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Assessing the Development Level of Logistics for Sustainable Cities in Urban Agglomeration Based on a Multi-Layer Complex Network

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Abstract: Evaluating the development level of urban logistics can significantly inform policies for the sustainable development of each city in an urban agglomeration. This study analyzed the logistics development of 11 cities in the Guanzhong Plain urban agglomeration (GPUA) of China. Compared to traditional urban logistics evaluation methods considering individual attributes, this study constructed a multi-layer complex logistics network of urban agglomerations (MCLNUA) based on complex network theory, which takes into account the multiple connections between cities. The development levels of logistics in these cities were evaluated from a multi-dimensional perspective of “point–line–surface”, (the “point” represents the node characteristic index of the city, the “line” represents the strength and direction of urban logistics connections between cities, and the “surface” represents the cohesive subgroup of cities). An urban spatial hierarchy and corresponding spatial development plan for urban logistics were also developed. The results show that there are significant differences in logistics levels between different cities. The spatial structure of the overall network connections shows the pattern of being strong in the south and weak in the north, and strong in the east and weak in the west. There are differences in the strength of connections between cohesive subgroups. The research provides a reference for the sustainable development of regional logistics in other urban agglomerations.

Keywords: multi-layer network; logistics network; multi-dimensional analysis; developmental evaluation



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1. Introduction

With the rapid development of global economic integration and technology, the logistics industry is playing an increasingly important role in economic development. This is particularly true for achieving efficient development of integrated and sustainable urban agglomeration. The acceleration of regional integration, and the concept of the sustainable development of cities, have encouraged research on urban agglomerations, which are the highest form of spatial organization in the mature stage of urban development. The importance of developing urban agglomerations was particularly emphasized in the outline of 13th Five-Year Plan proposed by the Chinese government. Therefore, this study uses the Guanzhong Plain urban agglomeration (GPUA) of China as the research object, analyzes the development level of urban logistics and constructs the multi-layer complex logistics network of the GPUA, and finally realizes the evaluation of the development level of urban logistics, which is intended to provide a theoretical basis for the future logistics development planning of this urban agglomeration.

The strength of the logistics connection between cities affects the overall function of each city and the region [1]. The urban logistics network is an inseparable organic system, formed by the cooperation of cities with different hierarchies and scales within the region. The interconnection between cities forms the foundation of the network [2]. Each city is embedded in the logistics network, rather than acting independently. Cities are both constrained by the network and can benefit from the network. The embeddedness, such as connections, network positions, and network structure of each node determine the role of each city [3].

The logistics connections between cities can be divided into infrastructure connections, flow connections, and logistics enterprise connections [4]. Infrastructure connections are mainly represented by transportation routes. Flow connections refer to the exchange of freight volume between cities. At present, the typical methods used by scholars on logistics network evaluation include the entropy method, principal component analysis, and cluster analysis. However, these methods have generally used the individual attributes of a city to evaluate the logistics level and have not considered the interconnections between cities. In fact, cities are generally embedded in complex logistics networks. Most previous studies have used the individual attributes of a city to evaluate the logistics level but have not considered the interconnections between cities. A few studies have considered the interconnections involved in only a type of transportation logistic. To address this research gap, this study applied complex network theory and integrated the road freight network, railway freight network, and logistics enterprise network to construct a multi-layer complex logistics network of urban agglomeration (*MCLNUA*). The model takes into account the connections between cities and logistics networks and enables the comprehensive study of the development level of urban node logistics, from the multiple dimensions of “point–line–surface”.

At the theoretical level, this study uses complex network theory to conduct exploratory research on the evaluation of the logistics development level in urban agglomerations, with the aim to improve the evaluation theory of logistics development level in urban agglomerations to a certain extent. At the practical level, we expect to comprehensively evaluate the development level of logistics in urban agglomerations more scientifically. In addition, depending on the evaluation results, policies are formulated for the sustainable development of each city in an urban agglomeration.

For the “point” dimension, we analyzed the centrality and development potential of cities. For the “line” dimension, we analyzed the strength of the connections in the logistics network and the city’s primary direction. For the “surface” dimension, we analyzed the density of the connections between the embedded cohesive subgroups and other cohesive subgroups. These cohesive subgroups are direct, close, and interconnected collections composed of urban individuals. Next, the study recommends guidelines for logistics development planning for the Guanzhong Plain urban agglomeration (*GPUA*) based on the city hierarchy, with the goal of improving the overall logistics development efficiency of the *GPUA*. Assessing the logistics development level of cities in *GPUA* from multiple dimensions is vital for effective urban management. The evaluation results can provide valuable support for constructing regional logistics development plans to improve the efficiency of urban logistics and encourage sustainable urban development. Moreover, the results could be used to strengthen the cooperation between logistically connected node cities.

The rest of this paper is organized as follows. Section 2 presents the literature review. Section 3 constructs the *MCLNUA* model for the *GPUA* and introduces the index for evaluating the level of urban logistics. Section 4 provides the results and discussion. The final section of this study presents the conclusions and recommendations. Figure 1 presents the research framework.

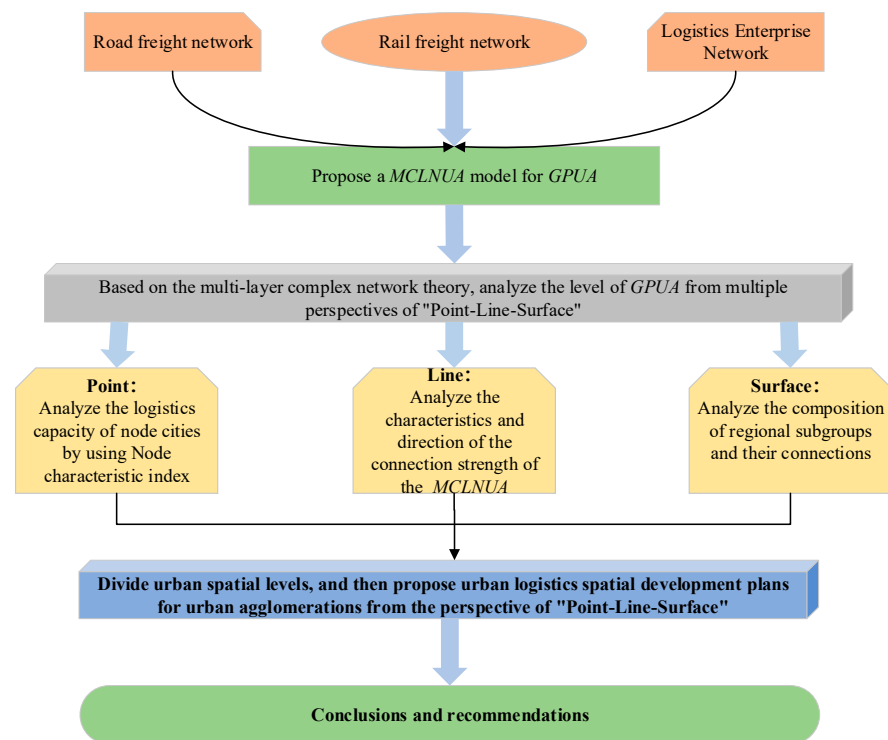


Figure 1. The research framework.

2. Literature Review

2.1. Evaluation of Urban Logistics Level

Existing research evaluating regional logistics capabilities can be divided into two groups: the evaluation index used to evaluate regional logistics capabilities, and the evaluation method used to evaluate those capabilities.

