou (see Figure 1).

Figure 1. Distribution of Candidate Emergency Logistics Centers in the YRDA.

4. Stage 2: Emergency Logistics Center Location Optimization

Emergency materials generally come from the community's assistance and emergency logistics center reserves, most of which originate from the latter due to the weak economy and strong time-sensitive characteristics of emergency logistics. Therefore, a reasonable choice for the construction site of an emergency logistics center and the scientific stock of emergency materials can reduce the impact of COVID-19. Research scopes on emergency logistics issues vary from system design, site selection, material distribution, path positioning, etc., among which site selection and material distribution are the basis of emergency logistics planning. This paper applied the location-routing problem (LRP) to analyze this problem. The LRP assumes that there are multiple potential outbreak (or other disasters) sites and alternative sites for emergency facilities before an outbreak occurs, and a portion of the alternative sites are selected to establish emergency logistics centers.

Based on the 12 alternative cities selected by the principal component analysis above, we further introduced a stochastic planning model with minimum cost and time as the objective function. Meanwhile, with other constraints such as maximum time limit, warehouse capacity limit, probability level limit, and transportation volume limit, the NSGA-II algorithm was used to calculate the emergency material distribution volumes within the YRDA.

4.1. Model Assumptions

The assumptions of the biobjective model were as follows [23,24,26]:

(1) Each city has a certain radius to provide basic material reserves for neighboring cities when responding to emergencies.
(2) The distance between the potential outbreak site and the emergency logistics center construction site is known.
(3) The number of alternative emergency logistics centers is fixed.
(4) Each emergency logistics center has a sufficient number of vehicles.
(5) The emergency transport mode is road transport, and the road accessibility between each emergency logistics center and the affected point is accessible.
(6) The demand for materials at each outbreak site is unknown, they all obey normal distribution, and the demands are independent from each other.
(7) Emergency materials are essential for maintaining daily life, and materials requiring refrigeration and other special storage requirements are not included.

4.2. Symbol Description

h Set of emergency supplies $h \in H$.

i Set of alternative emergency logistics centers $i \in I$.

j Set of outbreak sites $j \in J$.

a Types of warehouses $a \in A$.

r_h Unit volume of material h.

Z_h Unit storage cost of material h.

C_a Construction cost of type a warehouse.

U_a The maximum capacity of type a warehouse.

G_h Unit retail price of material h.

$D_{ijh}(\xi)$ Demand of material h from alternative emergency logistics center i to outbreak point j under scenario ξ.

O_{ia} response time to receive information of warehouse a in alternative emergency logistics center i.

m The maximum number of emergency logistics centers to be built.

ξ Outbreak scenario.

$\mathrm{P}(\xi)$ The probability of occurrence of the outbreak scenario ξ.

ω_h Coefficient of material h, indicating the emergency material demand level.

T_{ij} Transportation time from alternative emergency logistics center i to outbreak point j ($T_{ij} = \frac{L_{ij}}{v}$).

L_{ij} Distance from alternative emergency logistics center i to outbreak point j.

v Average vehicle speed from each emergency logistics center to each outbreak site.

T_{max} The longest time acceptable to the affected point.

α Confidence level of a satisfied demand.

x_{ia} Equals 1 if an a type warehouse is established as an emergency logistics center in the alternative emergency logistics center i, otherwise it is 0.

y_{ij} Equals 1 if the outbreak point j is assigned to the alternative emergency logistics center i, otherwise it is 0.

$S_{ijh}(\xi)$ Transportation quantity of material h from alternative emergency logistics center i to outbreak point j under disaster situation ξ.

4.3. Model Design

The biobjective site selection model is established as following:

$$min\sum_{i\in I}\sum_{a\in A}x_{ia}C_a+\sum_{h\in H}\sum_{i\in I}b_{ih}Z_h+\sum_{h\in H}\sum_{i\in I}b_{ih}G_h \tag{1}$$

$$min\sum_{i\in I}\sum_{j\in J}\sum_{a\in A}\sum_{h\in H}P(\xi)\omega_h T_{ij}S_{ijh}(\xi)x_{ia}+\sum_{a\in A}\sum_{i\in I}O_{ia}S_{ijh}(\xi)x_{ia} \tag{2}$$

