



How Much Do Urban Terminal Delivery Paths Depend on Urban Roads – A Research Based on Bipartite Graph Network

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ABSTRACT

The structural deficiencies of the terminal delivery path often make it the main culprit of urban traffic congestion and environmental pollution. Traditional studies of express networks regarded them as an independent entity, ignoring the endogenous role of urban road network morphology and structure. To solve this problem, this paper explored the spatial dependency of terminal delivery routes in Xi'an City based on the idea of a bipartite graph network. A spatial dependency matrix of delivery paths–urban roads was constructed by abstracting delivery paths as node-set A and urban roads as node-set B. In addition, three spatial dependencies indexes, including degree centrality, betweenness centrality and closeness centrality were introduced to analyse the coupling features of these two objects. The results show that these dependency measures can reflect the coupling features of urban terminal delivery paths and urban roads. Firstly, degree centrality demonstrates terminal delivery path coverage and coupling hierarchy and scale-free nature. Secondly, betweenness centrality presents the road utilisation balance of terminal delivery paths. Thirdly, closeness centrality explains how easy it is for delivery paths to connect with others.

KEYWORDS

terminal delivery; delivery path; bipartite graph network; urban logistics; urban road; spatial network.

1. INTRODUCTION

Over the past decade, more and more consumers have preferred to shop online because of the convenience of delivery service and greater selection. The growth of e-commerce has not only led to the rapid development of the express industry but has also created problems for last-mile parcel delivery [1, 2]. The pressures on last-mile delivery can be summarised as follows: traffic congestion, higher logistics costs, greater pollution and lower efficiency [3, 4].

The problem of higher costs has been solved in some areas. Joint distribution has been accepted by express companies to share costs. Joint delivery alliances are established considering heterogeneous fleets and operations [5]. Some cost-sharing models have been developed according to the ratio of income distribution [1]. Cost reduction can also be achieved by optimising the logistics network. The Steiner tree and PNSMT algorithm have been used for logistics networks when the size of the logistics is large and the number of delivery nodes is not so large [6]. In practice, some intermediate pickup points are set up to offer two delivery options to customers. If customers pick up their parcels directly from intermediate pickup points, the total cost of delivery can be reduced [7]. As the demand for deliveries surges, traditional vehicle types and capacities cannot meet the rapid response of e-commerce customers. Electric vehicles and drones have been developed to solve this problem. The rapid development of drones shows that large-scale last-mile delivery is becoming more advanced. The use of drones can significantly reduce labour costs. Online companies and express delivery services have already developed many technologies and conducted research on the potential applications [8]. In addition, centralised micro depositories and parcel lockers also provide a solution for last-mile delivery [2, 9], and these facilities are set up to be shared by customers in their vicinity [10].

Efficiency is as important as cost reduction in terms of last-mile delivery [3]. Similar methods can be used for these two purposes, such as delivery mode. The mode to simplify the process is established by considering resource integration and redistribution. Furthermore, the method that uses a single delivery mode is replaced by

a two-stage delivery model, which reduces the total operation time by more than 20% [11]. When the delivery address and time window are changed, both the delivery cost and efficiency can be optimised by an interference management model [12]. When vehicle capacity is much smaller than the demand, and a distribution station delivers to many customers door to door, a model must be created to optimise the shortest path of each delivery vehicle [13]. On the other hand, when the delivery demand is smaller than vehicle capacity, combining order shipments is preferred to improve delivery efficiency [14, 15]. Moreover, a combination of home delivery and customer pickup has been developed to make the delivery system more effective and economical [16]. This combination can also be used in first-mile pickup and last-mile delivery [17]. Finally, the location of the transfer station also plays a role in overall efficiency [18].

Minimising pollution is of great importance for the sustainable development of society. Therefore, more and more urban infrastructures are built in favour of pedestrians, cyclists and public transport [19]. Delivery services also contribute to the reduction of exhaust emissions, especially bicycle-based crowdsourced fleets, which have a significant competitive advantage over traditional fleets with cars [20, 21]. The balance between delivery time and reduced emissions has been explored, and results show that most female consumers choose environmentally friendly delivery options [4, 22]. Simultaneously, electric vehicles contribute greatly to the environment thanks to cleaner energy [23]. As a result, combining multiple delivery fleets is a reason to focus on them to minimise emissions.

In general, the emerging discussion about last-mile delivery has mainly concerned the methods to solve these problems. According to research, the structural defects of delivery networks contribute to these problems. Indeed, the road network plays a role in the delivery network, affecting delivery efficiency, cost and the environment. As we all know, the urban terminal delivery system relies on urban roads and has to share space resources with other modes operating on urban roads. The shape, structure and extent of the urban road network directly determine the design and development of the delivery network. What is the maximum capacity of an urban road to accommodate delivery paths? Has the current spatial layout of delivery reached or exceeded the threshold for dependence on urban roads? Is the spatial distribution of delivery paths highly dependent on a few urban roads or evenly distributed? Is the space relied on by the delivery path the core space of the city? The answers to these questions can provide new visions to solve the above problems. However, current research has not paid attention to the capacities of and dependency on urban roads. If urban roads carry too many delivery paths, it is hard for route planning to improve efficiency and cut down the cost eventually without taking road capacity into consideration. To date, little is known concerning the impact of network development on delivery operations.

To fill this gap, the main purpose of this paper is to identify delivery path dependency on urban roads. For this purpose, the coupling network between the urban terminal delivery paths and the urban roads must be established. The primitive approach to constructing a network usually regards delivery outlets as nodes and abstracts the delivery routes between outlets as edges, which can then be used to study the topological connectivity of distribution networks. So, the delivery network is regarded as an independent network, neglecting the endogenous role of urban road network. Actually, the spatial dependence network between delivery paths and urban roads is a binary network. Therefore, a bipartite graph network is suitable for constructing the dependence network. Furthermore, coupling characteristics can be presented according to the characteristics of the coupling network. The bipartite graph network model is used to construct the network. There, statistical network parameters are used to describe and analyse the coupling features, namely degree centrality to explain the coverage of the delivery path, betweenness centrality to describe the balance of road use and closeness centrality to show network connectivity of the terminal delivery across the road.

We have organised the remainder of the paper as follows. Related studies are presented in Section 2. Both the data and method used to establish the bipartite graph network are covered in Section 3. Results are given in Section 4. Section 5 contains the discussion and conclusion.

2. RELATED STUDIES

Research on the express network focuses mainly on the structure and deployment of the backbone network. With the expansion of the service scope of express companies, the structure of the express network has a great impact on delivery service and cost. Since the distribution centres in each city are interconnected and form the backbone of the whole network, the hub-and-spoke structure is accepted as the main structural model for

network construction and resource allocation optimisation [24, 25]. In vast regions, the multi-hub network was researched for package transportation. Instances provided by FedEx Express Europe showed the efficiency of the hub assignment model [26]. From the perspective of coverage, the closeness of express network connection decreases from the provincial level to the county level. Also, the self-organisation mechanism of the network leads to the complexity of the express logistics network [27]. The main models used to optimise the network include SNA (social network analysis), QAP, rank-size analysis and GIS (geographic information system), as summarised in *Table 1*.