In terms of research on the evaluation indicators of urban logistics, scholars have established a variety of evaluation indicators based on the actual situation. Banomyong et al. [5] analyzed Vietnam's national logistics system across four key dimensions: infrastructure, service provider, shipper/consignee, and institutional framework. Zou et al. [6] established an evaluation index system of urban logistics competitiveness based on the economic development level, logistics business scale, and information level. Their study also evaluated the logistics competitiveness of 18 sample cities. Bookbinder and Tan [7] reorganized 20 specific criteria into 6 areas to determine logistics development tiers (i.e., infrastructure, performance, information system, human resources, and the business and political environments). Their research also compared the logistics systems of Europe and Asia.

In terms of research on the evaluation method of urban logistics [8–12], Lan [13] used the entropy method to evaluate the logistics and economic development levels of Beijing, Shanghai, Guangzhou, Chongqing, and Tianjin in China. In the same research area, Li et al. [14] analyzed the development of node cities in a road freight network and evaluated the grain distribution capacity of cities involved in the “Belt and Road”. Additionally, Liu et al. [15] evaluated the logistics development level of all provinces in China using a principal component analysis (PCA) and cluster analysis.

Previous studies generally used the city's own attributes to evaluate the regional logistics development level. However, cities are not independent individuals, instead being embedded in the logistics network [16]. Therefore, these approaches cannot comprehensively evaluate the urban logistics development level. Namely, the logistics development level of a certain city depends on not only its own attributes but also its connections with other cities in the network.

2.2. Urban Logistics Network Analysis

Most previous studies on urban logistics network analysis have investigated the characteristics and spatial pattern of urban logistics networks. The logistics network is generally constructed based on two types of relationships: the freight volume connections between cities, and the connections between logistics enterprises.

In terms of research focusing on the freight volume connections between cities, Matsumoto [17] added cargo flow as an indicator based on international air passenger flow and assessed the development of air passenger and cargo flow networks in three major regions: Asia, Europe, and the Americas. The study also evaluated the logistics capabilities of nine hub cities in these three regions. Tsekeris [18] used the original survey data of road freight traffic in Greece from 2004 to 2012 to analyze the interregional trade network and provided recommendations for planning a Greek national logistics hub network. Other studies have investigated cities and regional networks of different scales from the perspective of aviation [19], railway [20] and highway [21] passengers, and cargo flow [22].

In terms of research about connections between logistics enterprises, Joyez [23] found that the organization network of logistics enterprises is helpful in comparing the degree of inter-city connections and is closely integrated with the construction of the city network. A-level logistics enterprises are high-quality enterprises certified by the Chinese logistics management department in accordance with the “Classification and Evaluation Index of Logistics Enterprises”. Focusing on A-level logistics enterprises in the Yangtze River Delta in China, He et al. [24] investigated the spatial and temporal evolution at the metropolitan and regional levels, respectively, and provided valuable recommendations for the rational planning of logistics spaces. By analyzing the network data of China’s top 100 logistics companies and using the chain network model method, Zong et al. [25] investigated the hierarchical structure, spatial differentiation, spatial connection, and evolutionary characteristics of the urban network in China.

The research discussed above mainly focused on the level of the single-layer network, such as a network based on the inter-city freight volume, the inter-city transportation lines, and the logistics enterprise connections. An analysis based on a complex multi-layer network is more realistic and is more effective for providing practical and operational recommendations.

2.3. Construction of Complex Logistics Network

Complex logistics networks are composed of multiple connections between urban nodes [4]. The construction of multi-layer networks is based on different types of connections. As a result, cities occupy different status and enjoy different connectivity in multi-layer networks. The diverse connections of relationships in each sub-network layer shape the complementarity of the network [26]. Multi-layer complex network theory has been increasingly explored [27], with two key research focuses with respect to complex logistics networks. The first focuses on the structural characteristics of logistics networks. For example, focusing on types of cargo ships in ocean transportation, Gao et al. [28] developed a bi-level programming model for solving container shipping network design problems. Pais Montes et al. [29] studied the characteristics of logistics networks and discussed the rationality of its application to general cargo and containership routes. Ge et al. [30] analyzed the structural characteristics of the “Belt and Road Initiative” air logistics network from a geospatial perspective. Several scholars have also studied the structural characteristics of the air freight network [31], coastal container network [32], and maritime freight network [26].

Another concern in existing research on complex logistics networks is the robustness analysis of logistics networks. For example, Wang et al. [33] established a reliability simulation model of an emergency logistics network under random attacks and selective attacks. Wang et al. [34] defined the complex logistics network as a logistics infrastructure network and analyzed its robustness. Agustina Calatayud et al. [35] provided evidence that the structure of a multi-layered maritime shipping network experienced different levels of

vulnerability for international freight flows. Yang et al. [36] studied the controllability robustness of a complex logistics network using a nonlinear load-capacity model and provided practical recommendations for achieving good connectivity after a cascading failure of a logistics network. The complex network methodology takes the research object into consideration by placing it in its relationship network; consequently, this method has remarkable advantages when studying the research object with group attributes. Nevertheless, most current studies are confined to a certain feature of the network, while few studies can comprehensively consider the network features to implement evaluation.

In summary, the methods used to investigate the development level of regional urban logistics are mostly based on a specific city's attribute indicators using the entropy method, principal component analysis, and other methods. However, cities are not independent entities in the logistics network, and there are different types of connections between cities. Most studies have focused on a single type of connection. With the continuous application and expansion of multi-layer network theory, studies on the construction of logistics networks based on this multi-layer approach have mainly focused on the internal multi-layer dynamics of a freight network topology. Few studies have investigated the level of urban logistics development from the viewpoint of a multi-layer complex network (Table 1 shows the comparison of the three evaluation methods). This makes it difficult to comprehensively analyze the logistics status and logistics development potential of cities in an urban agglomeration.

Table 1. A comparison of comprehensive evaluation methods.

| Method | Scope of Application | Pros and Cons |
|--|---|--|
| Entropy method | Lower dimensional data, clearer evaluation indicators, single attribute data | An objective evaluation method that avoids bias caused by human factors. Possible distortion of weights and invalid results |
| Principal component analysis (PCA) and cluster methods | Higher dimensional data, strong connections between variables, data classification, single attribute data | Achieve data dimensionality reduction. Convenient calculation and operation. Loss of some effective data |
| Complex network theory | Higher dimensional and complex data, data with network structure, multi-attribute data | A comprehensive evaluation method, ability to consider connections between data, and require clear data structures. Requirements for data quality are high |

Therefore, this study evaluates the development level of urban logistics from the perspective of the logistics connections between cities. The study focused on 11 node cities in the *GPUA*, combining road freight volume, railway lines, and logistics enterprise connections to study the inter-city relationships. Using complex network theory, we analyzed the development level of urban logistics in the *MCLNUA* from the three dimensions of "point–line–surface". The study provides a useful reference for the further development of urban logistics in the *GPUA*.

3. Model Construction and Data Sources

3.1. Model Construction

3.1.1. The Structure of Multi-Layer Logistics Network in Urban Agglomeration

The logistics connections between cities can be divided into infrastructure connection, flow connection, and logistics enterprise connection [4]. Infrastructure connections are mainly represented by transportation routes and provide necessary conditions for logistics connections to occur between cities. Flow connections refer to the exchange of freight volume between cities and form the core of the inter-city connections. Logistics enterprises

are defined as the professional organizations that conduct logistics activities and constitute the functional elements of the inter-city logistics network.