Subject to

$$\sum_{h\in H}b_{ih}r_h\le\sum_{a\in A}x_{ia}U_a \quad \forall_i\in I \tag{3}$$

$$\sum_{a\in A}x_{ia}\le 1 \qquad \forall_i\in I \tag{4}$$

$$\sum_{i\in I}\sum_{a\in A}x_{ia}\le m \tag{5}$$

$$T_{ij}x_{ia}y_{ij}+O_{ia}x_{ia}\le T_{max} \quad \forall i\in I,a\in A\,,j\in J \tag{6}$$

$$\frac{b_{ih}}{S_{ijh}(\xi)}\ge\frac{S_{ijh}(\xi)}{D_{ijh}(\xi)}\ge 1 \quad \forall i\in I,h\in H\,,j\in J \tag{7}$$

$$Pr\left\{D_{ijh}(\xi)\le S_{ijh}(\xi)y_{ij}\right\}\ge\alpha \quad \forall i\in I,h\in H\,,j\in J \tag{8}$$

$$\sum_{i\in I}\sum_{j\in J}y_{ij}\ge\sum_{a\in A}\sum_{i\in I}x_{ia} \tag{9}$$

$$y_{ij}-x_{ia}\le 0 \qquad \forall i\in I,a\in A\,,j\in J \tag{10}$$

$$\sum_{i\in I}y_{ij}=1 \qquad \forall j\in J \tag{11}$$

$$x_{ia}\in\{0,1\} \;\; \forall_i\in I\,,a\in A \tag{12}$$

$$b_{ih}>0 \quad \forall_i\in I\,,h\in H \tag{13}$$

$$y_{ij}\in\{0,1\} \quad \forall i\in I,j\in J,y_{ij}\ge 0 \tag{14}$$

$$S_{ijh}(\xi)>0 \quad \forall i\in I,j\in J,\;h\in H \tag{15}$$

Equation (1) is the objective function, which consists of three parts: the construction cost of the warehouse, the storage cost of emergency materials, and the procurement cost of emergency materials. Equation (2) is the objective function, which consists of two parts: the transportation volume of all materials and the response time. Equation (3) indicates that the sum of the volume of each type of emergency material does not exceed the total capacity of the warehouse. Equation (4) indicates that up to one warehouse can be constructed in each alternative emergency logistics center for each type of warehouse. Equation (5) indicates that the total number of warehouses does not exceed m. Equation (6) indicates that the total transport time and response time do not exceed the maximum acceptable reaction time at the affected point. Equation (7) indicates that the transport volume is not greater than the stock reserve, the demand is not greater than transport quantity, and the ratio of transport quantity to demand is controlled within a reasonable range. Equation (8) indicates that in the case of uncertain demand, it is not required that each scenario satisfy all the demand quantities, as long as the probability of satisfying all the demands is greater than α. Equation (9) indicates that once the emergency logistics center is established, it has the ability to provide services with one or more than one points assigned to it. Equation (10) indicates that services can only be provided to the outbreak site through the emergency logistics center. Equation (11) indicates that one outbreak site is assigned to one established emergency logistics center service. Equations (12)–(15) indicate the constraints of the decision variables.

For the constraint (8), let $M = D_{ijh}(\xi) - S_{ijh}(\xi)y_{ij}$, then the expected value of M is: $E(M) = E\left(D_{ijh}(\xi)\right) - S_{ijh}(\xi)y_{ij}$, the variance of M is: $D(M) = D\left(D_{ijh}(\xi)\right)$. Let $\eta = \frac{M-E(M)}{\sqrt{D(M)}}$, and because $M = D_{ijh}(\xi) - S_{ijh}(\xi)y_{ij} \leq 0$, it is equivalent to $\eta = \frac{M-E(M)}{\sqrt{D(M)}} \leq -\frac{E(M)}{\sqrt{D(M)}}$. Therefore, constraint (8) can be transferred to:

$$Pr\left\{\eta \leq -\frac{E(M)}{\sqrt{D(M)}}\right\} \geq \alpha \tag{16}$$

Set the probability distribution function as $\Phi(\eta)$. If the random constraint (8) holds at a confidence level of α, then when and only when $\Phi(\alpha)^{-1} \leq -\frac{E(M)}{\sqrt{D(M)}}$, according to the above derivation, we have:

$$\Phi(\alpha)^{-1}\sqrt{D\left(D_{ijh}(\xi)\right) + E\left(D_{ijh}(\xi)\right)} \leq S_{ijh}(\xi)y_{ij} \tag{17}$$

where $D\left(D_{ijh}(\xi)\right)$ and $E\left(D_{ijh}(\xi)\right)$ are the variance and expected mean of the demand at the affected point, respectively, so constraint (8) can be converted to constraint (17).

