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Article

# Study on the Structural Layout of Urban Network for Large-Scale Emergency Rescue Resource Distribution

**Xiaowei Wu * and Jun Tian**

School of Environment and Civil Engineering, Dongguan University of Technology, Dongguan 523808, China
* Corresponding authors: wxw@dgut.edu.cn

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**Abstract:** This paper focuses on optimizing the layout of the urban network structure for the distribution of large-scale emergency rescue resources, in order to improve the efficiency of emergency response and the utilization rate of resources. The research takes 33 townships in Dongguan City as the object, and constructs an evaluation system for the comprehensive emergency logistics capabilities under the COVID-19 situation, covering four aspects: economy, logistics, emergency, and information capabilities. Through principal component analysis, the indicators are dimensionally reduced and screened, and the comprehensive emergency logistics scores of each township are calculated and ranked. Based on the modified gravitational model, the layout of the central city and the radiating townships is determined, and the ten major epidemic prevention and control emergency logistics circles of Dongguan City are constructed. The research results provide theoretical support and practical guidance for the urban emergency management system, helping to enhance the emergency response capabilities of cities in major safety incidents, and also providing a reference for the optimization of emergency logistics networks in other cities.

**Keywords:** emergency rescue; resource distribution; urban network; sudden public health incident; emergency logistics network optimization

## 1. Introduction

In recent years, various sudden public events have occurred frequently, such as SARS in 2003 [1] and the COVID-19 pandemic in 2020 [2]. These events are highly harmful, have a wide impact range, and last for a long time, posing a great threat to people's life and health safety, and also bringing huge challenges to the government's emergency management work. When dealing with these sudden public events, the construction of the emergency rescue resource distribution network becomes particularly important [3,4]. However, existing research in this field has some deficiencies, such as mainly focusing on the construction of theoretical models [5,6], insufficient consideration of dynamic changes and uncertain factors in actual operations [7,8], and relatively weak research on large-scale emergency rescue resource distribution networks [9,10], especially when facing sudden public health events, how to quickly and effectively allocate and distribute resources remains an urgent problem to be solved.

Traditional urban emergency rescue methods and emergency resource allocation cannot cope with such a complex situation [11,12]. To effectively resist the invasion of urban emergencies and reduce the damage caused by disasters to the city, not only do multiple emergency service departments need to act jointly, but also a large amount of emergency materials needs to be promptly configured and dispatched, thus forming a rapid response and highly efficient emergency resource linkage system. However, without a good mechanism as a guarantee, even with sufficient emergency resources, there may still be situations where resources cannot reach the disaster area, resulting in one side of an emergency outbreak and urgent need for rescue materials, while the other side has accumulated rescue materials, which not only increases the burden on rescue material guarantee personnel but also delays the rescue opportunity, causing greater losses.

Therefore, formulating a comprehensive and predictive distribution network planning for the city, especially optimizing the structural layout of large-scale emergency rescue resource distribution networks, is the core of the entire planning. Scientific planning of emergency rescue resource distribution points can enable the entire emergency system to effectively function, completely changing the situation where rescue materials are mainly collected, transported, and distributed by temporary organizations at all levels of government.

This study aims to optimize the structural layout of the large-scale emergency rescue resource distribution network in the city to improve emergency response efficiency and resource utilization. By constructing a scientifically reasonable distribution network, it can effectively cope with the uncertain demands in sudden public events, reduce the disorder of emergency logistics, and reduce the impact of "shortage effect" on rescue work. In addition, this study will also provide theoretical support and practical guidance for the urban emergency management system, helping cities to quickly form a rapid response and highly efficient emergency resource linkage system when facing major safety events, thereby minimizing the damage caused by disasters to the city. At the same time, the research results can also provide reference for other cities, promoting the optimization and upgrading of the national emergency logistics network and enhancing the overall emergency rescue capacity of the country.

## 2. Research on the Layout of Urban Network Structure for Large-Scale Emergency Rescue Resource Distribution

To address the multiple and simultaneous demands for emergency services during the emergency response process, a multi-objective and multi-replication decision-making model is established based on the multi-attribute decision-making method for the Spoke point layout. In the axillary layout network system, some hub points (Hub points) with functions such as centralized, classification, operation, and dispatching and commanding centers are selected to be established in the nodes (Spoke points). Through the facilities of the Hub points, the facility resources within the area are linked together to continuously supply the required service resources to the emergency demand points. Considering the uncertainty of the Hub points, this project will start from the construction level of the logistics network of 33 townships and streets in Dongguan City, combined with the relevant situations of the COVID-19 pandemic, based on the relevant methods and theories of the axillary network. Since the axillary network is a network with differentiated node function positioning and certain limitations in the connection relationship between nodes, its good network connectivity and economic concentration make it highly practical in the planning of emergency rescue networks. This network structure was first proposed by O, Kelly in 1987. Based on the axillary network, this area's axis city and various logistics nodes in emergency logistics are calculated and determined. At the same time, the modified gravitational model is used to analyze and select the radiating points of townships and streets within the area and their layouts to construct a more efficient and economically balanced integrated emergency resource distribution urban network, promoting the formation of a comprehensive emergency system that combines "daily service economy and timely emergency response". For the axillary emergency logistics network, we usually define it as a network system for providing human resources and emergency materials needed to respond to sudden events such as natural disasters, social security, and public health incidents, based on the centralized transportation network system of large logistics hub centers.