The nodes in the network include 11 cities in the *GPUA*. The edge of the sub-network layer implies different types of connections. Table 2 shows the meanings of the sub-network layers and nodes. The sub-network layer is represented by $G_s(V_s, E_s, W_s)$, where $V_s = \{V_s^i, i = 1, 2, 3 \dots, n\}$, representing the collection of city nodes in the urban agglomeration. The expression $E_s = \{e_s^{ij}, i, j = 1, 2, 3 \dots, m\}$ represents the set of connection edges between cities in the urban agglomeration; and W_s represents the weight set of each edge in E_s . If city i and city j are connected, it is set to W_s^{ij} . Matrix W_s is expressed as

$$W_s = \begin{bmatrix} 0 & w_{12} & \cdots & w_{1(n-1)} & w_{1n} \\ w_{21} & 0 & \cdots & w_{2(n-1)} & w_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ w_{(n-1)1} & w_{(n-2)2} & \cdots & 0 & w_{(n-1)n} \\ w_{n1} & w_{n2} & \cdots & w_{nn-1} & 0 \end{bmatrix} \tag{1}$$

Table 2. The meaning of sub-network and node.

| Variable | Sub-Network | The Meaning of Node |
|----------|------------------------------|---|
| G_s^1 | Road freight network | The city where entities stop for loading and unloading during road freight |
| G_s^2 | Railway freight network | The city where a freight station is located for loading and unloading goods |
| G_s^3 | Logistics enterprise network | The city where the logistics company is located |

The connection properties of each edge in the sub-network layer differ, and the methods of measuring the weight of the connection edge between cities also differ. To calculate the weights of the connecting edges between cities in the road freight network, Olariaga [37] demonstrated the reliability of applying the gravity model to analyze cargo transportation between cities and regions. As such, this study applies the traditional gravity model to calculate the node urban road freight connection strength.

To calculate the edge weight in a railway freight network, other studies have demonstrated the feasibility of using the number of railway lines to calculate the strength of connections between cities [38]. Therefore, this study uses the number of lines between freight stations in each city to measure the weight of the railway freight network connection (not considering the connection between cities themselves).

To calculate the edge weight in the logistics enterprise network, other studies have demonstrated the significance of applying the interlocking network model [39] to analyze the relationship between urban network nodes. Therefore, this study uses the interlocking network model to investigate the weights of interconnections in the logistics enterprise network. Table 3 provides the specific meanings and calculation methods used.

Table 3. The edge weight of network connection and calculation method.

| Variable | Meaning | Calculation Method |
|----------|--|--|
| W_s^1 | Road freight network edge weight | Gravity model [37,40–43] |
| W_s^2 | Rail freight network edge weight | Number of railway freight lines [36,44,45] |
| W_s^3 | Logistics enterprise network edge weight | Interlocking network model [39,46–49] |

3.1.2. Construction of MCLNUA

Multi-layer networks can be roughly divided into two categories based on the heterogeneity of nodes and connecting edges [50]: multi-dimensional networks and multi-layer dependent networks. The network nodes of each layer in the multi-layer dependent network can be different, with strong dependencies among the network nodes of each layer. The failure of a certain layer of network nodes can directly lead to the failure of the nodes associated with it in other layers, leading to a cascading failure [51–54]. This is inconsistent with the multi-layer network proposed in this study; as such, this study adopted a multi-dimensional network, with a network in each single layer. The set of nodes in each layer network is identical, and the types of relationships within each layer of the network differ [35,52].

This study constructed a multi-layer network consisting of fixed nodes connected by different relationship types [50,53]. The multi-layer network consists of n nodes and m networks. Nodes are present in the sub-networks of each layer in the form of a set. The number of network nodes in each layer is the same, and the network nodes between different layers need to correspond on a one-to-one basis. This study does not consider the differences of connections between nodes of different sub-network layers [54]. Figure 2 shows the process of superimposing multi-layer networks with each sub-network [31,50,53,55]. Sub-networks G_s^1 , G_s^2 , and G_s^3 have the same nodes and different edges, and the network G is generated using aggregation mapping. Equation (2) shows the aggregation process, where G continues to have the same node and contains the connection information to all edges.

$$G(V, E, W) = G_s^1(V_s^1, E_s^1, W_s^1) \cup G_s^2(V_s^2, E_s^2, W_s^2) \cup G_s^3(V_s^3, E_s^3, W_s^3) \quad (2)$$

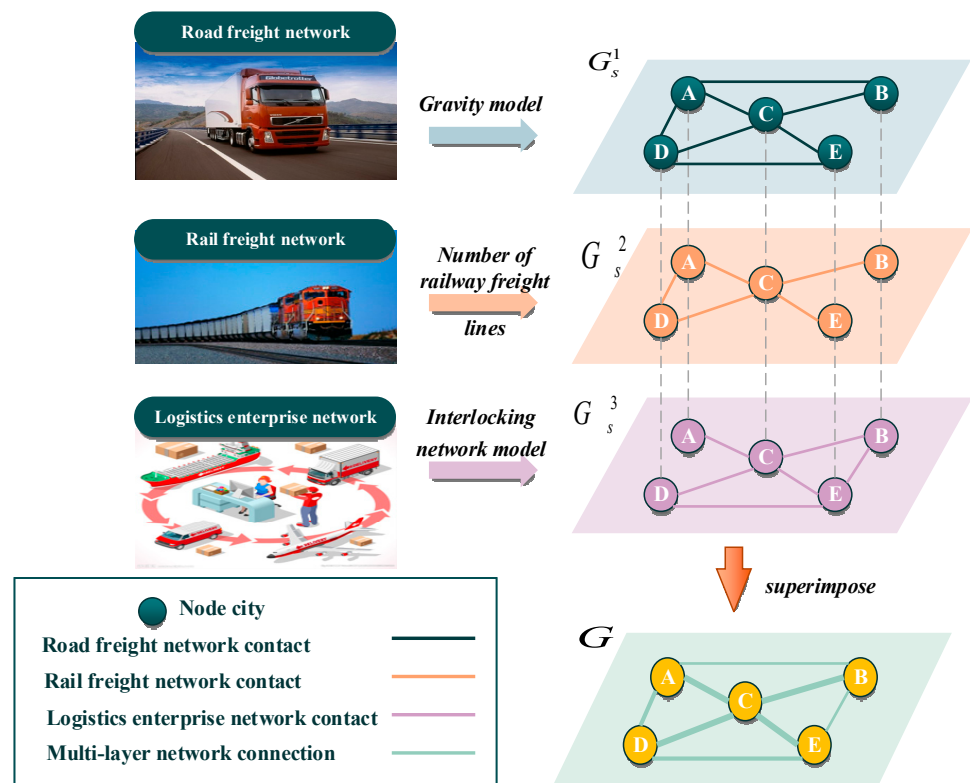


Figure 2. The construction process of MCLNUA.

Widely used methods to define single-layer networks can also be used to study multi-layer aggregate networks. This study mapped the aggregation of edge weights in the multi-layer network [56] to generate the edge weights of the MCLNUA. The construction principles are as follows:

1. If the same node is present in each layer of the network during the superposition process, it is positioned as a node in the *MCLNUA*;
2. If there are multiple edges connected between nodes in different layers after superposition, we define the union of the edges between the layers as the edges of the *MCLNUA*;
3. If a node can reach another node, we assume another node can also reach that node, that is, the *MCLNUA* is an undirected network.

3.2. Evaluation Index System of Urban Logistics Level for *MCLNUA*

3.2.1. Node Characteristic Index

Basic Network Structure Characteristics

1. Node strength

The node strength represents the sum of the edge weights of the node and all adjacent edges. In weighted networks, the indicator of “node strength” is more accurate compared to the indicator of “degree of nodes” for expressing the proximity of one node with other nodes [57]. The expression S_i represents the strength, as follows:

$$S_i = \sum_{j \in N_i} w_{ij} \quad (3)$$

2. Weighted degree

The weighted degree (*WD*) of a node is defined by considering both the degree and strength of node i . The WD_i of the node is defined as follows:

$$WD_i = \alpha \times k_i + (1 - \alpha) \times S_i \quad (4)$$

where k_i is the degree of node i and represents the number of nodes connected to node i [58]; and α is an adjustable parameter with α value of 0.5.