5. Empirical Analysis

The nondominated sorting genetic algorithm with elite strategy (NSGA-II) is based on a genetic algorithm and adds fast nondominated sorting of individuals before the selection operation, which enhances the probability of good individuals staying and is suitable for the calculation of multi-objective models. Thus, the NSGA-II algorithm was chosen in this paper to solve the emergency logistics site selection problem in the multiobjective case, with the following steps.

5.1. Data Setting

In this paper, 41 cities in the Yangtze River Delta Area were selected as potential outbreak sites, 12 of which were set as alternative nodes for constructing emergency logistics centers. Given the service scope of these twelve cities can cover the whole Yangtze River Delta Area, on this basis, six cities were selected as the final nodes for the emergency logistics centers. The latitude and longitude coordinates and population quantity information of 41 cities were obtained from the official websites and the statistical Yearbook of each province and city (Table 5).

The Euclidean distance approach was used to calculate the intercity distance, so that the longitude of the potentially affected point j was lat_j and the latitude was lng_j. The average value of 6371 km was taken as the earth radius R, i.e., the distance between two cities L_{ij} was calculated as follows:

$$L_{ij} = 2Rsin^{-1}\begin{pmatrix} sin^2\left(\frac{\pi}{180}\Delta lat_{ij}\right) \\ +cos\left(\frac{\pi}{180}lat_j\right)cos\left(\frac{\pi}{180}lat_i\right)sin^2\left(\frac{\pi}{180}\Delta lng_{ij}\right) \end{pmatrix}^{\frac{1}{2}} \tag{18}$$

$$\Delta lat_j = \frac{lat_j - lat_i}{2} \tag{19}$$

$$\Delta lng_j = \frac{lng_j - lng_i}{2} \tag{20}$$

Table 5. Latitude and Longitude of Cities in the YRDA.

No.	City	Longitude	Latitude	No.	City	Longitude	Latitude
1	Shanghai	121.4726	31.23171	22	Quzhou	118.8726	28.94171
2	Nanjing	118.7674	32.04154	23	Zhoushan	122.1069	30.01603
3	Wuxi	120.3017	31.57473	24	Taizhou	121.4286	28.66138
4	Xuzhou	117.1848	34.26179	25	Lishui	119.9218	28.45199
5	Changzhou	119.947	31.77275	26	Hefei	117.283	31.86119
6	Suzhou	120.6196	31.29938	27	Huaibei	116.7947	33.97171
7	Nantong	120.8646	32.01621	28	Haozhou	115.7829	33.86934
8	Lianyungang	119.1788	34.60002	29	Suzhou (Anhui Province)	116.9841	33.63389
9	Huai'an	119.0213	33.59751	30	Bengbu	117.3624	32.93404
10	Yancheng	120.14	33.37763	31	Fuyang	115.8197	32.89697
11	Yangzhou	119.421	32.39316	32	Huainan	117.0254	32.64595
12	Zhenjiang	119.4528	32.2044	33	Chuzhou	118.3163	32.30363
13	Taizhou	119.9152	32.48488	34	Liuan	116.5077	31.75289
14	Suqian	118.2933	33.94515	35	Maanshan	118.5079	31.68936
15	Hangzhou	120.1536	30.28746	36	Wuhu	118.3765	31.32632
16	Ningbo	121.5498	29.86839	37	Xuancheng	118.758	30.94567
17	Wenzhou	120.6721	28.00058	38	Tongling	117.8166	30.92994
18	Jiaxing	120.7509	30.76265	39	Chizhou	117.4892	30.65604
19	Huzhou	120.1024	30.8672	40	Anqing	117.0536	30.52482
20	Shaoxing	120.5821	29.99712	41	Huangshan	118.3173	29.70924
21	Jinhua	119.6495	29.08952				

The distance L_{ij} between the emergency logistics center i and the affected point j can be found from Equation (17). It was assumed that all the distributions of emergency materials were via road transportation. The number of the resident population (10,000 people) in each city is shown in Table 6.

