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Mining Spatial Correlation Patterns of the Urban Functional Areas in Urban Agglomeration: A Case Study of Four Typical Urban Agglomerations in China

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Abstract: Urban agglomeration is a higher stage of urban development. Exploring the spatial correlation of functional areas is important for promoting high-quality urban development. However, recently the research on urban functional areas is mainly focused on how to identify urban functional areas, and they lack some methods to analyze the spatial correlation patterns of urban functional areas. Therefore, firstly, this study uses POI data and a deep learning model to identify the urban functional areas of four typical urban agglomerations in China. Then, we create a new method to mine the spatial correlation patterns of urban functional areas from two levels (city and cities in one urban agglomeration). Moreover, we find that various graphs well express the spatial correlation patterns. Based on the above, we establish a new technical process for mining the spatial correlation of urban functional areas. The main conclusions are as follows: (1) The multilayer detailed division of the functional area is helpful to mine the spatial correlation pattern of the functional area. (2) The rank of each city in the urban agglomeration can be divided according to the urban functional area; there are great differences in richness and scale of the mixed-functional areas in the urban agglomeration, but there is little difference among the urban agglomerations. (3) The spatial correlation patterns of the functional areas in the first-rank cities of each urban agglomeration area are highly similar. (4) There is a certain spatial correlation pattern of functional areas in Chinese urban agglomerations. (5) There are great differences in the similarity of spatial correlation patterns between cities in one urban agglomeration, and the spatial relationship of similarity may not surround the most developed cities. This research will help urban planners to develop functional areas in different cities.

Keywords: urban function; spatial correlation pattern; urban agglomeration; point of interest

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1. Introduction

With the rapid development of urbanization in China during the past few decades, four typical urban agglomerations have emerged: the Beijing–Tianjin–Hebei, the Yangtze River Delta, the Pearl River Delta, and Chengdu–Chongqing [1,2]. These urban agglomerations have experienced the rapid aggregation of populations in the central cities and the rapid development of industries [3]. Moreover, the industries are radiating to the surrounding cities, which are more attractive to the larger populations in the surrounding cities, and even the whole country [4]. As big cities become more attractive to the population [5], they are faced with problems such as shortages of public services, such as education and medical service, traffic congestion, and deteriorating air quality [6,7]. As China enters a new era of high-quality urban development [8,9], these cities have put forward new ideas on the spatial optimization of urban functional areas, but the task of controlling "big city disease" is still difficult [10,11]. Therefore, it is urgent to understand the distribution of urban functional areas at the city level and the urban agglomeration level. Considering that the development of urban agglomerations is closely related, urban functional areas may generally have mutual influence in urban agglomerations, except in natural development. However, does a unique spatial correlation pattern exist in the process of the functional interaction for Chinese urban agglomerations? Exploring this problem is of great significance for scientifically formulating high-quality urban development strategies so as to promote the coordinated development of urban agglomerations.

Urban functional areas refer to the distribution space of various functions in a city, which play an important role in the rational formulation of urban development strategies [12]. In recent years, the Chinese government has required the establishment of a scientific urban planning system to rationally arrange the urban production space, living space, and ecological space, and to achieve high-quality urban development [13]. The scientific formulation of urban planning requires a fine analysis of the spatial layout of urban functional areas [14], so the relevant research on urban functional areas becomes more and more important.

In recent years, the main research on urban functional areas has been to use multisource big data to carry out the fine identification of urban functional areas. The data mainly include POI (point-of-interest), high-resolution remote sensing images, taxi tracks, OSM (open street map) road networks, etc. [15–17]. POI data is widely used among them [18]. Many researchers have developed methods to identify functional areas based on the data. At present, it can be divided into two categories: one is to identify urban functional areas by combining the POI data with high-resolution remote sensing images to make up for the deficiency of remote sensing images in the characterization of urban features [19]; the other is to improve the natural language processing model, such as Word2vec, to mine the semantic features and spatial distribution features of POIs so as to realize the recognition of urban functional areas [20,21]. Although these two methods have achieved a high accuracy, at present the identification and analysis of urban functional areas is mainly isolated to the central area [15,22,23] or blocks [24,25] of a single city. There are few comparative studies on the spatial correlation patterns of urban functional areas in urban agglomerations.

However, there is no technical framework suitable for mining the spatial correlation pattern of urban functional areas. This is mainly because the development of functional areas between different cities has significant regional characteristics [26]. The zoning characteristics of different functional types are different between cities, and therefore the area of all kinds of functional areas. In addition, there is no definite standard to measure the boundary of urban sprawl [27], and the roads on the edge of a city are mostly irregular [28]. Therefore, the specific scope of a functional area that should be identified is not clear, and the functional area is roughly divided at the edge of the identification scope. This is a challenge to the rational division of functional area units in urban fringes [29]. However, it is difficult to identify and evaluate the functional areas of the city center and reflect the overall characteristics of the functional areas of the whole city.