### *2.1. Selection of the Hub of the Radial Network Structure for Resource Distribution in the Urban Network*

Establish a construction of the evaluation system for regional epidemic prevention emergency logistics capabilities. This project takes Dongguan City as the research object. The administrative division structure of Dongguan City is simple; there is no district-level administrative division, but it is directly composed of townships and sub-districts. This model makes administrative management more efficient. Dongguan City is a prefecture-level city under the jurisdiction of Guangdong Province and is one of the four prefecture-level cities without districts in China. Dongguan City has 4 sub-districts and 28 towns, as well as the Songshan Lake Management Committee. The selection of evaluation indicators for the epidemic prevention emergency logistics capabilities of the cities within the region and the construction of the system should first be to conduct quantitative analysis of the comprehensive epidemic prevention emergency logistics capabilities of the 4 sub-districts and 28 towns in Dongguan City and the Songshan Lake Management Committee. On this basis, they should be ranked and the main axis positions should be determined, which is conducive to providing certain reference basis for the subsequent layout of radiating towns and sub-districts and the construction of the radial emergency logistics network; Secondly, this evaluation system established based on academic theory and real data can comprehensively, objectively and scientifically measure and evaluate the emergency logistics capabilities of the region as a whole and individual, which is conducive to subsequently identifying corresponding weak links and conducting a series of qualitative analyses to improve the overall emergency logistics capabilities and logistics efficiency of the region. Therefore, choosing relevant indicators with comprehensiveness, rationality, feasibility and scientific and constructing this evaluation system is the foundation and key of the subsequent analysis.

The construction of the evaluation index system usually follows the following basic principles and methods: (1) The comprehensiveness principle. The content and scope of emergency logistics capabilities are extensive and there are many influencing factors. Therefore, it is necessary to consider and select comprehensively from various different levels and aspects; (2) The scientific and objectivity principle. For the selection of relevant indicators, it mainly relies on previous literature as the basis, follows the principles of scientific, objectivity and rationality, and selects typical, persuasive, and clearly meaningful indicators; (3) The feasibility principle. This principle means that the constructed model has operability and the selected indicator data must have accessibility to ensure the authenticity of the data source and the persuasiveness of the conclusion; (4) The universality principle. This principle means that the index system constructed from the selected indicators to the evaluation method to the constructed model has expansibility and universality, can be applied to most situations, and ensures its promotional significance. This project research refers to the studies on the evaluation indicators of hub-and-spoke logistics networks and emergency logistics by domestic and foreign literature, combines the actual situation of this COVID-19 epidemic and the availability of data, and through questionnaire consultations and visits to emergency logistics experts and a large number of on-site town and street investigations, a comprehensive index evaluation system for the emergency logistics capabilities of 33 towns and streets in Dongguan City has been formed. This system adds several indicators related to epidemic prevention and control on the basis of the original emergency logistics indicators, which is also the main contribution of this index system, mainly divided into four main levels: the economic capacity of the epidemic emergency logistics system, the logistics capacity of the epidemic emergency logistics system, the emergency capacity of the epidemic emergency logistics system, and the information capacity of the epidemic emergency logistics system, and 23 specific related indicators, as shown in Table 1.

***Table 1.*** Evaluation System for Emergency Physical Comprehensive Capabilities under the COVID-19 Pandemic.

| Target layer | Criterion layer | First-level indicator | Second-level indicator | Unit | Serial number |
|---|---|---|---|---|---|
| Comprehensive Evaluation of the Emergency Logistics Capacity for the COVID-19 Pandemic in Dongguan City | Economic capacity of the epidemic emergency logistics system | The hard driving force of epidemic prevention and control in the economy | Population density in the epidemic area | People per square kilometer | X1 |
| | | | Investment in fixed assets related to social epidemic prevention | Chinese Yuan | X2 |
| | | | Investment in fixed assets of the logistics industry | Chinese Yuan | X3 |
| | The logistics capacity of the epidemic emergency logistics system | Scale of logistics in key epidemic areas | The number of logistics parks in the epidemic-stricken areas | Units | X4 |
| | | | Freight volume during the epidemic period | Ton | X5 |
| | | Transportation support capacity in the epidemic area | Total logistics mileage in the epidemic area | Kilometer | X6 |
| | | | The newly added emergency and green lanes mileage in key epidemic areas | Kilometer | X7 |
| | | | The volume of civilian vehicle traffic during the epidemic period | Vehicle | X8 |
| | | Logistics network capacity in the epidemic-stricken area | The density of logistics nodes in the epidemic area | Per square kilometer | X9 |
| | | | Logistics route density in epidemic areas | Kilometers per square kilometer | X10 |
| | | | Logistics network connectivity in the epidemic area | Kilometers per unit * square kilometers | X11 |