3. Weighted clustering coefficient

The weighted clustering coefficient (*CW*) of a node reflects the degree of the agglomeration of the network. The CW_i is represented as follows:

$$CW_i = \frac{1}{S_i(k_i - 1)} \sum_{jk} \frac{w(i, j) + w(i, k)}{2} a_{ij} a_{jk} a_{ki} \quad (5)$$

$$\begin{cases} a_{jk} = 1, & \text{if node } j \text{ and node } k \text{ are connected;} \\ a_{jk} = 0, & \text{if node } j \text{ and node } k \text{ are not connected;} \end{cases} \quad (6)$$

where nodes j and k are any direct neighbors of node i .

Centrality Index

1. Weighted degree centrality

The weighted degree centrality (*WDC*) [32] directly reflects the possibility of a direct connection between the node and other nodes in the network. The WDC_i is expressed in Formula (7):

$$WDC_i = k_i^\alpha \times \left(\frac{S_i}{k_i}\right)^{(1-\alpha)} \quad (7)$$

where S_i is the strength of node i ; k_i is the degree of node i ; and α is the assigned parameter with α value of 0.5.

2. Weighted closeness centrality

Weighted closeness centrality (*WCC*) uses the distance to measure how easily node i connects with all other nodes. *WCC* is the reciprocal of the average weighted shortest

path length from node i to other nodes in the network. It reflects the degree of network accessibility. The greater the weighted closeness centrality of a node is, the more important the node is in the network. The WCC is expressed in Formula (8):

$$WCC_i = \frac{n - 1}{\sum_{j \neq 1, j \neq i}^n d_{ij}^w} \tag{8}$$

In traditional network research, the distance between nodes is measured by the number of edges connecting nodes or the actual distance between nodes. However, this method does not reflect the intensity of logistics connections between cities and is therefore not suitable for this study’s MCLNUA [59]. Instead, “effective distance” [60] has been shown to be effective and practical when applied to networks that interact with information flow. The average weighted shortest path length d_{ij} is calculated using Formulas (9) and (10):

$$P_{ij} = \frac{F_{ij}}{\sum_i F_{ij}} \tag{9}$$

$$d_{ij} = 1 - \ln P_{ij} \tag{10}$$

where P_{ij} is the ratio of information flow from node i to node j ; and F_{ij} is the information flow from node i to node j . In this study, F_{ij} is the value of the logistics connection strength between city i and city j .

The Influence of Nodes

Identifying influential nodes in complex networks is of great significance to urban development planning [61]. This study uses the clustering degree algorithm (CDA) [62] to calculate the influence of nodes (INV). Figure 3 shows the calculation flowchart. The algorithm defines the influence of the node based on the WD, the clustering degree (CD) of nodes, and the contribution of neighbors. The INV is defined as shown in Formula (11).

$$INV(i) = CD_i + \sum_{j \in I_i} \frac{w(i, j)}{w_{max}} CD_j \tag{11}$$

where W_{max} is the maximum edge weight; and CD_i is the clustering degree of node i , as shown in Formulas (12) and (13):

$$CD_i = WD_i \times f(i) \tag{12}$$

$$f(i) = \frac{1}{e^{-cw_i}} \tag{13}$$

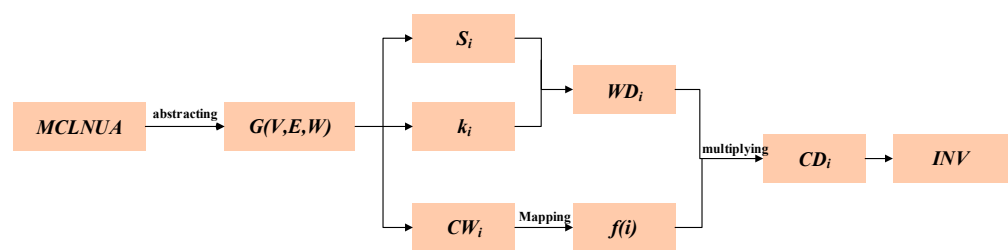


Figure 3. The CDA algorithm flow chart.

3.2.2. Strength and Direction of Connection for Urban Logistics

The dynamics associated with logistics connections between cities are mainly reflected in two ways: the strength and the direction of the urban logistics connection. First, this study uses the gravity model, the number of railway transportation routes, and the interlocking network model to determine the strength of the logistics connection between cities in each

sub-network. Second, each single city has another closest city for logistics, which is defined as the primary direction of the city. To more intuitively analyze the direction of the city's logistics elements, the membership model [63] is used to determine the direction of urban logistics connections between cities in the network.

Formula (14) [64] has been shown to be effective in analyzing other urban factor flows. As such, it is used to analyze the main functional directions of the logistics networks in different cities:

$$W = \frac{w_{ij}}{w_i} \quad (14)$$

where w_{ij} is the connection strength between city i and city j ; w_i is the total connection strength of city i ; and W is the ratio of the connection strength intensity of the two cities to the total connection strength of city i . A larger value of W is associated with a stronger connection strength between city i and city j , when considering the connection strength of city i .

3.2.3. Cohesive Subgroups

A cohesion subgroup is a collection of urban individuals that are direct, close, and interconnected. This is an important entry point for urban network research. A cohesive subgroup is a bridge connecting an individual city and an urban network. Cities are interconnected first to form various cohesive subgroups. Then, cohesive subgroups are interconnected to form a complex city network [65]. Cohesive subgroups reflect the trend of inter-city contact and cooperation, representing a close relationship at the level of cooperation and exchange [66]. To further encourage the sustainable development of cities, this study explores the status and role of urban individuals in the *MCLNUA*, and comprehensively analyzes the tendency of logistics connections between cities. We used the Concor algorithm to analyze cohesive subgroups in the *MCLNUA* with Ucinet software and calculated the density of connections within and between subgroups.

3.3. Research Region and Data Sources

The Guanzhong Plain Urban Agglomeration Development Plan was proposed in 2018 to accelerate the cross-disciplinary integration of transportation, logistics, and other industry to optimize urban scale and structure. The *GPUA* is one of the main urban agglomerations in western China but has a low logistics development level compared with other urban agglomerations. As such, evaluating the logistics level of *GPUA* is useful for exploring current problems and proposing feasible solutions. The research area is shown in Figure 4.

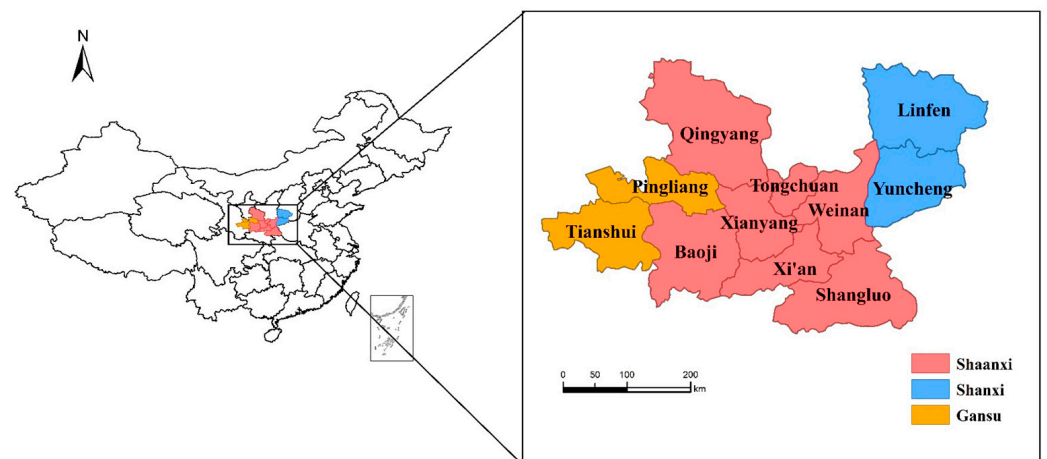


Figure 4. The study area.