Table 1 – Related studies on express network

Reference No.	Main/Terminal network	Issues	Model
[28]	Main	Spatial layout	SNA/Rank-size analysis
[29]	Main	Express network structure and connection	Near analysis
[30]	Main	Express network structure	QAP/GIS spatial analysis
[31]	Main	Express network structure	SNA and GIS
[27]	Main	Express network connection density	QAP
[25]	Main	Express network structure	Hub-and-spoke
[32]	Main	Express network structure	SNA/GIS
[33]	Main	Express network structure	/
[17]	Terminal	First-mile pickup and last-mile delivery operations	Numerical experiments and regression analysis
[34]	Terminal	Reuse old kiosks as parcel lockers	Travelling salesperson problem
[35]	Terminal	Shared micro-depots network	Case study and location planning optimisation
[36]	Terminal	Last-mile delivery network	The two-stage stochastic program, branch-and-price (BP) algorithm
[37]	Terminal	Vehicles quantity for last-mile delivery	Two-stage stochastic program
[38]	Terminal	Crowdsourcing logistics	/
[39]	Terminal	Strategic distribution network design	Metamodel simulation-based optimisation
[40]	Main and terminal	Parcel transportation planning	/
[41]	Main	Vehicle routing planning with time windows	Branch-and-price algorithm
[42]	Main	Route optimisation	The fuzzy linear programming model
[43]	Terminal	Delivery route optimisation in a smart urban environment	NP-hard and greedy algorithm

Some research dealing with the express network concentrates on its vulnerability and stability. Unexpected attack events or emergencies tend to give rise to the removal of network outlets or delivery paths. So, express network robustness analysis and optimisation methods are of great importance to express network operations and service levels of express companies. The robustness of air and land delivery networks was studied under node city removal and random delivery route removal considering the geographical characteristics of city nodes in the express network and parcel delivery [44]. The topology of the distribution network was described by obtaining the nationwide distribution network and the route data of a courier company; an importance evaluation matrix was constructed to determine the important nodes in the distribution network, and the robustness of the distribution network was presented by using them as test indicators [45]. Likewise, the topology of an urban courier network was studied. In this network, the topology of the urban courier network was defined by the complex network theory, and the importance of the network nodes was determined by using the importance evaluation matrix. Also, the concept of network structure entropy was combined with the simulation study of the urban courier network for resistance to destruction [46]. Later, network connectivity, global network efficiency and local network efficiency were looked at as the main indicators of the network

vulnerability assessment model, and the importance of network nodes was confirmed by using the importance evaluation model, and the node hierarchy was divided as the basis for targeted attacks; the network data of a private courier company is used as an example to verify the effectiveness of the model [47]. The topological characteristics and vulnerability of China's express network based on complex network theory were analysed. The topological characteristics of an express network were researched, and the results showed that the network was scale-free and had the property of a small world [48]. The change in network structure and total cost after the failure of a hub were studied, the change of hub node express processing volume after hub node failure was presented, and the impacts on adjacent hubs and paths were analysed [49].

A direct solution to address last-mile delivery pressures is vehicle routing planning or routing mode and organisation innovation. A dynamic vehicle method for home delivery and customer pickup was proposed [15]. A generalised variable neighbourhood search heuristic was implemented to study the traveling salesman problem with last-mile delivery time windows in online shopping [10]. A variant of the clustered traveling salesman problem with time windows was researched. Then, a two-stage model for package delivery was offered that includes walking and driving for a single driver. This model was applied in an actual vehicle round for a parcel delivery company in London and cut down the delivery time by more than 20% [11]. To increase the percentage of successful deliveries and minimise the delivery cost, a multi-objective multi-depot station vehicle path planning problem was put up, and a mixed integer programming model was established to solve the problem [50]. In terms of successful delivery rate in multi-depot e-commerce and minimising delayed delivery time, vehicle fuel consumption was taken into consideration. A heuristic initialisation method with a greedy search strategy was used [51]. Recently, a new model for joint delivery of trucks and drones was introduced, vehicle routing, in this case, was researched, and a mixed integer planning model with time windows was also established to minimise the total cost of delivery [8, 52]. In conclusion, vehicle routing is helpful to reduce delivery costs, fuel consumption and operation cost.

Lastly, most delivery paths do not have other modes and have to depend on urban roads. Therefore, the structure and level of urban roads play roles in delivery path distribution. In terms of the relationship between delivery paths and urban roads, the current research discussed the impact of road characteristics such as the longitudinal slope on delivery paths [53]. Few types of research covered spatial characteristics, and the theory of path dependency was used for public transport services [54]. For city logistics, most researchers made efforts to plan routes in road networks, and delivery path dependency on roads was unclear.

3. MATERIALS AND METHODS

According to the research objective, we need to prepare the delivery paths and urban roads data, and then process these data for constructing the adjacency matrix by the principle of a bipartite graph network. All the data analysis is conducted by Python coding. The methodological framework is developed as shown in *Figure 1*.

3.1 Data source

Due to data acquisition feasibility, major courier networks in Xi'an City were selected for the study. Firstly, according to the data published by the State Post Bureau in 2021, the leading courier company SF Express continues to have a higher growth rate than the industry as a whole in terms of courier business volume and network distribution density. Secondly, YUNDA Express has a large volume of network data, and its growth rate of express business volume in 2021 significantly outperformed the average growth rate of the industry. Thirdly, YTO Express shows good potential in terms of scale layout and service quality and continues to rise in the timing ranking of the Cainiao index, with a market share of 15.1% in the first half of 2021. YTO's business volume grows by 50.14% year-on-year, with a growth rate higher than the average of domestic courier companies. Therefore, these three courier enterprises with good operational performance are taken as the research cases. The names and addresses of transfer and terminal delivery outlets were obtained from the YUNDA Express official network, the SF Express mini-program and the surveys on YTO Express Company.

3.2 Data processing

The originally collected data has been standardised to ensure integrity, authenticity and accuracy. After compilation, there are 26 transit stations and 563 terminal delivery points of YUNDA Express, and YTO Express has 48 transit stations and 502 terminal delivery points. As for SF Express, according to the delivery