| | | | | | |
|---|---|---|---|---|---|
| | | Support capabilities of logistics personnel in epidemic-stricken areas | The number of people employed in the logistics industry in the epidemic-stricken area | Units | X12 |
| | | | The number of on-duty logistics personnel during the epidemic period | Units | X13 |
| | Emergency capacity of the epidemic response logistics system | Emergency demand and supply capacity for the COVID-19 pandemic | Vaccination material reserve center (emergency material reserve point) | Units | X14 |
| | | | Emergency supplies for epidemic prevention reserves | Ton | X15 |
| | | | COVID-19 testing site (center for disease control and prevention) | Units | X16 |
| | | | Gross domestic product of the accommodation and catering industry | Chinese Yuan | X17 |
| | | | Number of health and epidemic prevention institutions | Units | X18 |
| | | | Number of beds in epidemic prevention and health institutions | Units | X19 |
| | | | The number of epidemic prevention and health care personnel | Units | X20 |
| | | Emergency financial support measures for the COVID-19 pandemic | Local defense and public security epidemic-related budget expenditures | Chinese Yuan | X21 |
| | | | Local medical and health epidemic public budget expenditure | Chinese Yuan | X22 |
| | | | Expenditure on local disaster prevention and emergency management during the epidemic period | Chinese Yuan | X23 |

## *2.2. Evaluation Process of Emergency Logistics Capacity of Townships in Dongguan City under the Pandemic Situation*

When constructing the comprehensive index system for the emergency logistics capabilities of the 33 townships in Dongguan City in response to the COVID-19 pandemic, in order to measure the emergency logistics capabilities of each affected area during the epidemic period more comprehensively, reasonably and objectively, a total of 23 evaluation indicators were selected from various levels and perspectives. This resulted in some indicators having overlap or strong correlation, which would cause unnecessary computational load and deviations in the subsequent model calculation and the selection of the hub points (Hub points) for the command center functions. Therefore, in order to ensure the objectivity and accuracy of the calculation results, while retaining the features with the greatest variance contribution in the dataset, it is necessary to perform dimensionality reduction and secondary screening of the indicators based on correlation analysis and principal component analysis. This ensures the comprehensiveness and rationality of the final principal component indicators. Based on this, the scores and rankings of the comprehensive emergency logistics capabilities of all 33 townships in Dongguan City were calculated and sorted.

The sources of all original indicator data in this study are the 2022 Dongguan Statistical Yearbook, Statistical Bulletin and the epidemic-related data released on the Dongguan official website. For detailed information, please refer to Appendix A: Original Data of Emergency Logistics Capabilities for Epidemic Prevention and Control in Townships of Dongguan City (2022).

(1) Principal Component Analysis

Firstly, using the SPSS software, the data in Appendix A were subjected to correlation detection and principal component analysis based on the 23 epidemic-related emergency logistics indicators mentioned above. Key indicators with strong correlations were then selected. Due to the inconsistent units among different indicators, a unified dimension processing was necessary first. For the data in Appendix A, the range standardization was mainly adopted, and then the analysis was conducted through SPSS. The specific results are shown in Tables 2 and 3.

***Table 2.*** KMO and bartlett test.

| | | |
|---|---|---|
| KMO sampling adequacy index | | 0.847 |
| Bartlett's sphericity test | Approximate chi-square | 2709.652 |
| | Degree of freedom | 253 |
| | Significance | <0.001 |

Table 2 indicates: The KMO value is 0.847, which is greater than 0.5. This indicates that it is suitable for principal component analysis. The significance of the Bartlett's sphericity test is less than 0.001, which means it meets the prerequisite conditions for principal component analysis. The sample size of this project is 33 (the number of towns, sub-districts and parks in Dongguan City), and the number of indicators is 23. Therefore, the sample size is greater than the number of indicators, meeting the conditions of KMO and Bartlett's test.