The data about urban road freight were collected from the statistical yearbooks of each city, and the missing values in the yearbooks were filled in using interpolation. Then, the study applied a gravity model to calculate the strength of the road freight connection between cities. Data about the railway freight network were collected by collating the China Railway Map website [67] and the freight business station data in the China Railway Freight Online Business Office. Network data about logistics companies were collected from the national corporate credit information publicity system; corporate information was queried based on the data of China's top 100 logistics companies in 2018 [68]. Then, this study applied the interlocking network model algorithm invented by Taylor [39] to calculate the strength of the logistics companies between cities.

Figure 5 shows the calculation process of the *MCLNUA* model.

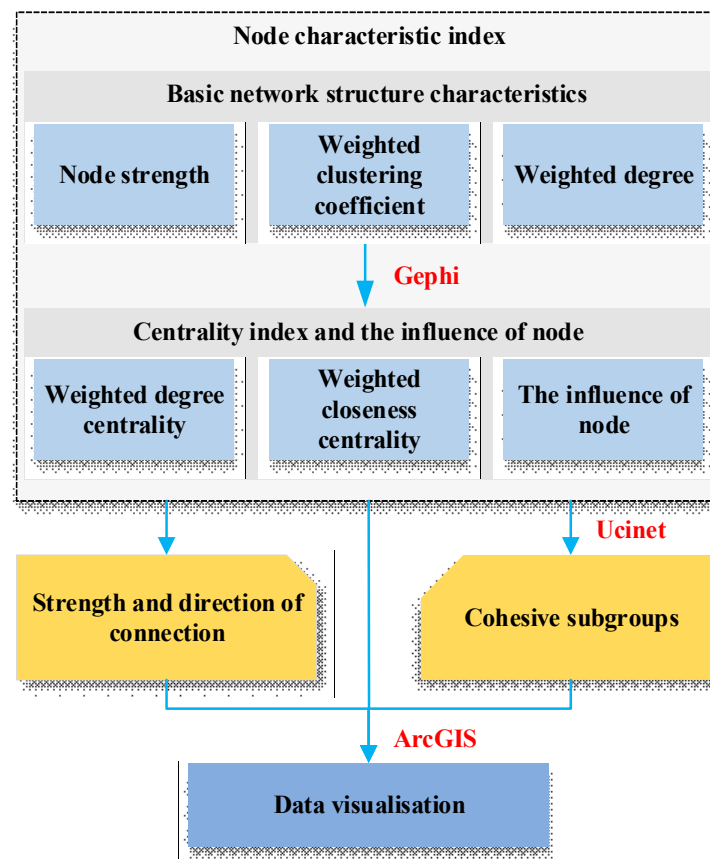


Figure 5. The calculation process of the *MCLNUA* model.

4. Results and Discussion

Evaluating each city's logistics development level is important for advancing integrated regional development and further encouraging sustainable urban development. This study's findings provide a complete assessment for evaluating the development level of each node city in the *MCLNUA*.

4.1. Analysis of Node Characteristic Index of *MCLNUA*

4.1.1. Node Centrality Analysis

The *WDC* reflects the local characteristics of the network, and the *WCC* reflects the global characteristics of the network. This study calculates the *WDC* and *WCC* of each city in the *GPUA*, and then ranks the results. Table 4 shows the numerical ranking of each city index, and Figure 5 shows the regional distribution of urban centrality indicators.

Table 4. The sorting of the node characteristic index values.

| No. | | Weighted Degree Centrality (WDC) | | Weighted Closeness Centrality (WCC) |
|--------------------|-----------|----------------------------------|-----------|-------------------------------------|
| 1 | Xi'an | 12.118 | Xi'an | 0.317 |
| 2 | Xianyang | 10.445 | Weinan | 0.307 |
| 3 | Weinan | 9.880 | Baoji | 0.301 |
| 4 | Baoji | 8.750 | Linfen | 0.297 |
| 5 | Linfen | 8.577 | Tianshui | 0.295 |
| 6 | Yuncheng | 8.459 | Xianyang | 0.295 |
| 7 | Tongchuan | 8.348 | Yuncheng | 0.294 |
| 8 | Tianshui | 8.157 | Tongchuan | 0.294 |
| 9 | Shangluo | 7.808 | Shangluo | 0.289 |
| 10 | Pingliang | 7.062 | Qingyang | 0.283 |
| 11 | Qingyang | 7.051 | Pingliang | 0.283 |
| Standard deviation | | 1.437 | 0.010 | |

The WDC intuitively reflects the possibility of a direct connection between a city and other cities in the MCLNUA. A greater WDC value for a city indicates a closer connection between the node and other nodes in the network. Xi'an has the largest WDC value (12.1178) and is the core city in the G_{PUA}. The WDC values for Xianyang, Weinan, and Baoji exceed 8.7. The WDC values of Shangluo, Pingliang, and Qingyang are all less than 8.0, indicating that these cities are weakly connected with other cities in the G_{PUA}. The standard deviation of the WDC value is 1.432, indicating that the logistics development level of cities in the network differ significantly.

The WCC refers to the degree to which a city is located in the center of the MCLNUA and reveals the relative reachability of the node. A node with a larger WCC value is at the center of the overall network. The WCC value of a city is consistent with its geographic location. For example, Xi'an, Weinan, and Baoji are located in the overall center of the G_{PUA} and have relatively high WCC values. The WCC values of cities in the G_{PUA} gradually decrease from the center to the edge, based on the geographical location of each city in the MCLNUA. The WCC values of the edge cities in the G_{PUA} are close to 0.28. The standard deviation of the city WCC value is 0.01, indicating that the logistics network has good accessibility.

In general, Xi'an, Xianyang, and Weinan have a relatively high logistics development level, and strongly influence the logistics network in the G_{PUA}. However, Shangluo, Pingliang, and Qingyang have a relatively low logistics development level. The values of several basic indexes illustrate that the edge cities in the G_{PUA} are less affected by the radiation from the central city. Figure 6 shows that the regions with a larger node characteristic index value are consistently in the center of the G_{PUA}, with significant variations in the level of logistics development between cities. The logistics development levels of the cities have not broken through the restrictions of provincial administrative regions to achieve good logistics interaction.

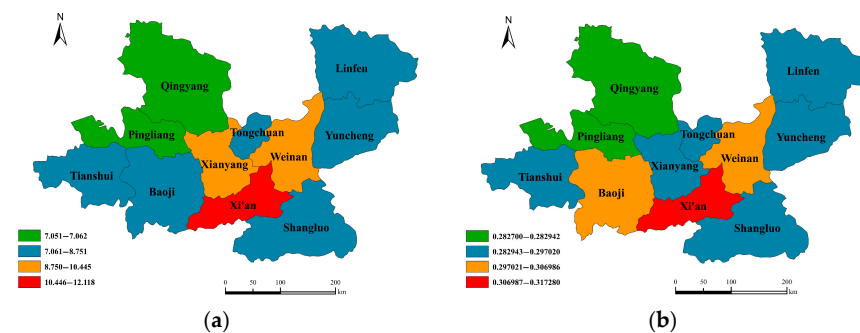


Figure 6. Regional distribution of urban node characteristic indicators in the G_{PUA}: (a) regional distribution of WDC; (b) regional distribution of WCC.