Table 6. The Population of Each City in the YRDA.

No.	City	Population	No.	City	Population
1	Shanghai	2480.30	22	Quzhou	256.86
2	Nanjing	931.97	23	Zhoushan	96.20
3	Wuxi	746.40	24	Taizhou	606.98
4	Xuzhou	908.39	25	Lishui	270.74
5	Changzhou	527.96	26	Hefei	937.34
6	Suzhou	1274.96	27	Huaibei	197.10
7	Nantong	772.80	28	Haozhou	499.87
8	Lianyungang	460.10	29	Suzhou (Anhui Province)	532.65
9	Huai'an	455.92	30	Bengbu	329.76
10	Yancheng	671.06	31	Fuyang	820.33
11	Yangzhou	456.10	32	Huainan	303.47
12	Zhenjiang	321.10	33	Chuzhou	398.85
13	Taizhou	451.68	34	Liuan	439.43
14	Suqian	498.82	35	Maanshan	216.07
15	Hangzhou	813.83	36	Wuhu	364.58
16	Ningbo	613.66	37	Xuancheng	250.10
17	Wenzhou	833.75	38	Tongling	131.22
18	Jiaxing	367.38	39	Chizhou	134.33
19	Huzhou	268.06	40	Anqing	416.68
20	Shaoxing	447.64	41	Huangshan	133.11
21	Jinhua	493.90			

We defined three types of warehouses constructed in the six emergency logistics centers as small, medium, and large, and the construction cost (million RMB) and capacity (million m^3) of each type of warehouse are shown in Table 7. Under emergencies such as COVID-19, we select two types of emergency supplies, the necessities of life and outbreak relief supplies, for example, drinking water, convenient food, medicine, and protective products, etc. The unit volume (m^3), unit storage cost (RMB), unit procurement cost (RMB), unit population demand (set), and material coefficient are shown in Table 8.

Table 7. Construction Cost and Capacity of Emergency Warehouse.

Type of Warehouse	Construction Cost	Capacity
Small	1300	50
Medium	2200	100
Large	4050	200

Table 8. Data Related to Emergency Supplies.

Types of Emergency Supplies	Volume per Unit	Unit Storage Cost	Unit Purchasing Cost	Unit Population Demand	Material Coefficient
Water (liter)	0.015	0.100	2	6	10
Convenient food (kg)	0.100	0.300	30	3	8
Drugs and protective items (set)	0.010	3	25	1	6
Tent (set)	0.259	40	80	0.250	4
Sleeping bag (set)	0.427	65	50	1	4
Lighting devices (pcs)	0.010	3	10	0.250	2

Further, we set two types of scenarios for the outbreak: level I for the significant emergent situation and level II for the emergent situation, with probabilities of 0.40 and 0.60, respectively. In general, the population affected by emergencies in China is about 0.08; for level I and level II, we set them as 0.04 and 0.02 of the resident population. When the number of people affected exceeds 100,000, the emergency logistics center response time cannot exceed 20 min and supporting vehicles must arrive within 5 h. When the number of people affected is less than 100,000, the emergency logistics center response time is no more than 15 min, supporting vehicles must arrive within 4 h, including loading and vehicle preparation time, and the average speed of emergency vehicles was set as 60 km/h.

5.2. Results

According to the NSGA-II algorithm and parameter settings, the algorithm population was set at 200, as well as the number of iterations. The confidence level was 0.8, with the crossover probability and mutation probability set at 0.7 and 0.3, respectively. MATLAB R2021a was used on a computer with Intel (R) Core (TM) i7-10710U and 16 GB of installed memory. After the experiment, the optimal solution set of the site selection model was determined and it is shown in Figure 2. The three points were located on the Pareto front surface as the Pareto optimal solutions.