***Table 3.*** Total variance explained by eigenvalues and their contribution rates.

| Ingredient | Initial eigenvalue | | |
|---|---|---|---|
| | Eigenvalue | Variance percentage | Accumulation (%) |
| 1 | 19.379 | 84.255 | 84.255 |
| 2 | 1.568 | 6.818 | 91.073 |
| 3 | 1.139 | 4.952 | 96.025 |
| 4 | 0.368 | 1.600 | 97.625 |
| 5 | 0.298 | 1.295 | 98.920 |
| 6 | 0.071 | 0.311 | 99.231 |
| 7 | 0.061 | 0.265 | 99.496 |
| 8 | 0.032 | 0.137 | 99.633 |
| 9 | 0.029 | 0.125 | 99.759 |
| 10 | 0.019 | 0.082 | 99.841 |
| 11 | 0.010 | 0.043 | 99.883 |
| 12 | 0.008 | 0.036 | 99.920 |
| 13 | 0.004 | 0.019 | 99.938 |
| 14 | 0.003 | 0.015 | 99.953 |
| 15 | 0.003 | 0.013 | 99.966 |
| 16 | 0.002 | 0.009 | 99.976 |
| 17 | 0.002 | 0.008 | 99.984 |
| 18 | 0.002 | 0.007 | 99.991 |
| 19 | 0.001 | 0.005 | 99.996 |
| 20 | 0.000 | 0.002 | 99.998 |
| 21 | 0.000 | 0.001 | 99.999 |
| 22 | 7.629E-05 | 0.000 | 100.000 |
| 23 | 4.996E-05 | 0.000 | 100.000 |

Extraction method: Principal Component Analysis method

Table 3 indicates: The 23 principal components can fully explain the values of the 23 indicators. Since the normal requirement for cumulative explanatory power (variance percentage) needs to reach over 85%, this condition is met.

(2) Comprehensive Emergency Logistics Capability Score of Towns and Sub-districts in Dongguan City under the Pandemic Situation

Based on the score coefficients of principal component characteristics and variance contribution rate (as shown in the formula below), the comprehensive emergency logistics capability scores of 33 town and sub-districts in Dongguan City were calculated and ranked. The scores of the principal components were calculated based on the rotated component matrix (Table 4). The total score of the first principal component was 84.255, the total score of the second principal component was 6.818, and the total score of the third principal component was 4.952. The specific final comprehensive score results are shown in Table 5.

The comprehensive emergency logistics capability score of the city under the pandemic situation (F) = 87.74% of the first type component score (F1 score) + 7.10% of the second type component score (F2 score) + 5.15% of the third type component score (F3 score);

*Table 4.* Rotated Component Matrix [a] .

| Serial number | Ingredient | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| X1 | -0.081 | 0.002 | 0.987 |
| X2 | 0.728 | 0.575 | 0.011 |
| X3 | 0.703 | 0.617 | 0.012 |
| X4 | 0.778 | 0.468 | 0.043 |
| X5 | 0.925 | 0.157 | -0.238 |
| X6 | 0.885 | 0.438 | -0.139 |
| X7 | 0.833 | 0.537 | -0.078 |
| X8 | 0.884 | 0.441 | -0.109 |
| X9 | 0.883 | 0.414 | -0.155 |
| X10 | 0.883 | 0.440 | -0.146 |
| X11 | 0.729 | 0.614 | 0.095 |
| X12 | 0.853 | 0.399 | 0.127 |
| X13 | 0.852 | 0.507 | -0.078 |
| X14 | 0.812 | 0.511 | 0.214 |
| X15 | 0.805 | 0.581 | 0.054 |
| X16 | 0.814 | 0.525 | 0.196 |
| X17 | 0.831 | 0.545 | 0.030 |
| X18 | 0.800 | 0.590 | -0.014 |
| X19 | 0.418 | 0.903 | 0.072 |
| X20 | 0.403 | 0.909 | 0.048 |
| X21 | 0.457 | 0.881 | -0.076 |
| X22 | 0.439 | 0.890 | -0.064 |
| X23 | 0.422 | 0.894 | -0.054 |

Extraction method: Principal Component Analysis method.
Rotation method: Caesar Normalization Maximum Variance Method.

The rotation has converged after 5 iterations.

*Table 5.* Comprehensive Scores and Rankings of Emergency Logistics Capabilities of 33 Townships in Dongguan City under the Pandemic Situation.