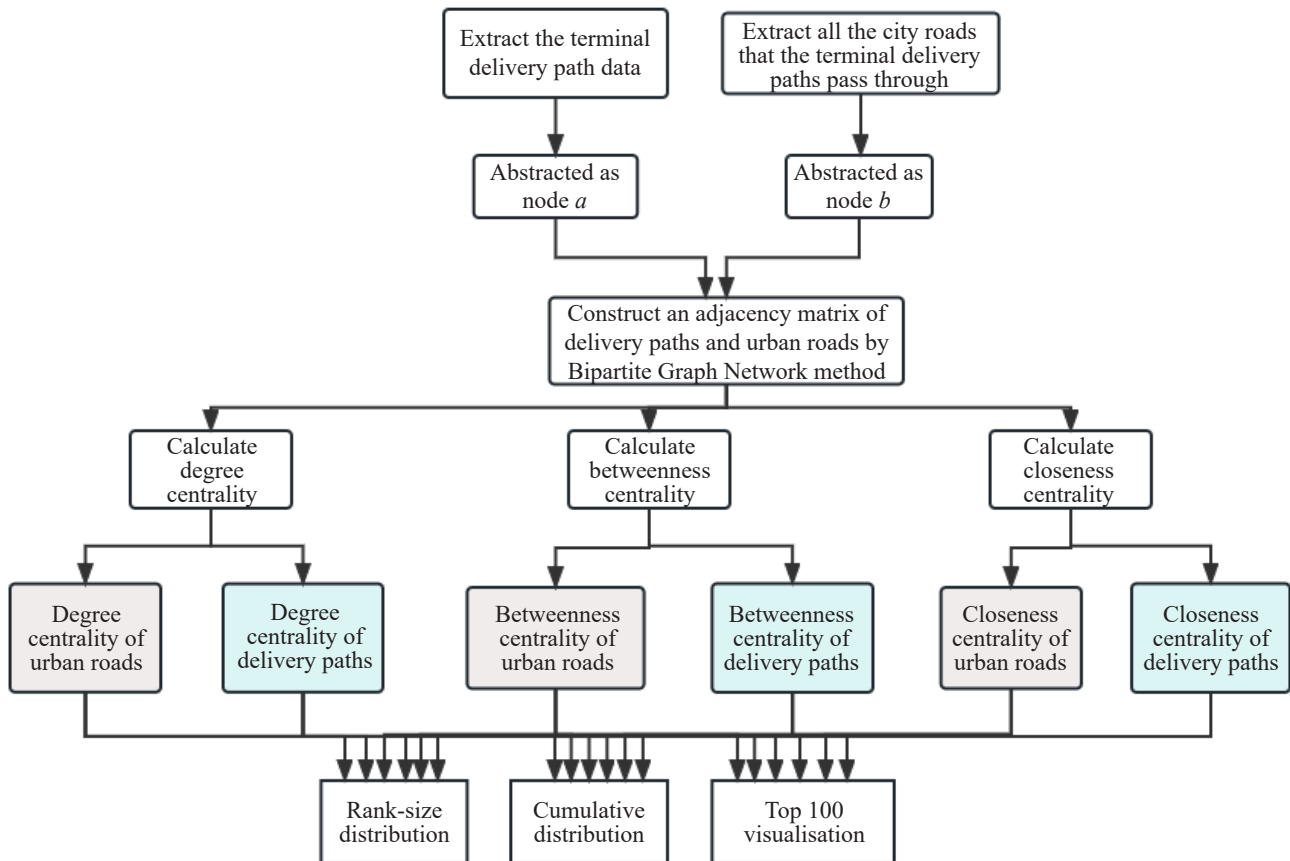


Figure 1 – Methodological framework

process of this company, goods arrive at the Northwest Distribution Centre and then are distributed to transfer stations in Xi’an, so that point-to-point delivery is made from the transfer station to each individual customer. Since the number of end customers is not easy to count, the end customers have been grouped and classified according to the 1 km range of cooperative retail stores or Feng Chao stores, and finally, 121 SF Express transit stations in Xi’an have been identified, and 1,883 terminal delivery points including downstream cooperative retail stores and Feng Chao stores have been identified. So, there are a total of 195 transit stations and 2,948 terminal delivery points.

3.3 Method

There are generally three main ways to model urban terminal delivery networks using complex network theory: route space, node space and node transit space. A bipartite graph is a special model in graph theory that is often used to define the topology of complex networks. A bipartite graph contains two types of nodes with different properties and disjoint, where one node represents an event or activity, and the other node represents the participants of these events or activities. These two nodes follow a certain coupling principle to form a bipartite graph, i.e. different types of nodes are connected to each other, whereas the same types of nodes are not adjacent to each other, resulting in a connected edge containing both types of nodes.

When we use bipartite graphs to model the node and line spaces of the logistics network, the bipartite graphs can be constructed based on node and line information. We can construct the underlying unweighted matrix, and then load the weights to obtain the node and line spaces. It is assumed that the unweighted adjacency matrix A_{ij}^L is obtained. A_{ij}^L can be described by Equation 1.

$$A_{ij}^L = \begin{cases} 1, & \text{there is a direct line between node } i \text{ and } j \\ 0, & \text{there is no direct line between node } i \text{ and } j \end{cases} \quad (1)$$

Degree centrality (DC) is the most important indicator for measuring the position of a node in the network. In network analysis, centrality is often used to determine the importance or influence of nodes in a network. The simplest measure is degree centrality, which means that the higher the degree of a node, the more important

that node is. The assumption behind this metric is that an important node is one that has many links. Degree centrality can be described by Equation 2. If it is necessary to compare the importance of nodes in different networks, a normalisation of the value of degree centrality can be implemented as Equation 3.

$$C_D(v_i) = d_i = \sum_j A_{ij} \tag{2}$$

$$C_D'(v_i) = \frac{d_i}{N-1} \tag{3}$$

where N means the total number of nodes in the network that node v_i belongs to.

The second indicator is betweenness centrality (BC). In the constructed bipartite graph network of express terminal delivery paths and urban roads, the degree centrality of node a_i (terminal delivery paths) characterises the number of connected urban road nodes, while the degree centrality of node s_j (urban roads) characterises the number of terminal delivery paths connected to them. It can be seen that the greater the degree centrality of the delivery route, the greater the number of urban roads through which the route passes, while the greater the degree centrality of an urban road, the greater the number of end-delivery paths through which it passes. The cumulative degree distribution function (CDF) or degree distribution function (DF) of a node is usually used to represent the properties of the degree distribution. Since the cumulative distribution function is the integral of the probability density function, which can fully represent the probability distribution of random variables, this paper uses the CDF metric to analyse the degree distribution patterns of dispatch routes and urban roads in urban end-delivery networks.

Betweenness centrality characterises the proportion of nodes in the shortest paths, described as Equation 4. The larger the centrality, the greater the number of shortest paths generated through the point, and thus the index can describe the influence of the point in the network. If an urban road is one of the nodes located between a certain pair of delivery paths (n in total), the betweenness centrality of that urban road node increases by $1/n$ units. This metric reflects the connectivity relationship between delivery paths. Similarly, the betweenness centrality of the delivery path node a_i can characterise the connectivity of urban roads. The larger the betweenness centrality, the more important the urban road space through which the delivery path passes. The calculation of BC can be shown by Equation 4.

$$BC_i = \sum_{v_s \neq v_i \neq v_t, s < t} \frac{\sigma_{st}(v_i)}{\sigma_{st}} \tag{4}$$

where σ_{st} means the total number of the shortest path from node s to node t ; $\sigma_{st}(v_i)$ means the number of this shortest path that passes through the node v_i .