4.1.2. Node Influence Analysis

Cities are not independent in the network. Identifying the influence of nodes is important when developing a reference for urban logistics planning. The influence of each node city in the *GPUA* is calculated using the *CDA*, shown in Table 5.

Table 5. The ranking list of *INV* of cities.

| Rank | 1 | 2 | 3 | 4 | 5 | 6 |
|------------|----------|----------|--------|----------|-----------|-----------|
| City | Xianyang | Weinan | Xi'an | Baoji | Yuncheng | Tongchuan |
| <i>INV</i> | 398.9 | 357.8 | 352.7 | 282.5 | 264.5 | 257.8 |
| Rank | 7 | 8 | 9 | 10 | 11 | |
| City | Tianshui | Shangluo | Linfen | Qingyang | Pingliang | |
| <i>INV</i> | 246.5 | 226.5 | 208.0 | 186.3 | 116.4 | |

The results show that Xi'an is not the most influential node city for logistics when considering the *INV* results in the *GPUA*. Rather, the most influential city is Xianyang, which is geographically close to Xi'an. In terms of urban functions, Xianyang is a core component of the international metropolis of Xi'an and has the most potential for development. Weinan and Baoji are node cities with high *INV* values. Geographically, Baoji is west of Xi'an, adjacent to Xi'an and Xianyang. Weinan is northeast of Xi'an and is strongly radiated by Xi'an. Weinan serves as an important logistics connection point between Xi'an and other cities and is a candidate to become an important sub-hub logistics city in the *GPUA*.

Linfen, Qingyang, and Pingliang have the smallest influence values in the *GPUA*. For Linfen, the *INV* value is low, but the centrality value is high. This illustrates that Linfen's logistics development level is relatively high, but its impact on the entire network is low in the *GPUA*. Qingyang is in the southwestern direction of the *GPUA*. It is far from the core city and is weakly affected by the central city. Pingliang is northwest of the *GPUA* and is positioned at a different provincial level with Xi'an. It has a lower central degree value and a lower logistics development level.

In general, the *INV* value of each city in the *GPUA* is different. The *INV* value of the city in the central area is significantly higher compared to the *INV* values of the cities in the peripheral area in the *GPUA*, which shows polarization characteristics. The overall logistics development level of the *GPUA* has not achieved integrated development across the region.

4.2. Analysis of Connection Strength and Direction of *MCLNUA*

Figure 7a shows the connection strengths across the *MCLNUA*. The main logistics connections of cities remain concentrated in individual provinces, with relatively weak inter-provincial connections. From the perspective of the spatial structure characteristics of the network connection, the overall network connection is stronger in the south than that in the north, and stronger in the east than that in the west. There is a clear edge effect of the cities in the *GPUA*, with a weak logistics connection between the marginal cities and other cities in the *GPUA*.

Figure 7b shows the primary direction of logistics flows in the *MCLNUA*. Pingliang's primary direction is Tianshui, and the primary direction of other cities in the *GUPA* is Xi'an. In addition, the primary direction of Xi'an points to Xianyang, and has clear geographical proximity. The primary direction of the marginal cities remains towards Xi'an, and the primary direction of the marginal cities is not close to the middle city geographically. This indicates that the radiation role of Xi'an has not been maximized, and the logistics cities are polarized.

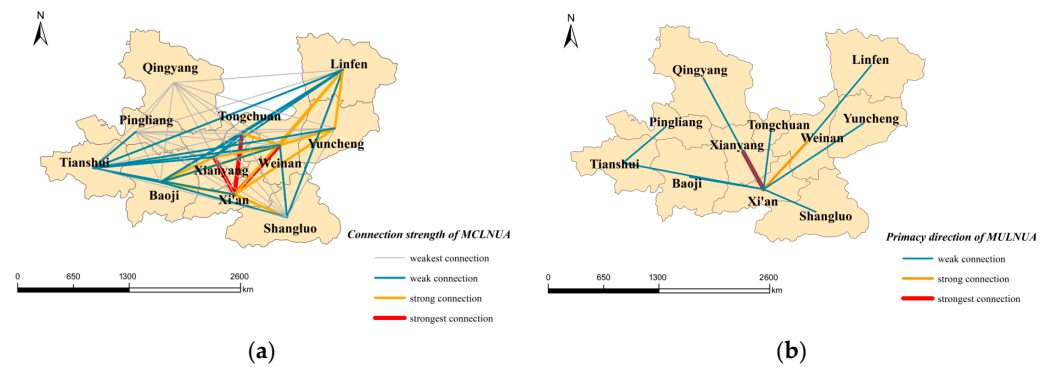


Figure 7. Diagram of connection strength and primary direction of MCLNUA: (a) connection strength of MCLNUA; (b) primary direction of MULNUA.

4.3. Analysis of Cohesion Subgroups of MCLNUA

This study used Ucinet software to divide the cities in the GPU into different cohesion subgroups and to describe the composition of subgroups in the MCLNUA. The MCLNUA of the GPU is divided into four cohesion subgroups (i.e., I, II, III, IV) by the Concor algorithm (L, 1968) in Ucinet software. Combined with the analysis of the regional geographic location, Figure 8 shows the regional distribution of cohesion subgroups. The cities in each cohesion subgroup show high geography proximity.

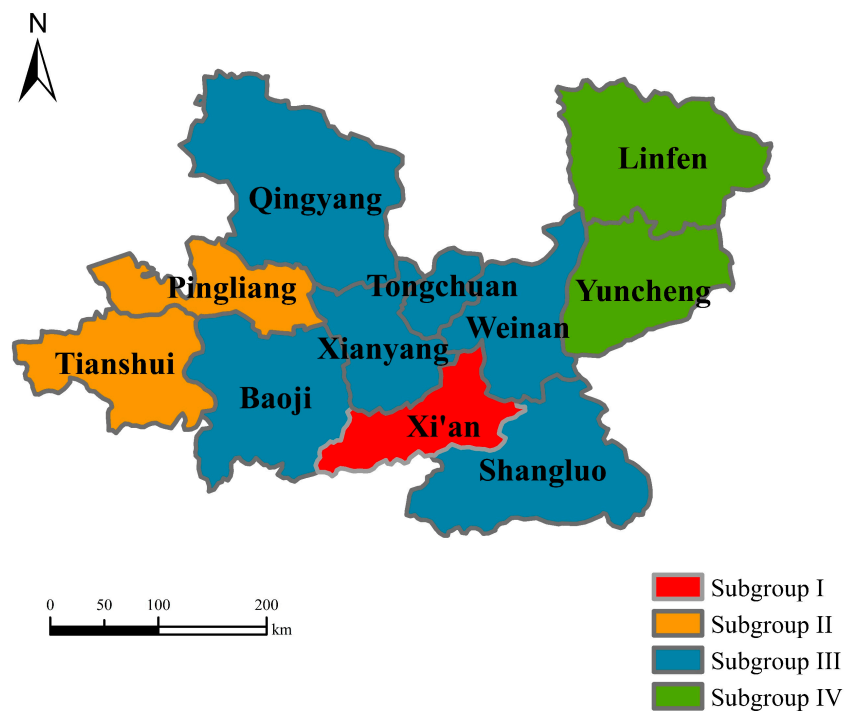


Figure 8. Regional distribution of cohesion subgroups.