| Township/Urban District Names | F1 score | F1 score | F1 score | F1 score | F1 score |
|---|---|---|---|---|---|
| Songshan Lake Management Committee | 11.87054 | 10.64251 | 0.204815695 | 11.18174827 | 1 |
| Wengang Street | 7.786064 | 6.276842 | 1.160522631 | 7.337226847 | 2 |
| Dongcheng Street | 6.999859 | 6.462062 | 0.963443043 | 6.650376513 | 3 |
| Changan Town | 6.905763 | 6.679728 | 0.874702941 | 6.578692508 | 4 |
| Nanxiang Street | 6.819343 | 5.946223 | 1.009803817 | 6.457751797 | 5 |
| Humen Town | 6.471958 | 6.625212 | 0.788725249 | 6.189755445 | 6 |
| Houjie Town | 5.515246 | 5.40404 | 0.741826454 | 5.26118512 | 7 |
| Changping Town | 5.421228 | 5.271225 | 0.771387757 | 5.170785516 | 8 |
| Tangxia Town | 5.139799 | 4.683549 | 0.71902068 | 4.879425119 | 9 |
| Wanjiang Street | 5.119291 | 4.412451 | 0.847000422 | 4.84878212 | 10 |
| Lao Bin Town | 3.735507 | 4.066843 | 0.580476451 | 3.596328164 | 11 |
| Dala Town | 3.352419 | 3.235601 | 0.575112958 | 3.200899101 | 12 |
| Daliang Mountain Town | 3.337548 | 3.16395 | 0.549089825 | 3.181421622 | 13 |
| Shilong Town | 3.185049 | 2.903505 | 0.693867199 | 3.036588723 | 14 |
| Fenggang Town | 3.113927 | 3.300988 | 0.517140518 | 2.993292549 | 15 |
| Zhangmoutou Town | 2.829362 | 2.788217 | 0.540747544 | 2.708417363 | 16 |
| Gaobei Town | 2.644056 | 2.532558 | 0.492670254 | 2.525192314 | 17 |
| Shige Town Shatian Town | 2.63227 | 2.361122 | 0.655159228 | 2.511058555 | 18 |
| Dongkeng Town | 2.363774 | 2.634957 | 0.457760755 | 2.284735555 | 19 |
| Huangjiang Town Zhongchang Town | 2.264572 | 1.813391 | 0.57512533 | 2.145412787 | 20 |
| Chaishan Town | 2.074757 | 2.11624 | 0.479479176 | 1.995434186 | 21 |
| Hengli Town | 1.981141 | 1.941831 | 0.442614839 | 1.899008656 | 22 |
| Qingxi Town | 1.942219 | 1.729123 | 0.599416007 | 1.857840372 | 23 |
| Qiaotou Town | 1.864516 | 1.72652 | 0.522770408 | 1.785524169 | 24 |
| Maocheng Town | 1.559689 | 1.901746 | 0.389314423 | 1.523619707 | 25 |
| Daojiao Town | 1.421342 | 1.701753 | 0.462870724 | 1.391823565 | 26 |
| Shihe Town | 1.397767 | 1.693564 | 0.384094351 | 1.366494303 | 27 |
| Hongmei Town | 1.33314 | 1.422969 | 0.419448705 | 1.292399456 | 28 |
| Qisi Town Wangniudun Town | 1.080308 | 0.940331 | 0.455132918 | 1.038128916 | 29 |

| | | | | | |
|---|---|---|---|---|---|
| Xiegang Town | 0.566904 | 0.663549 | 0.371952158 | 0.563712527 | 30 |
| Township/Urban District Names | 0.376051 | 0.26729 | 0.432144274 | 0.37122156 | 31 |
| Songshan Lake Management Committee | 0.334204 | 0.677637 | 0.362526507 | 0.360049152 | 32 |
| Wengang Street | 0.070885 | 0.174137 | 0.385812342 | 0.09445652 | 33 |

From Table 5, which shows the comprehensive scores of 33 townships in Dongguan City (including one management committee), it can be seen that the distribution of the emergency logistics level for epidemic prevention and control in these 33 townships is uneven, with significant differences in capabilities. The top-ranked is the Management Committee of Songshan Lake, with a score of 11.18, which is nearly 5 points higher than the second-place Duancheng Township; the scores of the next 3 to 8 places vary slightly, all within the range of 0 to 1 point. The comprehensive scores of the cities ranked 29th and later are all zero, indicating that the overall emergency logistics capacity is relatively weak under the epidemic situation. The last-place Xiegang Town has a comprehensive score of 0.09, which is nearly 11 points lower than that of the Management Committee of Songshan Lake, showing a huge gap. This directly indicates that the development of emergency logistics in Dongguan City is extremely unbalanced. The investment in emergency logistics and the establishment of the system are concentrated in one or a few townships, but fail to effectively drive the further development and improvement of the remaining townships or the entire region. After completing the comprehensive ability measurement and ranking of emergency logistics under the epidemic situation for the 33 townships in Dongguan City (including the Management Committee of Songshan Lake), we usually take the townships with higher comprehensive scores, that is, those with complete logistics facilities, developed economy, and significant influence, as the hub points for network construction. The cities with lower comprehensive scores, that is, those with relatively slower development, are positioned as spoke nodes.

## *2.3. The Radiation Points Town and Street Layout of Dongguan*

In the hub-and-spoke emergency logistics network for epidemic prevention, the stronger the comprehensive emergency logistics capability of the hub (Hub point), the wider its radiation range and the greater its radiation influence. The layout of the surrounding radiation points (Spoke points) will also change accordingly. Currently, most scholars at home and abroad use the gravitational model, the break point theory, etc. to study the influence degree and radiation range of regional cities. Therefore, by combining the literature with the characteristics of the hub-and-spoke emergency logistics network, this chapter selects the modified gravitational model to determine the radiation range of the hub (Hub point) and calculate the layout of the radiation point cities.