Thirdly, closeness centrality reflects the ease of interconnection of nodes by calculating the inverse of the average distance from the node to other nodes and is a key indicator of the accessibility of nodes in the network. In the delivery path and urban road bipartite graph network, since the delivery paths and urban road nodes are interconnected, closeness centrality can measure the ease of connecting the delivery paths with urban roads. Let the average shortest distance of a node be d_i (as shown in Equation 5), then closeness centrality can be expressed by Equation 6. The smaller d_i is, the closer the node is to other nodes.

$$d_i = \frac{1}{n-1} \sum_{j \neq i} d_{ij} \tag{5}$$

$$CC_i = \frac{1}{d_i} \frac{n-1}{\sum_{j \neq i} d_{ij}} \tag{6}$$

4. RESULTS

4.1 Coupling network

In this paper, we construct the spatial adjacency matrix of the urban terminal delivery network and the urban road network based on the bipartite graph network. The adjacency method is applied as follows: the urban roads through which the terminal delivery paths in Xi'an City are abstracted as nodes s , and the set $S(s_1, s_2, \dots, s_n)$ of the urban road network is obtained. The 0-1 adjacency matrix of terminal delivery paths and

urban roads is constructed by abstracting all terminal delivery paths of Xi'an SF Express, YUNDA Express and YTO Express as nodes $A(a_1, a_2, \dots, a_m)$.

The specific operation includes three steps. In step one, the road network data of Xi'an City is downloaded from OSM (OpenStreetMap), and the data of the link whose road name is empty is deleted. The geodata frame array of road data is constructed, and an array file of 25873×5 is obtained to draw the road network structure as shown in *Figure 1*. According to the design idea of the paper, a road can only be a record, so the road data are fused and reindexed according to "name" to obtain 1,586 groups of road data. Step two is to get the delivery path OD data. First we construct the delivery path of OD data based on the above delivery relationship, and, based on this, we obtain the latitude and longitude geographic location information of the starting and ending points of the delivery path. Finally, $2,925 \times 5$ sets of delivery paths are obtained and added to the road network, as shown in *Figure 2*.

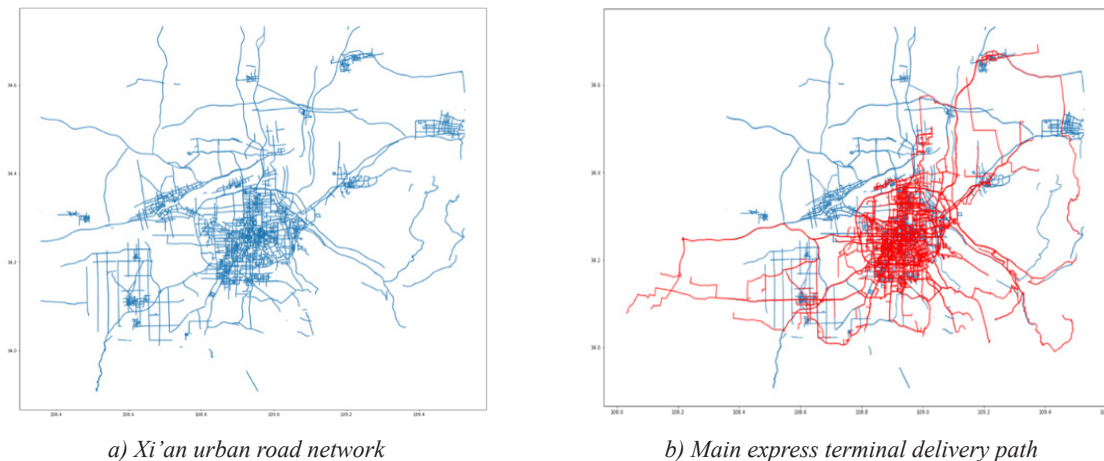


Figure 2 – Spatial relationship between roads and express terminal delivery paths in Xi'an City

In step three, the delivery path is matched with the urban road, and the adjacency matrix is constructed. In the construction of the 0-1 adjacency matrix, a delivery path is considered to be connected to an urban road if it passes through that road, and is given the value of 1, while the opposite is given the value of 0. Therefore, it is preferred to determine whether the delivery path passes through a road beforehand. Since both objects are lines, they cannot be judged directly by the point-space connection, and there is no prefabricated tool, the delivery path is processed technically here, i.e. points are generated on the line at a certain distance, and then the points are matched with the road according to a certain threshold. If the urban road is matched with more than one point, it may indicate that the delivery path passes through that road. The spacing is set at 10 metres. If the spacing is too small, not only will the computation time increase, but other roads at the intersection will be considered, resulting in inaccurate results. If the spacing is too large, it will cause some delivery paths which cannot match the road. Then, the threshold for matching delivery paths and urban roads is set to 10 metres in the paper. So, 187,031 points have been obtained after processing the delivery path point distance, and 126,947 points remain after selecting the distance within 10 metres from the road. Finally, we select the data with intersections greater than 1 and finally obtain the adjacency matrix between delivery paths and urban roads with 9,616 edges. The structure of the bipartite graph network is tested using the data analysis method in Python.

4.2 Coverage of terminal delivery path based on degree centrality

According to the calculation with Python, the average degree of urban roads in Xi'an is 13.36, and the node name with the highest node degree is the Science and Technology Road (106), which means there are 106 delivery paths through this road, and the degree decreases in the order of North Zhangba Road (104), West Section of South Second Ring Road (101), South TaiBai Road (98) etc. The node degrees of urban roads in Xi'an are plotted in the rank-size distribution (as shown in *Figure 3a*), which shows the "long tail" characteristic indicating that only a few urban roads have high degrees, while most of the remaining nodes have small degree values and are close to each other, reflecting the coupling of terminal delivery paths and urban roads. This explains the hierarchical and scale-free nature of the coupling between terminal delivery paths and urban

roads. In the field of spatial geography, the negative exponential function proposed by Clark (1951) can be said to be the classic model for empirical studies of urban space. The fitting function in this paper verifies this negative exponential function ($y=ae^{-bx}$), and the fitting index (R^2) of the node degree rank-size distribution of urban roads is 0.9736, which is a very high fit. To improve the differentiation of the view, 30 node degree values were selected for plotting and fitting, and the curve fitting index (R^2) of the cumulative distribution of node degrees of urban roads was 0.9581, as shown in *Figure 3b*.