Due to the weak cost-effectiveness and strong time sensitivity of emergency logistics, it is required that emergency logistics guarantee activities occur safely in the shortest time. Therefore, on the basis of the cost evaluation, the optimal solution should have a minimum transport time. According to the optimal solution set (three points above), six cities (Hefei, Hangzhou, Xuzhou, Wenzhou, Changzhou, and Shanghai) were finally selected to construct emergency logistics centers, with Hefei serving eight cities, Hangzhou nine cities, Xuzhou eight cities, Wenzhou three cities, Changzhou eight cities, and Shanghai five cities, implying the service mode of interprovincial emergency logistics (See Figure 3).

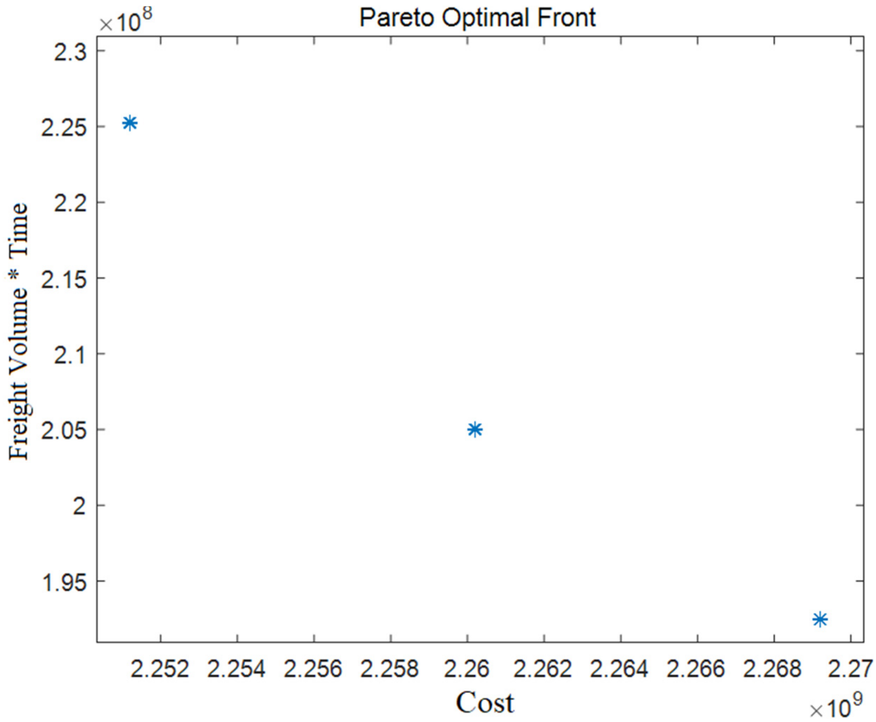

Figure 2. Pareto Optimal Solutions (* is the value of freight volume * time and cost).

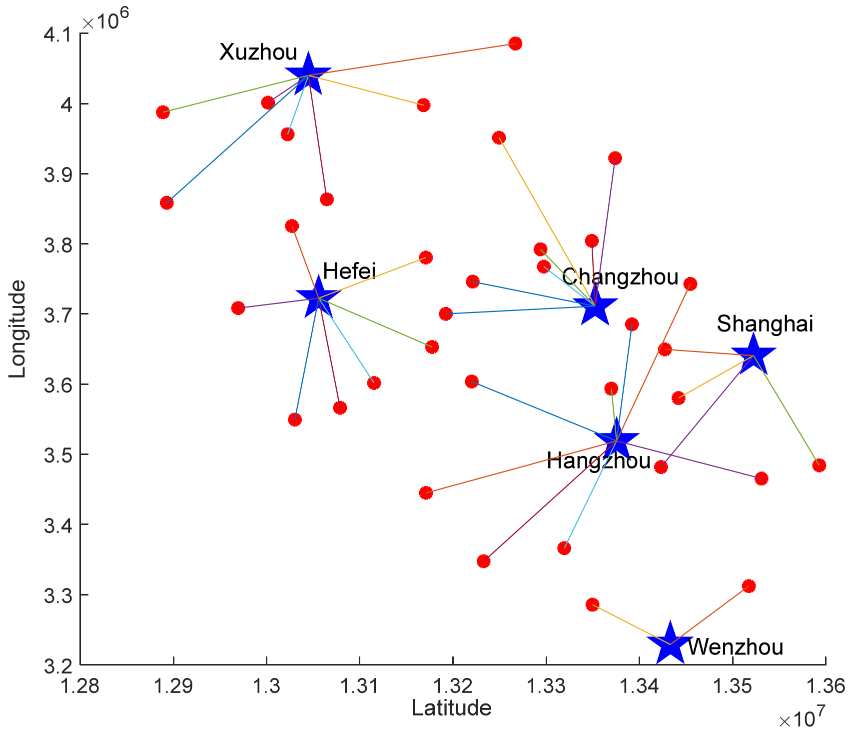

Figure 3. The Distribution of Emergency Centers with Minimum Transport Time. Note: The stars stand for six selected cities, and red dots are the cities they serve.