(1) Modified Gravitational Model Based on the COVID-19 Epidemic

The gravitational model (Gravity Model) originated from Newton's "universal gravitation" model in physics. It effectively connects geography and physics, and was first applied to the study of population migration in social sciences by Reventzhan in 1880. This model holds that the research object can be measured by corresponding "quality" indicators, and the interaction between the objects is concentrated at a certain point. Therefore, the gravitational connection and intensity between points can be used to study the interrelationships between the objects. Its basic model form is:

$$G_{ij} = \frac{K_{ij} M_{ij} M_{ij}}{D_{ij}} \tag{1}$$

Here, $G_{ij}$ represents the gravitational strength between nodes $i$ and $j$, $M_{ij}$ and $M_{ij}$ represent the "mass" of the research object, $D_{ij}$ represents the generalized distance between $i$ and $j$, and $K_{ij}$ is the adjustment coefficient.

One of the important features of the gravitational model is that, while maintaining the basic form unchanged, certain parameters and components can be appropriately modified to be applicable to different fields of research. Therefore, in line with the research direction of this study, the generalized distance between the research objects, namely $D_{ij}$, will be revised and improved. Usually, in the research on regional logistics connections, $D_{ij}$ is generally taken as the spatial distance between two nodes. However, in this study, when dealing with the regional connections of emergency logistics during the COVID-19 pandemic, transportation time and efficiency are among the most important factors. Therefore, we cannot only consider the simple spatial distance. We need to incorporate the monetary and time costs of logistics activities, and also need to make choices regarding emergency transportation tools and methods. Thus, the model construction for the "comprehensive distance" between cities is revised as follows:

$$D_{ij} = \sqrt[3]{d_{ij} * c_{ij} * t_{ij}} \tag{2}$$

Among them, $D_{ij}$ represents the "combined distance" between two townships; $d_{ij}$ represents the shortest distance for road transportation between the two townships; $c_{ij}$ indicates the average road transportation rate between the two townships; $t_{ij}$ represents the average road transportation time between the two townships. All the data in this part are sourced from China Logistics Network, Dongguan Logistics Network, Guangdong Statistical Yearbook and Baidu Maps. Multiple average transportation prices and freight times for logistics routes between each pair of townships in Dongguan were selected as the values for $c_{ij}$ and $t_{ij}$ to ensure the authenticity and objectivity of the data. Finally, according to Formulas 1 and 2, the "combined distance" between each pair of townships in Dongguan was calculated separately.

(2) The intensity of emergency logistics attraction connections in Dongguan's townships under the COVID-19 pandemic

Based on the modified gravity model, the spatial gravity connection intensity of 33 townships in Dongguan was calculated. According to the literature and the actual research object of this paper, the final form of the gravity model adopted is as follows:

$$G_{ij} = \frac{KM_iM_j}{D_{ij}} \tag{3}$$

Among them, $G_{ij}$ represents the logistics attraction force from town i to town j; $M_i$ and $M_j$ represent the quality, which are replaced in this section with the emergency logistics comprehensive capability scores calculated according to Table 5; $D_{ij}$ is the "combined distance" between town *i* and town *j*; *K* is the gravitational constant, which does not affect the calculation results and is usually taken as 2. Based on the above formula, the intensity of emergency logistics gravitational connection among all townships in Dongguan City during the epidemic period was calculated. The results are shown in Table 6.

***Table 6.*** Gravitational Linkage of Emergency Logistics in 33 Townships of Dongguan City during the Epidemic Period (Comprehensive Distance).