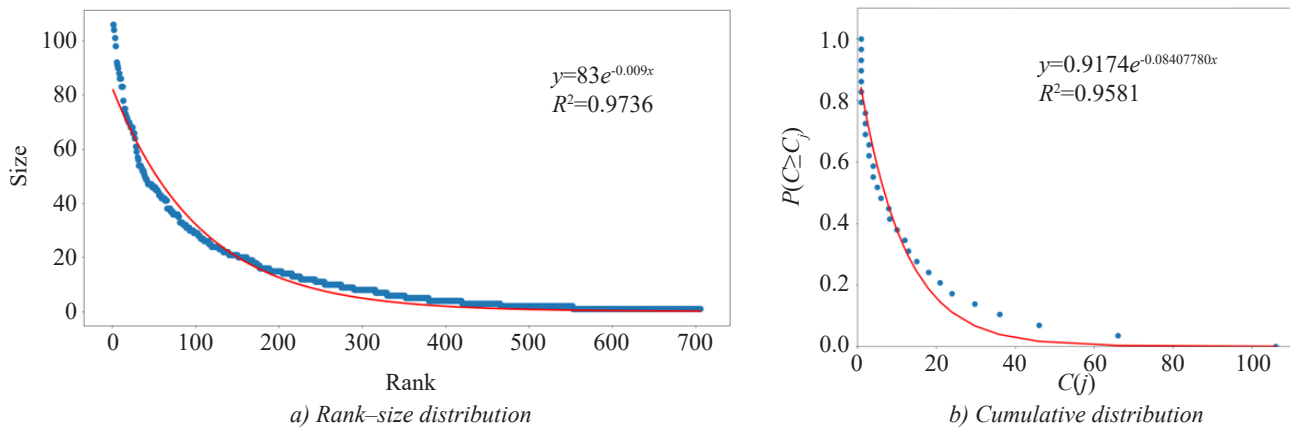


Figure 3 – Degree centrality of urban road

As for the delivery paths, the average degree of centrality is 3.455. The highest value is the degree centrality of delivery path No. 2294 at 16, which has to pass through 16 urban roads. The following degree centrality value is 14 for delivery path No. 2607 and No. 2299 and 13 for delivery path No. 2604. These delivery paths are located in the suburban areas of Xi'an City, which shows that the distribution of deliveries in these areas is not very dense. The rank-size distribution curve can reflect that a few delivery paths are too sparse due to the distribution of outlets, which leads to the extension of the delivery path. Statistically, the number of delivery paths with degree centrality lower than 3 is 1,085, accounting for 38.99% of the total number. It means that in these areas, the distribution of outlets is relatively dense, and these delivery paths pass through fewer urban roads and are responsible for a relatively small delivery area. However, the proportion of delivery paths passing through more than three urban roads is more than 60%, indicating that a large proportion of outlets cover a larger delivery area, which will contribute to low delivery efficiency and higher requirements for delivery path planning. The fit index (R^2) of the node degree rank-size distribution of the delivery path is 0.9040, which is a high fit. To improve the differentiation of the view, 30 degree-centrality values are selected for plotting and fitting, and the curve fitting index (R^2) of the cumulative distribution of the delivery path is 0.9569, as shown in *Figure 4*.

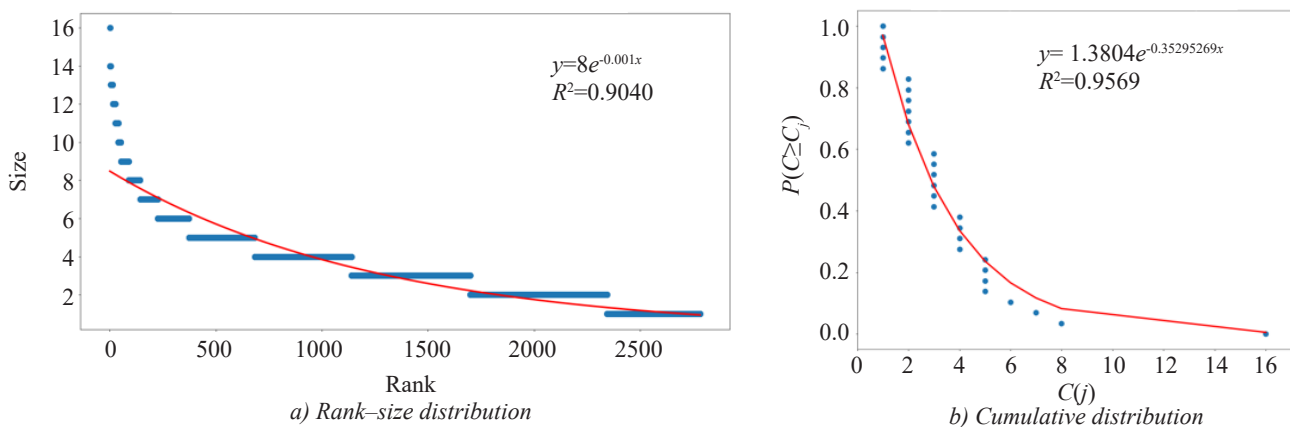


Figure 4 – Degree centrality of delivery path

The urban roads and delivery paths with top 100 degree centrality have been plotted to show the dependence of the delivery path on the road, and the values have been classified using the natural breaks method, as shown in *Figure 5*.

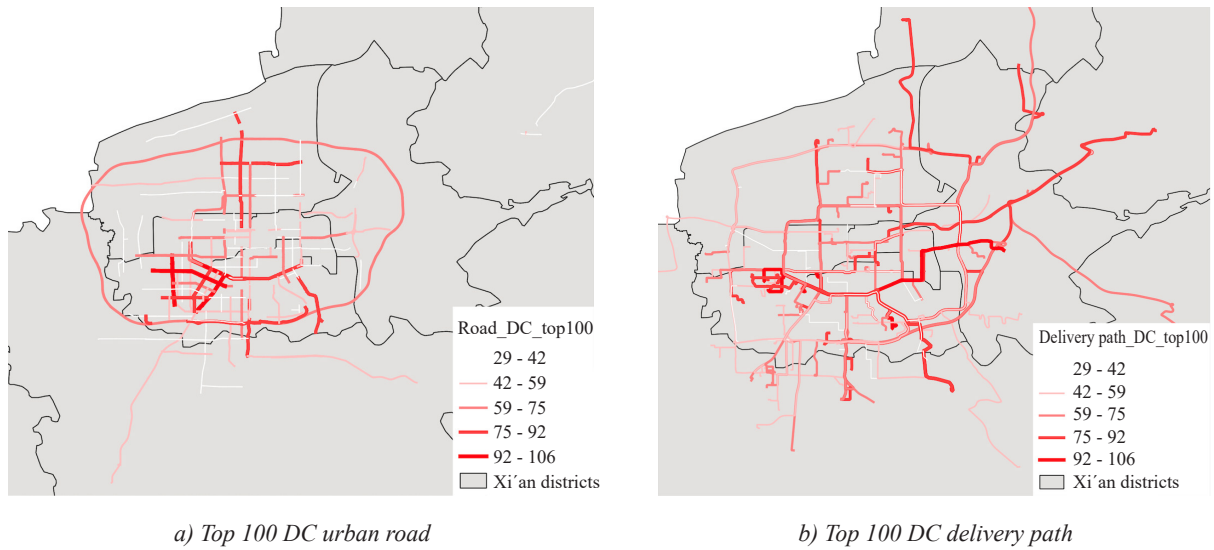


Figure 5 – Urban roads and delivery paths with top 100 DC

4.3 Road utilisation balance of urban road based on betweenness centrality

For the bipartite graph network constructed, the mean value of the betweenness centrality of urban roads is 0.003447, and the number of urban roads with betweenness centrality greater than 0.02 is 30 according to the statistic result in Python. This means that the dependence on these roads is relatively high. The urban roads with high betweenness centrality values mainly include Gao Xin Road, South Second Ring Road, Feng Cheng 8th Road, Chang’an South Road, Zhu Hong Road, Science and Technology Road etc. These urban roads are used frequently in the whole delivery network and tend to get congested. In addition, there are 721 urban roads with a betweenness centrality of 0, which indicates that the delivery paths use roads in a more concentrated way, and the spatial structure utilisation is unbalanced. The fitting index (R^2) of the centrality rank-size distribution of urban roads is 0.9704, which is a good fit. To improve the distinction of the view, 30 betweenness centrality values have been selected and fitted, and the fitting index (R^2) of the cumulative distribution curve of centrality values of urban roads is 0.8613, as shown in Figure 6.