5.3. Discussion

Table 9 exhibits the specific service conditions of each emergency logistics center, type of warehouse established, and quantity of materials stored. According to the results, the following findings are highlighted:

Table 9. Specific Allocation Plan with Minimum Total Transport Time.

Emergency Logistics Center	Affected Cities Served	Type of Ware-house	Number of Stored Materials (pic)					
			Water	Convenient Food	Drugs and Protective Items	Tent	Sleeping Bag	Lighting Devices
Hefei	Hefei, Huainan, Chuzhou, Liuan, Wuhu, Tongling, Chizhou, Anqing	medium	6,751,680	3,375,840	1,125,280	281,320	1,012,744	281,320
Hangzhou	Hangzhou, Wuxi, Nantong, Ningbo, Huzhou, Jinhua, Quzhou, Xuancheng, Huangshan	medium	9,392,880	4,696,440	1,565,480	391,370	1,408,916	391,370
Xuzhou	Xuzhou, Lianyungang, Suqian, Huaibei, Haozhou, Suzhou (Jiangsu Province), Bengbu, Fuyang	medium	9,173,160	4,586,580	1,528,860	382,215	1,375,950	382,215
Wenzhou	Wenzhou, Taizhou, Lishui	medium	3,696,840	1,848,420	616,140	154,035	554,526	154,035
Changzhou	Changzhou, Nanjing, Huai'an, Yancheng, Yangzhou, Zhenjiang, Taizhou, Maanshan	medium	8,708,520	4,354,260	1,451,420	362,855	1,306,286	362,855
Shanghai	Shanghai, Suzhou, Jiaxing, Shaoxing, Zhoushan	medium	10,080,120	5,040,060	1,680,020	420,005	1,512,026	420,005

Compared with regular logistics centers in the YRDA, the emergency logistics centers have a same scale (all medium size). Based on indicators such as economic development, accessibility or logistic demand, the logistic network shows a certain kind of hierarchy, with several clusters having different scales of logistic infrastructures [26]. However, under an emergency situation, the influence of economic or technical indicators is reduced, while time efficiency becomes the first priority. Therefore, the scale of logistics centers does not vary with traditional elements in the site selection. Complying with the literature, Shanghai, Hangzhou, and Wenzhou are still at the core position in establishing emergency logistics centers, while Ningbo, Suzhou, Nanjing, etc. are excluded.

The service scope of the emergency logistic center should break the executive or provincial boundary. Due to the independence of the administrative system, local governments of each city always consider and handle emergency activities in their own administrative division, which impedes the ability of emergency logistics centers. Traditionally, it is taken for granted that Heifei (same as Hangzhou, Xuzhou, Wenzhou, Changzhou, and Shanghai) should serve its sister cities in the same province (Anhui). However, such a mode is inefficient. According to our results, the operation of emergency logistics centers is more effective when it allows interprovincial activities. Shanghai can serve cities in Jiangsu and Zhejiang Province, Changzhou (Jiangsu province) has access to Maanshan (Anhui province), and so forth. Since the integration of the YRDA is deepening, collaborations on an integrated emergency logistics system could be put on the agenda.

It is also notable that Anhui Province was included in the YRDA in 2016, but some studies did not take it into consideration [27]. We argue that the joining of Anhui not only extends the research area but also may affect the result with more possibilities and solutions. For example, Hangzhou in Zhejiang Province can serve Huangshan in Anhui Province. So far, this study provides a reference for policymakers in the establishment of the emergency logistics network; however, considering the growth of the regional economy, population, or even the administrative area, a detailed analysis is suggested for its application in decision-making.