The cities in the MCLNUA are not in the same position and have a different degree of connection density with other cities. The cities that form a cohesion subgroup are closely related to each other, and there is a close logistics connection between the cities. The correlation density coefficient shows a more intuitive tendency and degree of affinity between cohesion subgroups. The density coefficients in the cohesion subgroups were analyzed to explore the relationship within the subgroups or between the subgroups. Table 5 shows the connection strength between the subgroups. A larger density coefficient value is associated with a closer connection within the subgroups or between the subgroups.

The numbers on the diagonal line in Table 6 represent the internal density coefficient of each subgroup. The internal density coefficient value of subgroup IV is the largest among the subgroups, reaching 11.90. This indicates there are frequent and close logistics resource interactions between cities in subgroup IV. The internal connection density values of subgroups III and II are 6.919 and 6.340, respectively. This indicates that a low closeness level of the internal connection between subgroup III and II, indicating they have not maximized the advantages of geographical proximity. The density of logistics connections in entire subgroups gradually decreases from the eastern region to the western region.

Table 6. The density coefficient of cohesion subgroups.

| Cohesion Subgroups | I | II | III | IV |
|--------------------|--------|-------|--------|--------|
| I | / | 7.005 | 18.470 | 11.005 |
| II | 7.005 | 6.340 | 5.653 | 5.470 |
| III | 18.470 | 5.653 | 6.919 | 6.452 |
| IV | 11.005 | 5.470 | 6.452 | 11.900 |

From the perspective of the connection density coefficient between different subgroups, the maximum density coefficient between subgroups is seen with subgroup I and subgroup III, reaching 18.470. The cities in subgroup III are geographically close to Xi'an, providing more logistics resources to interact with Xi'an. The cities in subgroup IV, Linfen and Yuncheng, are geographically far from Xi'an, however, their logistics connections with subgroup I are very close. The density coefficient between subgroup IV and subgroup I is 11.005, indicating these two subgroups have a pulling effect on each other's logistics development [69]. Xi'an is the city with the most intensive exchange and diffusion of logistics resources in the *GPUA* and has an advantage in controlling the exchanges and connections between other subgroups. Overall, Xi'an has a stronger radiation influence on the eastern region compared to the western region in the *GUPA*.

There is an overall high level of connection between subgroup I, composed of Xi'an and other subgroups. However, the strength of connection between other subgroups is lower compared to Xi'an. There are significantly different density coefficients between the subgroups in the *GPUA*. The overall density coefficient gradually decreases from east to west.

4.4. Urban Logistics Space Development Planning of *GPUA*

This study applied the natural breakpoint method [64] to divide the cities in the *GPUA* into four levels according to node strength. This served as the basis for the regional division. The first level cities are central cities, the second level cities are sub-central cities, the third level cities are in the core areas, and the fourth level cities are the radiation affected cities (see Table 7). Based on the urban logistics connection and spatial hierarchy of the *GPUA*, this study provides recommendations for improving the logistics spatial development layout of the urban agglomeration based on the analysis and evaluation of urban logistics capabilities.

Table 7. Classification of city levels in the *GUPA*.

| Level | City | City Hierarchy |
|--------------|--|--------------------------|
| First level | Xi'an | Central city |
| Second level | Xianyang, Weinan | Sub-central city |
| Third level | Baoji, Tianshui, Linfen, Yuncheng, Shangluo, Tongchuan | Core areas |
| Fourth level | Pingliang, Qingyang | Radiation affected areas |

1. Point—Analysis of node city hierarchy

The specific city hierarchy is as follows. First, according to the division of urban spatial hierarchy, Xi'an is divided into a central logistics city in the *GPUA*. Xi'an has a strong cultural history and economic and cultural strength. It maintains the function of a logistics center and occupies a leading position in the development of urban logistics. However, the regional radiation ability in the *GPUA* is not strong, and the interaction of Xi'an with other cities could be enhanced.

Second, Xianyang and Weinan are divided into sub-central cities. The two cities have close logistics connections with surrounding cities, and the Xi'an–Xianyang integration strategy is being implemented. The logistics development level of Xianyang is rapidly improving, which should not be underestimated.

Third, the core area is composed of 6 cities, headed by Baoji and including Tianshui, Linfen, Yuncheng, Shangluo, and Tongchuan. These cities have not maximized the advantage of the positive impact created by the logistics development of surrounding central cities and sub-central cities.

Finally, Pingliang and Qingyang are identified as radiation-affected areas and are in poor locations with low economic development levels and unsatisfactory factor flow intensity. They have become valley areas with respect to logistics development in the *GPUA*.

2. Line—Analysis of logistics development axis

The “Guanzhong Plain Urban Agglomeration Development Plan”, approved by the State Council of China in 2018, proposed the construction of a spatial pattern of “one circle, one axis, and three belts”. The study found that the central city (Xi'an) is connected with the sub-central city (Xianyang and Weinan) and its close core cities (Shangluo, Yuncheng, Linfen, and Tongchuan) to form a key logistics development axis. The central city (Xi'an) connects with the remaining core cities (Baoji and Tianshui) to form a sub-key logistics development axis. Table 8 shows two key logistics development axes, “Tongchuan–Xianyang–Xi'an–Shangluo” and “Xi'an–Weinan–Yuncheng–Linfen”, and one sub-key logistics development axis, “Tianshui–Baoji–Xi'an”. These comprehensively improve the city's logistics development level in the *GPUA*.

Table 8. Logistics development axis in the *GUPA*.

| No. | Logistics Development Axis | |
|-----|------------------------------------|-----------------------------------|
| 1 | Key logistics development axis | Tongchuan–Xianyang–Xi'an–Shangluo |
| 2 | Key logistics development axis | Xi'an–Weinan–Yuncheng–Linfen |
| 3 | Sub-key logistics development axis | Tianshui–Baoji–Xi'an |

Figure 9 shows the urban logistics space development plan of the *GPUA*. The key logistics development axis of “Xi'an–Weinan–Yuncheng–Linfen” relies on the Beijing–Kunming Expressway and Daxi–Xicheng high-speed railway to strengthen the logistics development level of Yuncheng and Linfen. The key logistics development axis of “Tongchuan–Xianyang–Xi'an–Shangluo” connects the vertical direction of urban development, and relies on the Baomao Expressway, Fuyin Expressway, Baohai High Speed Rail, and Yinxi–Xiwu High Speed Rail. The “Tianshui–Baoji–Xi'an” sub-key logistics development axis relies on the infrastructure of the Longhai Railway and Lianhuo Expressway to continuously strengthen logistics connectivity. This enables the western region to better implement the radiation role of Xi'an. Figure 10 provides a schematic diagram of the relevant highway and railway lines. Relying on the logistics development axis improves the pattern of a strong east and weak west, and a strong south and weak north when developing urban agglomeration logistics.

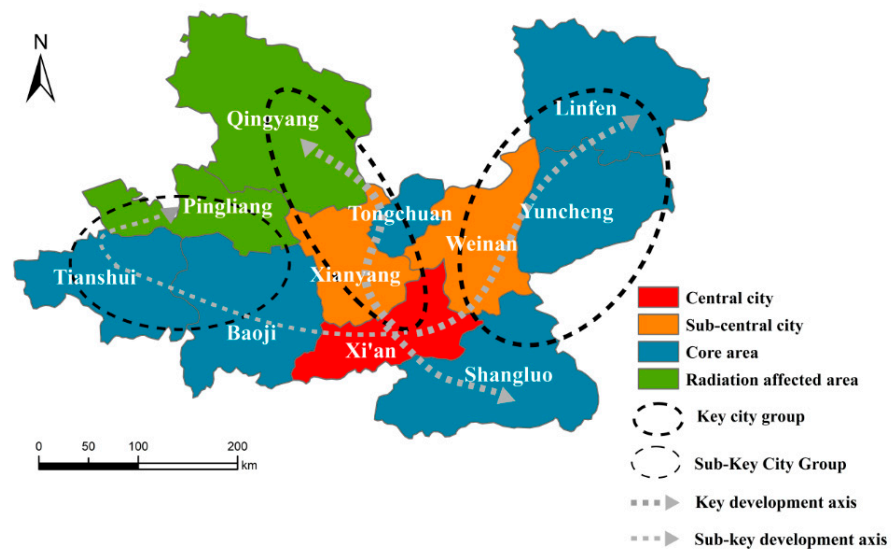


Figure 9. The layout of urban logistics space development planning in the GPUA.