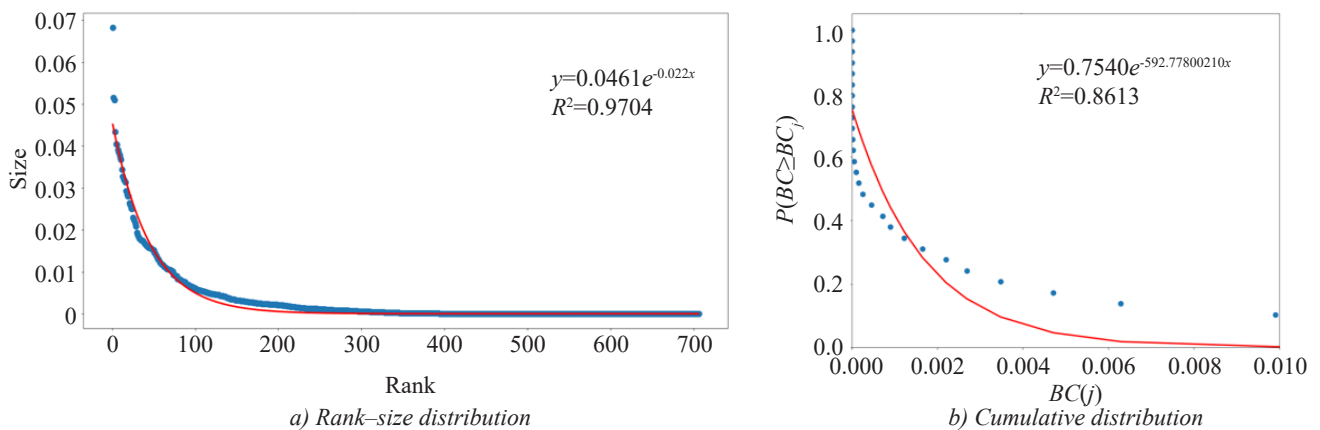


Figure 6 – Betweenness centrality of urban road

On the other hand, the mean value of the betweenness centrality of the delivery path is 0.000663. There are only 2 nodes with betweenness centrality greater than 0.02, 2,761 paths with a betweenness centrality value lower than 0.01, and 439 paths with a betweenness centrality value of 0. This indicates that most of the delivery paths play only a minor role in the implied spatial connectivity of urban roads. The fit index (R^2) of the rank-scale distribution for delivery paths is 0.9143, which is a good fit. To improve differentiation of the view, 30 betweenness centrality values have been selected and plotted, and the curve fitting index (R^2) of the cumulative distribution is 0.9652, as shown in Figure 7.

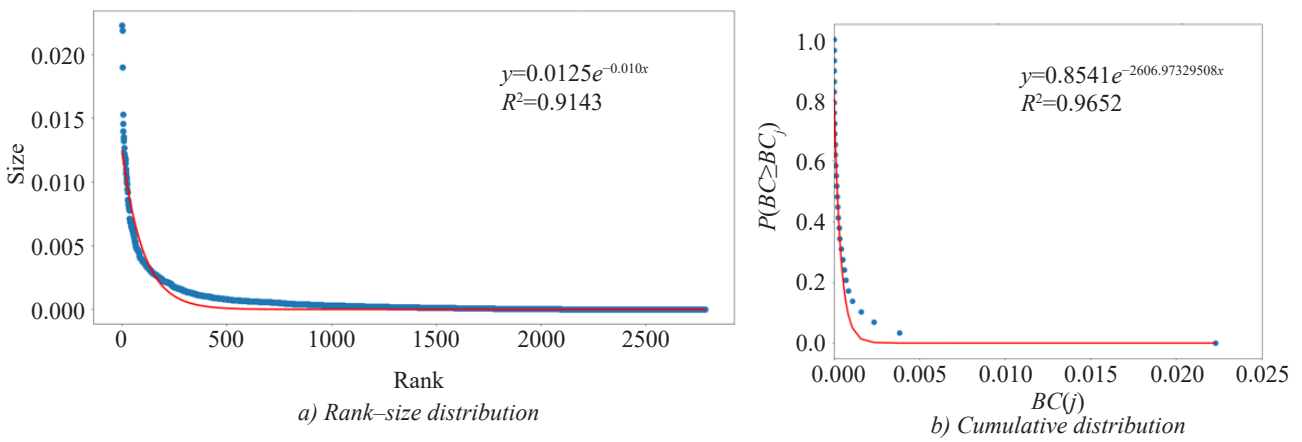


Figure 7 – Betweenness centrality of delivery path

The urban roads and delivery paths with top 100 betweenness centrality have been plotted to show the road utilisation balance, and the values have been classified using the natural breaks method, as shown in Figure 8.

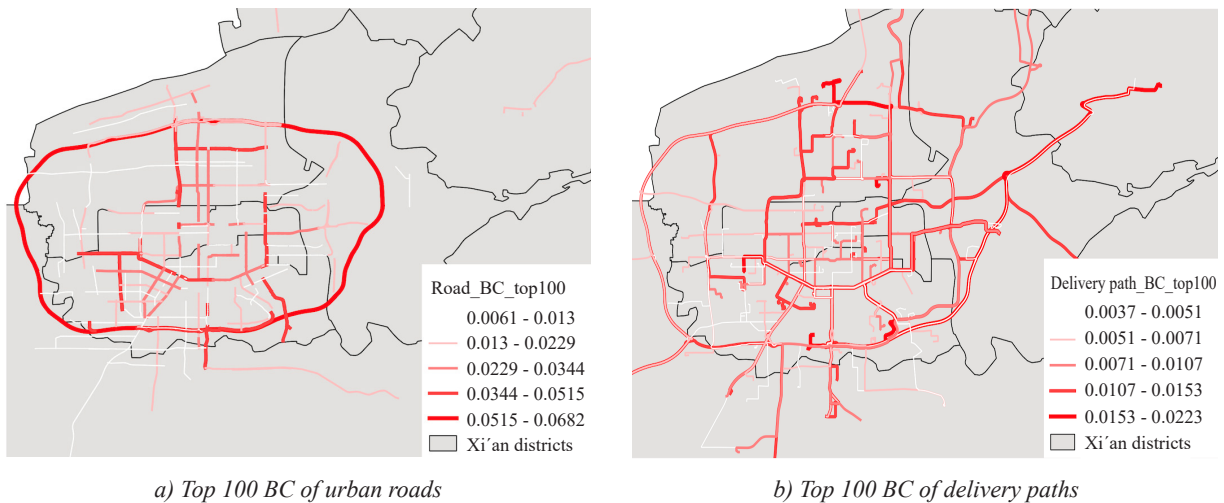


Figure 8 – Urban roads and delivery paths with top 100 BC

4.4 Network connectivity of terminal delivery path based on closeness centrality

For the bipartite graph network constructed, the average closeness centrality of urban roads is 0.2293. The urban roads with higher closeness centrality are South Second Ring Road West (0.327016), Southern Second Ring Road (0.326149), Southern Second Ring Road East (0.318253), Kunming Road (0.312589), Southern Taibai Road (0.303424) and Chang ‘an South Road (0.300501). Overall, the distribution of closeness centrality is relatively balanced, with most scattered around the average. The number of urban roads with high or low closeness centrality is small. There are 346 urban roads with closeness centrality greater than 0.4, 193 urban roads with closeness centrality values lower than 0.2, and 2951 urban roads with closeness centrality between 0.2 and 0.4. The fit index (R^2) of the urban road closeness rank-size distribution is 0.9542. To improve the differentiation of the view, 30 values have been selected for plotting and fitting, and the curve fit index (R^2) of the cumulative distribution is 0.8724, as shown in Figure 9.