6. Conclusions

For regular epidemic prevention and control in China, it is necessary to construct emergency logistics centers for providing living materials during a lockdown policy, as well as other disasters. This paper studied the location-allocation site selection and material allocation optimization of the emergency logistics center under uncertain demand. A two-stage model was proposed:

Stage 1 was the selection of candidate locations for the emergency logistics center based on the evaluation index system. By fully considering the four major factors including emergency demand and supply, logistics scale, economic development, and information technology development, the index system was built with 15 secondary indexes. The principal component analysis method was applied to conduct a dimension reduction analysis and extract the principal components from it. Further, comprehensive evaluation scores were obtained by evaluating the basic capacity of emergency logistics support in 41 cities in the Yangtze River Delta. Due to the imbalance of urban resources, the evaluation showed that the capacity of emergency logistics support varied from city to city. In order to ensure that all cities of the YRDA were covered, 12 cities were selected as the alternative locations for establishing emergency logistics centers: Shanghai, Suzhou, Hangzhou, Nanjing, Ningbo, Wuxi, Hefei, Wenzhou, Changzhou, Jiaxing, Fuyang, and Xuzhou.

Stage 2 was the location optimization of emergency logistics centers. A biobjective stochastic programming model was established under the condition of demand uncertainty, which not only considered shortening the transportation time of emergency rescue but also optimized the cost-effectiveness of emergency logistics. During the setting of the constraint conditions and parameters, more factors affecting the logistics location were considered, such as the cargo loss under uncertain demand, the maximum transportation time limit, the demand for emergency materials, etc. Moreover, the NSGA-II algorithm was adopted to verify the rationality of the model through an empirical analysis. Due to the strong timeliness and weak economy of emergency logistics, the scheme focusing on the minimum total time of rescue transportation was selected in the optimal solution set. The solution showed that the six cities of Hefei, Hangzhou, Xuzhou, Wenzhou, Changzhou, and Shanghai were the final places to establish emergency logistics centers. On the basis of ensuring that the 41 cities were within the service scope, the number of cities to establish emergency logistics centers was further reduced.

Several directions can be addressed for future research. First, the location of the emergency logistics center can be detailed from the city level to specific areas, and local policies can be considered for determining the exact positions. Second, more uncertain factors should be taken into account. For example, the impact of road accessibility caused by emergency situations is overlooked, which could have a certain influence on the transportation time and vehicles. Third, interprovincial cooperation is an important element of regional logistic system design; it could be more interesting to adjust the index and model from the perspective of the integration of the YRDA.