| Axis / Axis point | Songshan Lake Management Committee | Wengang Subdistrict | Laibus Town | Wanjiang Subdistrict | Tangxia Town | Houjie Town | Changping Town | Nancheng Town | Dongcheng Town | Humen Town | Changan Town |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Shi Pa Town | 3.00 | 1.68 | 1.15 | 0.37 | 1.38 | 1.68 | **6.06** | 1.07 | 2.13 | 1.75 | 1.50 |
| Wang Niu Deng | 0.96 | 0.72 | 0.40 | 0.67 | 0.39 | 0.52 | 0.44 | **2.72** | 0.65 | 0.49 | 0.46 |
| Hong Mei Town Xiegang Town | 1.63 | 0.81 | 0.55 | 0.84 | 0.65 | 0.91 | 0.69 | 0.86 | 0.89 | **5.83** | 0.88 |
| Qizhong Town | 0.23 | 0.09 | 0.08 | 0.11 | 0.14 | 0.12 | **5.15** | 0.13 | 0.17 | 0.13 | 0.12 |
| Gaobu Town | 0.91 | 0.44 | 0.36 | 0.43 | 0.43 | 0.53 | **6.52** | 0.65 | 0.67 | 0.51 | 0.54 |
| Zhangmudou | 5.70 | 5.71 | **3.49** | 0.71 | 1.80 | 1.61 | 4.02 | 1.03 | 1.18 | 1.71 | 3.95 |
| Dalianshan | 7.82 | 3.55 | 3.00 | 0.57 | **3.60** | 1.88 | 5.39 | 1.76 | 1.90 | 1.98 | 4.23 |
| Dalong Town | **9.18** | 6.02 | 3.53 | 0.75 | 2.78 | 2.44 | 5.07 | 1.33 | 1.52 | 1.07 | **5.70** |
| Shilong Town | **11.03** | 5.17 | 4.00 | 0.78 | 2.42 | 5.19 | 5.75 | 1.18 | 1.39 | 5.39 | **5.73** |
| Shijie Town Shatian Town | 6.46 | **5.75** | 2.97 | 0.01 | 1.03 | 3.79 | 4.27 | 0.34 | 1.50 | 4.14 | 4.40 |
| Fenggang Town | 7.64 | **5.68** | 2.78 | 0.75 | 2.78 | 1.07 | 4.00 | 1.35 | 0.15 | 3.69 | 3.92 |
| Dongkeng Town | 4.99 | 3.69 | 1.95 | **2.63** | 2.65 | 1.62 | 2.81 | 1.50 | 1.61 | 5.44 | 4.09 |
| Hengli Town | 7.37 | 2.99 | 2.37 | 0.20 | **3.22** | 0.74 | 3.41 | 1.26 | 0.38 | 4.08 | 3.85 |
| Chashan Town Zhongchang Town | 6.19 | 3.07 | **2.38** | 1.21 | 3.23 | 0.48 | 3.42 | 1.27 | 1.40 | 3.15 | 3.35 |
| Huangjiang Town | 5.15 | 2.89 | 1.98 | 2.67 | 2.68 | 2.56 | **5.85** | 1.55 | 1.66 | 2.63 | 2.79 |
| Daocao Town | 6.40 | 3.52 | 2.32 | 2.13 | 1.15 | 3.39 | 3.34 | 1.17 | **4.29** | 3.13 | 3.33 |
| Qiaotou | 6.54 | 4.29 | 1.86 | **2.51** | 2.52 | 3.08 | 2.67 | 0.34 | 3.44 | 2.79 | 2.97 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Machong Town | **8.30** | 2.37 | 1.70 | 2.30 | 2.31 | 4.04 | 3.97 | 1.06 | 5.10 | 3.81 | 4.05 |
| Qingxi Town | 3.58 | 2.35 | 1.15 | 1.55 | 1.56 | **5.90** | 1.65 | 2.07 | 2.13 | 1.75 | 1.86 |
| Shi Pa Town | 3.04 | 1.66 | 1.36 | 1.60 | 1.85 | 1.99 | 0.96 | 0.45 | 1.52 | 1.90 | 2.02 |
| Wang Niu Deng | 3.73 | 1.85 | 1.10 | 1.49 | 1.50 | 2.10 | 1.59 | **1.98** | 2.04 | 1.90 | 2.02 |
| Hong Mei Town Xiegang Town | 3.75 | 1.52 | 1.21 | 1.63 | **2.84** | 1.90 | 1.87 | 0.34 | 2.41 | 2.08 | 2.21 |

(3) Analysis of the Layout of Radiation Points in Towns and Sub-districts of Dongguan City

Based on the above data, we conduct the following analysis on the central axis and radiation point urban layout of the towns and sub-districts in Dongguan City:

Songshan Lake Management Committee: As a first-level node among the central axis cities in this area, its radiation effect on the 19 towns and sub-districts along the axis is quite obvious (except for Xiegang Town and Qixi Town). Therefore, its radiation range includes some of the 19 axis-point towns (except for Xiegang Town and Qixi Town), and at the same time, it has a high gravitational connection with Dalianshan, Dalong Town, Huangjiang Town, and Gaobu Town, and these four towns have a relatively small influence from other axis-point towns. Therefore, the Songshan Lake Management Committee focuses on radiating and driving these 19 towns along the axis except for Xiegang Town and Qixi Town.

Duancheng Sub-district: As a secondary node of the central axis town, the cities with strong gravitational connection include Shilong Town and Shijie Town. The three places have a close connection in the regional network, but the logistics infrastructure of Shilong Town and Shijie Town needs to be improved, and the emergency logistics comprehensive capacity is relatively backward. It is necessary to strengthen the coordinated development with the central area such as Duancheng Sub-district to improve the overall logistics efficiency and emergency response capability of the region. The comprehensive emergency logistics capacity of these two radiation point cities ranks in the middle position among the 33 towns, their own logistics infrastructure is relatively balanced, and the emergency development also needs to be further improved. The central node of Duancheng Sub-district needs to jointly exert the radiation effect to enhance and assist.

Liaobu Town: As a secondary node of the central axis town, the cities with strong gravitational connection include Gaobu Town and Dongkeng Town. The emergency logistics comprehensive capacity of these two cities radiated by Liaobu Town is between the 15th and 20th place, ranking 17th and 20th respectively. When Liaobu Town plays the role of radiation, it should also pay attention to providing assistance in terms of personnel, materials, and economy.