As for the delivery path, its average closeness centrality is 0.350341, the minimum value is 0.208564, and the maximum value is 0.461826. There are 334 delivery paths with closeness centrality greater than 0.4 and 26 delivery paths with closeness centrality lower than 0.25. Most delivery paths pass through a close number of urban roads, which seems to be relatively balanced. However, it can be seen that the proportion of delivery paths passing through more than 3 urban roads is more than 60%, which means that the number of urban roads passing through is higher. The fit index of the ranking-scale distribution is 0.9457, which is a good fit. To improve the view differentiation, 30 closeness centralities have been selected for plotting and fitting, and the fitting index of cumulative distribution is 0.8582, which means a high fitting degree, as shown in Figure 10.

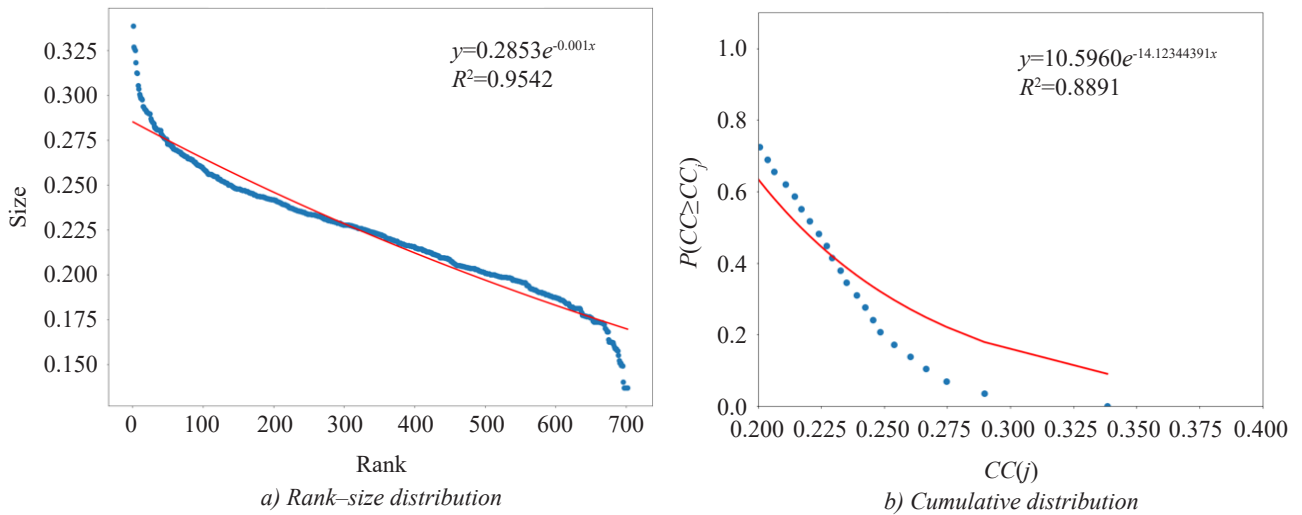


Figure 9 – Closeness centrality of urban road

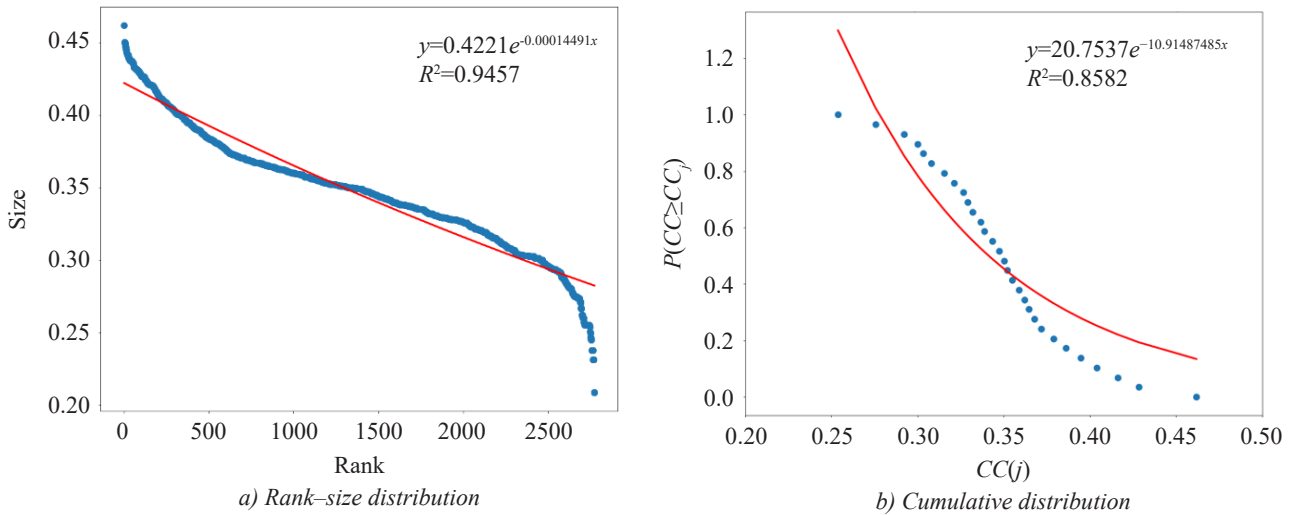


Figure 10 – Closeness centrality of delivery path

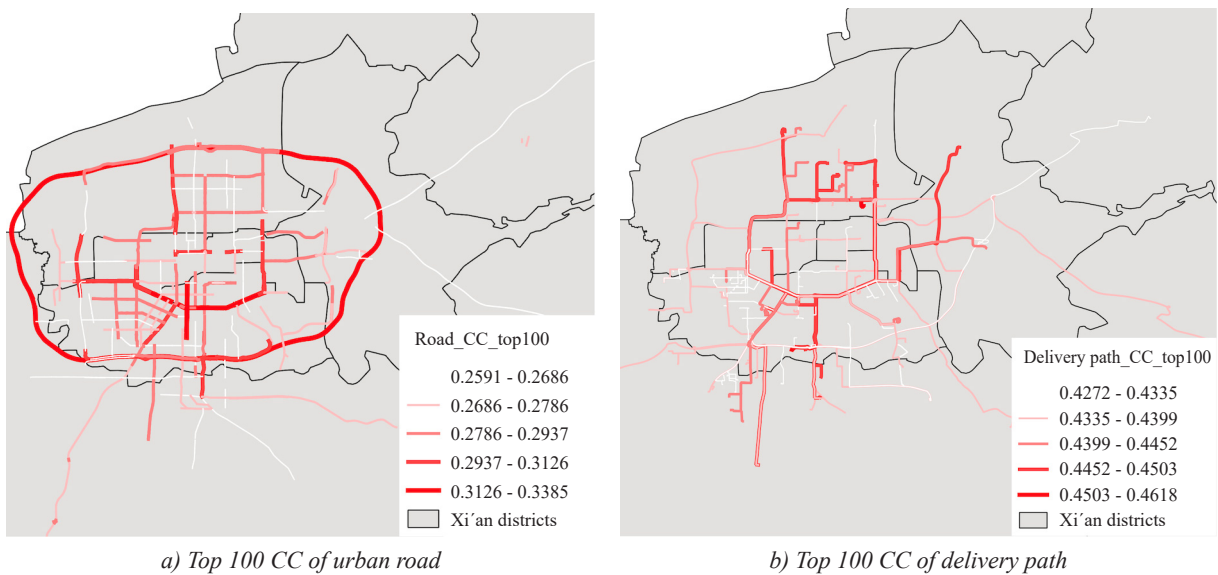


Figure 11 – Urban roads and delivery paths with top 100 CC

The urban roads and delivery paths with top 100 closeness centrality have been plotted to show network connectivity of terminal delivery paths, and the values have been classified using the natural breaks method, as shown in *Figure 11*.

5. DISCUSSION

The bipartite graph network provides a new perspective for studying the spatial layout of delivery routes, as well as coupling features of delivery paths and urban roads. When urban roads are selected as the route arrangement, the status of the spatial correlation and spatial dependence of delivery paths and urban roads is presented.

Firstly, the degree centrality of terminal delivery paths characterises the number of urban roads connected to them, while the degree centrality of urban roads characterises the number of terminal delivery paths connected to them. It can be seen that the greater the degree centrality of the delivery path, the greater the number of urban roads through which the route passes, while the greater the degree centrality of an urban road, the greater the number of terminal delivery paths through which it passes. According to the rank-size diagram, the “long tail” feature indicates that only a few urban roads have a high degree of centrality, while most of the other roads have a low degree of centrality and are close to each other. This implies a hierarchical and scale-free coupling of terminal delivery paths and urban roads. Those roads with a high degree of centrality can be identified as important roads. While the proportion of delivery paths passing through more than 3 urban roads exceeds 60%, it shows that a large proportion of delivery outlets cover a large area, which will lead to low delivery efficiency. In order to quickly respond to customer needs, the express company should evaluate these delivery paths or the layout of the terminal points.

Secondly, the mean value of the betweenness centrality of urban roads is 0.003447, and the number of urban roads with betweenness centrality greater than 0.02 is 30. It indicates that the dependence on these roads is relatively high. This finding can be combined with the above one to do more analysis on these key roads. On the other hand, the mean value of the betweenness centrality of delivery paths is 0.000663. The number of paths with betweenness centrality values greater than 0.02 is only 2, the number of paths with betweenness centrality lower than 0.01 is 2,761, and the number of nodes with betweenness centrality equal to 0 is 439, indicating that most delivery paths play little role in the implicit spatial connectivity of urban roads.