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References

1. Ivanov, D. Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transp. Res. Part E Logist. Transp. Rev.* **2020**, *136*, 101922. [CrossRef] [PubMed]
2. Araz, O.M.; Ramirez-Nafarrate, A.; Jehn, M.; Wilson, F.A. The importance of widespread testing for COVID-19 pandemic: Systems thinking for drive-through testing sites. *Health Syst.* **2020**, *9*, 119–123. [CrossRef] [PubMed]
3. Xu, H.; Fang, D.; Jin, Y. Emergency logistics theory, model and method: A review and further research directions. In Proceedings of the 2018 3rd International Conference on Communications, Information Management and Network Security (CIMNS 2018), Wuhan, China, 27–28 September 2018; pp. 188–192.
4. Kemball-Cook, D.; Stephenson, R. Lessons in logistics from Somalia. *Disasters* **1984**, *8*, 57–66. [CrossRef] [PubMed]
5. Thomas, M.U. Supply Chain Reliability for Contingency Operations. In Proceedings of the Annual Reliability and Maintainability Symposium, Seattle, WA, USA, 28–31 January 2002; pp. 61–67.
6. Duran, S.; Gutierrez, M.A.; Keskinocak, P. Pre-positioning of emergency items for CARE international. *Interfaces* **2011**, *41*, 223–237. [CrossRef]
7. State Council. The Decision on Accelerating the Construction of a Unified National Market. 2022. Available online: http://www.gov.cn/zhengce/2022-04/10/content_5684385.htm (accessed on 10 April 2011).
8. Yui-yip, L.; Zhang, J.; Ng, A.K.; Roozbeh, P. Implications of a pandemic outbreak risk: A discussion on China's emergency logistics in the era of coronavirus disease 2019 (COVID-19). *J. Int. Logist. Trade* **2020**, *18*, 127–135.
9. Uyanik, C.; Tuzkaya, G.; Oğuztimur, S. A literature survey on logistics centers'location selection problem. *Sigma J. Eng. Nat. Sci.* **2018**, *36*, 141–160.
10. Xiong, W.; Zhang, L.Y. Research on methods of distribution center facility siting. *Adv. Mater. Res.* **2014**, *989–994*, 5315–5318. [CrossRef]
11. Caunhye, A.M.; Zhang, Y.; Li, M.; Nie, X. A location-routing model for prepositioning and distributing emergency supplies. *Transp. Res. Part E Logist. Transp. Rev.* **2016**, *90*, 161–176. [CrossRef]
12. Wang, W.; Wu, S.; Wang, S.; Zhen, L.; Qu, X. Emergency facility location problems in logistics: Status and perspectives. *Transp. Res. Part E Logist. Transp. Rev.* **2021**, *154*, 102465. [CrossRef]
13. Rawls, C.G.; Turnquist, M.A. Pre-positioning of emergency supplies for disaster response. *Transp. Res. Part B* **2010**, *44*, 521–534. [CrossRef]
14. Shen, L.; Tao, F.; Shi, Y.; Qin, R. Optimization of location-routing problem in emergency logistics considering carbon emissions. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2982. [CrossRef] [PubMed]
15. Sun, Y.; Lu, Y.; Zhang, C. Fuzzy linear programming models for a green logistics center location and allocation problem under mixed uncertainties based on different carbon dioxide emission reduction methods. *Sustainability* **2019**, *11*, 6448. [CrossRef]
16. Hong, L.; Zhang, X. Study on location selection of multi-objective emergency logistics center based on AHP. *Procedia Eng.* **2011**, *15*, 2128–2132. [CrossRef]
17. Niroomand, S.; Bazyar, A.; Alborzi, M.; Mahmoodirad, A. A hybrid approach for multi-criteria emergency center location problem considering existing emergency centers with interval type data: A case study. *J. Ambient Intell. Humaniz. Comput.* **2018**, *9*, 1999–2008. [CrossRef]
18. Jiang, P.; Wang, Y.; Liu, C.; Hu, Y.C.; Xie, J. Evaluating critical factors influencing the reliability of emergency logistics systems using multiple-attribute decision making. *Symmetry* **2020**, *12*, 1115. [CrossRef]
19. Zhou, J.; Liu, B. New stochastic models for capacitated location-allocation problem. *Comput. Ind. Eng.* **2003**, *45*, 111–125. [CrossRef]
20. Cheng, Y.; Wang, L. A location model for capacitated alternative-fuel stations with uncertain traffic flows. *Comput. Ind. Eng.* **2020**, *145*, 106486. [CrossRef]
21. Geng, S.; Hou, H.; Zhang, S. Multi-criteria location model of emergency shelters in humanitarian logistics. *Sustainability* **2020**, *12*, 1759. [CrossRef]
22. Özmen, M.; Aydoğan, E.K. Robust multi-criteria decision making methodology for real life logistics center location problem. *Artif. Intell. Rev.* **2020**, *53*, 725–751. [CrossRef]
23. Maharjan, R.; Hanaoka, S. A credibility-based multi-objective temporary logistics hub location-allocation model for relief supply and distribution under uncertainty. *Socio-Econ. Plan. Sci.* **2020**, *70*, 100727. [CrossRef]
24. Wang, Y.; Peng, S.; Xu, M. Emergency logistics network design based on space–time resource configuration. *Knowl. Based Syst.* **2021**, *223*, 107041. [CrossRef]
25. Li, H.; Zhang, B.; Ge, X. Modeling emergency logistics location-allocation problem with uncertain parameters. *Systems* **2022**, *10*, 51. [CrossRef]
26. Ju, C.H.; Jiang, C.B.; Chen, M.Y. Research on logistics network infrastructures based on DEA-PCA approach: Evidence from the Yangtze river delta region in China. *J. Shanghai Jiaotong Univ.* **2012**, *17*, 98–107. [CrossRef]
27. He, M.; Zeng, L.; Wu, X.; Luo, J. The spatial and temporal evolution of logistics enterprises in the Yangtze River Delta. *Sustainability* **2019**, *11*, 5318. [CrossRef]