Wanjiang Sub-district: As a secondary node city of the central axis city, the towns with strong gravitational connection include Shatian Town and Zhongtang Town. The two towns radiated by Wanjiang Sub-district have emergency logistics comprehensive capacities between the 15th and 25th place, ranking 17th and 25th respectively. When Wanjiang Sub-district plays the role of radiation, it should also pay attention to the tendency of providing assistance in terms of personnel, materials, and economy.

Tangxia Town: As a secondary node city of the central axis city, the towns with strong gravitational connection include Zhangmudou Town, Fenggang Town, and Qingxi Town. The emergency logistics comprehensive capacities of the three towns radiated by Tangxia Town vary greatly, ranking 15th, 16th, and 25th respectively, indicating that although the physical space and comprehensive distance between the towns are relatively close, there is still a polarization phenomenon in logistics capacity and emergency level. Therefore, when Tangxia Town plays the role of radiation, it should pay attention to the tendency of providing assistance in terms of personnel, materials, and economy, and should pay more attention to the influence of Qingxi Town, striving to leverage the advantages of the city itself and reduce the differences with other towns.

Changping Town: As a secondary node city of the central axis city, the towns with strong gravitational connection include Shierdao Town, Xiegang Town, Qixi Town, and Hengli Town. The four towns radiated by Changping Town rank in the last ten places. Therefore, relying solely on Changping Town as the central axis city's radiation power is not enough. It is necessary for the first-level node Songshan Lake Management Committee and adjacent axis-point sub-districts to conduct corresponding radiation to Shierdao Town, Xiegang Town, Qixi Town, and Hengli Town. At the same time, the governments of these four towns should also pay more attention to the construction of emergency logistics and increase investment, striving to leverage the advantages of the city itself and reduce the differences with other towns.

Nan Cheng Town: As a secondary node city of the central axis city, the towns with strong gravitational connection are only Yuntoudun Town. Wangniudun Town ranked at the bottom two in the emergency logistics comprehensive capacity ranking. Its own logistics industry infrastructure is not complete enough, and the attention paid by the town government is insufficient, resulting in less investment and output in the industry, and the emergency development is relatively lagging. It is necessary for the South Town and the neighboring axis towns to jointly play a radiating role to improve and assist.

Dongcheng Town: It is a secondary node city of the axis city, and only Chaishan Town has relatively strong gravitational connections.

Although Chaishan Town has a relatively developed transportation network, the infrastructure of some logistics parks still needs to be further improved, and the informatization level and operational efficiency of logistics enterprises need to be enhanced to better adapt to market demands. When Dongcheng Town plays a radiating role, it should also pay attention to further improving infrastructure and enhancing logistics efficiency to promote the high-quality development of the regional logistics industry.

Based on the above node analysis results, the analysis results of the radiation capacity of towns and districts in Dongguan City are presented in Table 7.

***Table 7.*** Layout of Radiation Centers and Key Townships in Dongguan City.

| Central Town | Radiation coverage area |
|---|---|
| Songshan Lake Management Committee | Dalingshan Town, Dalong Town, Huangjiang Town |
| Wengang Street | Shilong Town, Shijie Town |
| Lao Bin Town | Gaobei Town, Dongkeng Town |
| Wan Jiang Street | Shatian Town, Zhongtang Town |
| Tang Xia Town | Zhangmoudou Town, Fenggang Town, Qingxiang Town |
| Hou Jie Town | Daocao Town |
| Chang Ping Town | Shihe Town, Xiegang Town, Qishi Town, Hengli Town Wangniudun Town |
| Nan Cheng Town | Chaishan Town |
| Dong Cheng Town | Hongmei Town |
| Humen Town | Dalingshan Town, Dalong Town |
| Changan Town | Radiation coverage area |

## 3. Conclusion

This study constructed an evaluation system consisting of 23 indicators to assess the comprehensive emergency logistics capabilities of 33 townships in Dongguan City. Using principal component analysis and the modified gravity model, the layout of the central township and the radiation point townships was determined, and ten emergency logistics circles for epidemic prevention and control were divided. The study found that the distribution of emergency logistics capabilities in Dongguan City was uneven. The management committee of Songshan Lake had the strongest capability, while Xiegang Town had the weakest, with a significant gap between the two. Based on this, it is suggested to strengthen infrastructure construction, especially to make key investments in the townships with weaker capabilities, and to promote regional collaboration and cooperation to optimize resource allocation, in order to improve the overall emergency response efficiency. This study provides theoretical support and practical guidance for the urban emergency management system and has reference value for the optimization of emergency logistics networks in other cities.

**Author Contributions**

Xiaowei Wu: Investigation, Funding acquisition, Writing-original draft. Jun Tian: Test results analysis and Review & editing.

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**Conflicts of Competing Interest**

The authors declare no competing interests.

**Data Availability statement**

Data will be made available on request.

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