Thirdly, the closeness centrality distribution of urban roads is relatively balanced, and most of them are scattered near the average. Only a minority of roads have high or low closeness centrality. Roads with high closeness centrality play important roles in the delivery service. They can also be identified as the key roads. At the same time, most of the delivery paths pass through a close number of urban roads, which seems to be relatively balanced. However, more than 60% of delivery paths need to pass through at least 3 urban roads to connect with another path, which means that the connection of delivery paths with each other is not very easy, and the closeness of delivery paths is not high. There is potential to develop more delivery paths.

6. CONCLUSION

The findings provide a novel insight into rechecking the relationship between delivery paths and urban roads. The urban roads can be seen as the supply, and the usage degree and their importance can be obtained from the above results. Urban roads are not evenly used. The case that some roads are less used is related to the layout of delivery networks. There is some potential for these roads to be more depended on. They are also meaningful in terms of the awareness of the impact on society, the economy and the environment. On the other hand, it is easier to early recognise urban roads that play important roles in connectivity. These roads need more attention and improvement, such as lane expansion or extension to more feeder roads. Some congestion problems might be predicted earlier according to the carry of these roads. As for the express companies, the results help them to analyse those delivery paths that go across more urban roads and why they cover such a large delivery area. Furthermore, does this result in lower efficiency? Is it necessary to reassign the subordinate relationship between transfer stations and terminal outlets?

The degree of spatial dependence of delivery paths studied in this paper belongs to static states identified at a particular point in time. Since any physical network is a dynamic and evolving network, it is necessary to introduce time series and study the spatial dependence of delivery routes by constructing the data on the temporal evolution of courier delivery routes and urban roads to determine whether the spatial arrangement

of delivery routes follows the law of “the better the worse”, or whether the spatial dependence of the delivery network has evolved to a balanced trend over time.

In conclusion, degree centrality can reflect road utilisation rate and delivery outlets layout. As for heavy roads, their transportation level should be improved. For other roads, managers should explore the reason why those roads are less used. The degree centrality of delivery path shows the delivery distance and outlets distribution. This can be referred to as the parameter of delivery path distribution planning. At the same time, betweenness centrality can also be used to recognise the key roads and key delivery paths. Lastly, closeness centrality indicates the connection of urban roads and delivery paths. The results help to analyse and improve the urban roads with low connection levels, such as by extension of feed lines to link with other roads.

In this paper, the degree of spatial dependence and the dependence space of courier delivery routes are determined based on bipartite graph networks. However, it does not answer how many delivery routes can be accommodated by urban roads in Xi’an and whether the current degree of spatial dependence of delivery routes in the city has reached the carrying capacity of urban roads. The capacity of urban roads to accommodate shipping routes depends on the slope of the road, the quality of the road surface, the number of lanes and the capacity of the road for other modes etc. It is a multidisciplinary and interdisciplinary field that deserves to be studied by researchers from different fields.

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贾果玲

城市末端派送路径对城市道路的依赖程度有多高——基于二分图网络的研究

摘要

末端派送路径的结构性缺陷往往使其成为城市交通拥堵和环境污染的罪魁祸首。传统的快递网络研究将其视为一个独立的实体，忽视了城市路网形态和结构的内生作用。为了解决这一问题，本文基于二分图网络的思想，探讨了西安市末端派送路径的空间依赖性。将派送路径抽象为节点集A，将城市道路抽象为节点集合B，构建了派送路径-城市道路的空间依赖矩阵。引入度中心性、介数中心性和紧密度中心性三个空间依赖指标，分析了这两个对象的耦合特征。结果表明，这些依赖性测度能够反映城市末端派送路径与城市道路的耦合特征。首先，度中心性展示了末端派送路径覆盖程度、耦合层次以及无标度性质。其次，介数中心性呈现了末端派送路径的道路利用均衡性。第三，紧密度中心性解释了派送路径之间联系的容易程度。

关键词：

末端派送；派送路径；二分图网络；城市物流；城市道路；空间网络