Figure 10. The layout of main highways and railways in the GPUA.

3. Surface—Analysis of the development of city groups

Mutual cooperation between cities avoids resource waste and supports sustainable and integrated urban development. This study divides the cities in the GPUA into the “Xi–Xian–Tong–Qing” city group, the “Wei–Shang–Lin–Yun” city group, and the “Bao–Ping–Tian” city group. These divisions were based on the analysis above of the urban logistics development level in the GPUA from different dimensions, and the urban spatial pattern described in the “Guanzhong Urban Agglomeration Urban Development Plan”. The first two are key city groups, and the latter is the sub-key city group, as shown in Figure 10.

First, Tongchuan and Xianyang are geographically similar to Xi’an. Xianyang, Tongchuan, and Qingyang belong to the same subgroup in the cohesive subgroup analysis above, so the four cities are in the same city group. This would facilitate improvements in the logistics development level of the core cities and its radiating areas of influence, expand the radiating influence of the core city of Xi’an, and advance logistics development for Qingyang.

Second, Linfen, Yuncheng, Weinan, and Shangluo in the east part of the GPUA are in the same city group. Yuncheng and Linfen are in the same province making the logistics

connections between the two cities relatively close. Weinan and Shangluo are in the same cohesive subgroup and are adjacent to Yuncheng and Linfen. It would be more beneficial for Weinan to further develop its logistics capability compared to the other three cities and to better play the role of a sub-central city.

Finally, Tianshui, Pingliang, and Baoji are in the same city group. This is because Tianshui and Pingliang belong to the same cohesive subgroup. While Tianshui and Pingliang are in the same province, there is only a weak connection between the cities. Baoji has a superior geographical location and large potential for logistics development, supporting the city's ability to maximize its advantages to drive logistics development in Tianshui and Pingliang, and further encourage the overall coordinated development of urban logistics.

5. Conclusions and Recommendations

This study evaluated the urban logistics development level of the *GPUA* based on complex network theory. The following diverse elements were considered: flow elements of the external connections of urban logistics (inter-city road freight volume), facility elements (inter-city railway lines), and functional elements (logistics enterprise connections). The development level of urban logistics was also evaluated from the multiple dimensions of "point–line–surface". As mentioned above, we have constructed a more comprehensive urban logistics network, which allows us to more scientifically describe the logistics attributes of a city and to evaluate the level of logistics development of urban agglomerations in this way. The research results improve upon past results that considered a single element and extend our understanding of methods for evaluating the logistics development level of an urban environment. In addition, the study offers a new way to improve the evaluation system of logistics networks. The main conclusions of this study are as follows:

First, in terms of node characteristic indicators in the logistics network of the *GPUA*, Xi'an ranks high in centrality and is in the core position of the *GPUA*. There are significant differences between the logistics development level of Xi'an and the level of other cities. Cities with high characteristic index values are generally concentrated in the center of the *GPUA*. In contrast, cities in the periphery have significant edge effects and lower logistics development levels. Xianyang, Weinan, and Baoji are the three cities with the most potential to develop into a sub-central hub. To encourage the joint development of cities in the region, it is important to strengthen the leading role of sub-hub cities in driving edge cities.

Second, the strength of the logistics connections between cities in the *GPUA* is significantly restricted by administrative boundaries, with relatively weak inter-provincial connections. The structure of the overall network is stronger in the south than in the north, and stronger in the east than in the west. Xi'an has a high level of economic development and is located in the geographic center of the *GPUA*. The primary action direction for marginal cities is towards Xi'an, not the intermediate cities that are geographically close to itself in the *MCLNUA*. This shows that with respect to the flow of logistics elements, elements usually point to cities with high levels of economic development and geographical centers.

Third, cities tend to have logistics connections with surrounding cities. The density coefficient of logistics connections within the subgroups shows a decreasing trend from the eastern region to the western region, with significant differences. Additionally, cities in the subgroups have significant geographic proximity, with provincial scope characteristics.

Accordingly, the corresponding recommendations are as follows:

First, it is recommended that the core position of Xi'an be improved in logistics networks. This includes coordinating the internal logistics connections of the *GPUA*, and fully exerting the core role of Xi'an. This would involve constructing a hierarchical transmission mechanism ranging from Xi'an to surrounding areas and then to peripheral areas. This would enable the surrounding areas of Xi'an to become a key node in the logistics network of the *GPUA*. This strategy of driving logistics development in surrounding cities may also continuously improve the weak core position of Xi'an.

Second, by relying on the two key logistics development axes of “Tongchuan–Xianyang–Xi’an–Shangluo” and “Xi’an–Weinan–Yuncheng–Linfen”, and the sub-key logistics development axis of “Tianshui–Baoji–Xi’an”, management departments should establish a more intensive infrastructure network to increase the direct route between the fringe area and the core city [70], while also strengthening the connections around the area. This solution would help break the restrictions of administrative regions, reduce the infrastructure gap between cities, and advance logistics connections between cities. In particular, the logistics connections between Qingyang, Pingliang, and other surrounding cities should be strengthened, to comprehensively encourage the multi-directional development of the logistics level of the *GPUA*.

Third, by focusing on the “Xi–Xian–Tong–Qing” city group, the “Wei–Shang–Lin–Yun” city group, and the “Bao–Ping–Tian” city group, the government should actively guide connections between the city groups to encourage the joint development level of urban logistics. This would accelerate the formation of a development pattern where the sub-central city and Xi’an help each other, and truly realize the integrated development of regional logistics in the *GPUA*.

Considering the single attribute and the group attributes of the city, the complex network evaluation methodology can evaluate the logistics development at the level of urban agglomeration, and also simultaneously fulfil the research of the logistics development level of individual cities in the urban agglomeration. Based on complex network theory, this study positioned cities as nodes to investigate the logistics development level in the *GPUA* using a “point–line–surface” dimension. The results provide useful references for government officials to develop policies, achieve the integrated development of regional logistics, and advance the sustainable development of cities.

However, the scope of this research study was limited due to data availability. In the future, more research funding and data access may enable the expansion of the research field, to include multiple urban agglomerations or to cover all of China (e.g., Beijing–Tianjin–Hebei urban agglomeration, Yangtze River Delta urban agglomeration), while verifying the scalability of the model through obtaining more data and analyzing more cases.

In addition, this study explored the development level of urban node logistics but did not deeply analyze the dynamic evolutionary process and essential mechanism of the logistics network involved in an urban agglomeration. Future studies should consider the use of complex network theory to explore the structural evolution mechanism and dynamic mechanism of the logistics network for urban agglomerations. Despite these limitations, this study adds value to the sustainable development of urban logistics by evaluating the level of urban logistics from multiple dimensions.

Author Contributions: F.M. established the research framework; Z.Y. drafted the manuscript and contributed to the materials and analysis; Z.Y., S.Z., H.H., and Z.S. carried out the result calculations; F.M., Z.Y., S.Z., K.F.Y., Q.S., and P.L. revised the manuscript together. All authors have read and agreed to the published version of the manuscript.

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