Considering the above situation, this article uses the POI data of four typical urban agglomerations (Beijing–Tianjin–Hebei, the Yangtze River Delta, the Pearl River Delta, and Chengdu–Chongqing) to identify the urban functional areas in the built-up area, and, on this basis, to try to use a new method to mine the spatial correlation patterns of urban functional areas in urban agglomerations. In this way, we provide a key reference for further promoting high-quality urban development.

2. Research Area, Data, and Method

2.1. Research Area

This study selected the Beijing–Tianjin–Hebei urban agglomeration (N 36.1°–42.6°, E 113.5°–119.85°), the Yangtze River Delta urban agglomeration (N 28.01°–34.46°, E 115.76°–122.83°), the Pearl River Delta urban agglomeration (N 36.1°–42.6°, E 113.5°–119.85°), and the Chengdu–Chongqing urban agglomeration (N 27.64°–32.33°, E 101.93°–109.25°) as research areas. Coordinated urban development exists in the four typical urban agglomerations, but they all have their own characteristics. The Beijing–Tianjin–Hebei urban agglomeration is significantly influenced by policy, while the Yangtze River Delta and the Pearl River Delta have a long history of development and are significantly influenced by the market, and Chengdu–Chongqing is a typical inland urban agglomeration with dual core cities. The development degree and policy orientation of these four urban agglomerations also differ to some extent. Therefore, using these study areas can improve the reliability of our result.

2.2. Data and Data Preprocessing

POI data is the point-of-interest in an electronic map which can accurately express the location, name, and other attributes of various ground objects in a city, such as a school, a factory, etc. The POI data from 2019, used in this study, were extracted from AMAP (https://lbs.amap.com/, accessed on 7 November 2019). The original data included 23 categories of first-level classification, 267 categories of second-level classification, and 869 categories of third-level classification. The data was clipped and duplicate data was removed. Then, the Mars coordinate system of the AMAP was converted into the WGS 1984 coordinate system to achieve deviation correction, and we deleted the types irrelevant to the classification of the urban functional areas such as place names and activities. Considering the POI's representation of functional areas, we used 13 first-level types related to functional areas as the basic POI types for functional area identification.

2.3. Method

2.3.1. The Method for Identifying Urban Functional Areas

In order to give consideration to the rationality of functional area identification of the urban central region and the marginal region, the place2vec model, which can quickly and accurately identify a relatively large range of urban functional areas based on POI data, and which has low requirements for identifying units, was selected to classify urban functional areas [21]. This method has taken into account the interrelationship between POIs when identifying functional areas. Considering that POI names can reflect the characteristics of functional areas to some extent [30], this study made a word cloud graph based on the various POI names to help further classify the urban functional areas. Aiming at the problem of irregular road networks or blocks in urban fringe areas, we decided to use 250 m $\times$ 250 m grid units as the basic units of the urban functional area identification to avoid limiting the extent of the urban built-up area. In order to better analyze the spatial correlation patterns, we carried out a detailed classification for the functional areas, as shown in Table 1. Finally, the overall accuracy of the functional area identification was 87.8%, which meets the requirements for further analysis.

2.3.2. The Method of Mining Spatial Correlation Pattern

The classification of urban functional areas generally exists as the mixture of various functional areas; that is, there are many single urban functions in a unit [31]. According to this characteristic, the mixed-functional area formed by the mixing of various single-functional areas is regarded as the deep inner fusion of various single-functional areas. On the contrary, the spatial correlation with other functional areas is the outer-associated relationship. In addition, to reflect the interactions of spatial correlations in an urban agglomeration, it is necessary to compare the similarities of the spatial correlations of the functions. Thus, the spatial correlations can be analyzed from a city level and an urban agglomeration level, as shown in Figure 1.

Table 1. Classification of functional areas.

Level1 Type	Level2 Type	POI Type
Nonbuilt-up	Nonbuilt-up	
Industry	Industry	Companies
Mixed-function area	Other level2 types of combinations	
Business	Catering Shopping Sports and leisure Accommodation Finance Life service	Catering Shopping Sports and leisure Accommodation Finance Life service
Residential area	Residential area	Residence
Public service	Transportation hub Science, education and culture Administrative office Healthcare service	Transport facilities services Scientific, educational and cultural services Government and social organizations Healthcare service
Green space and square	Green space and square	Scenic spot

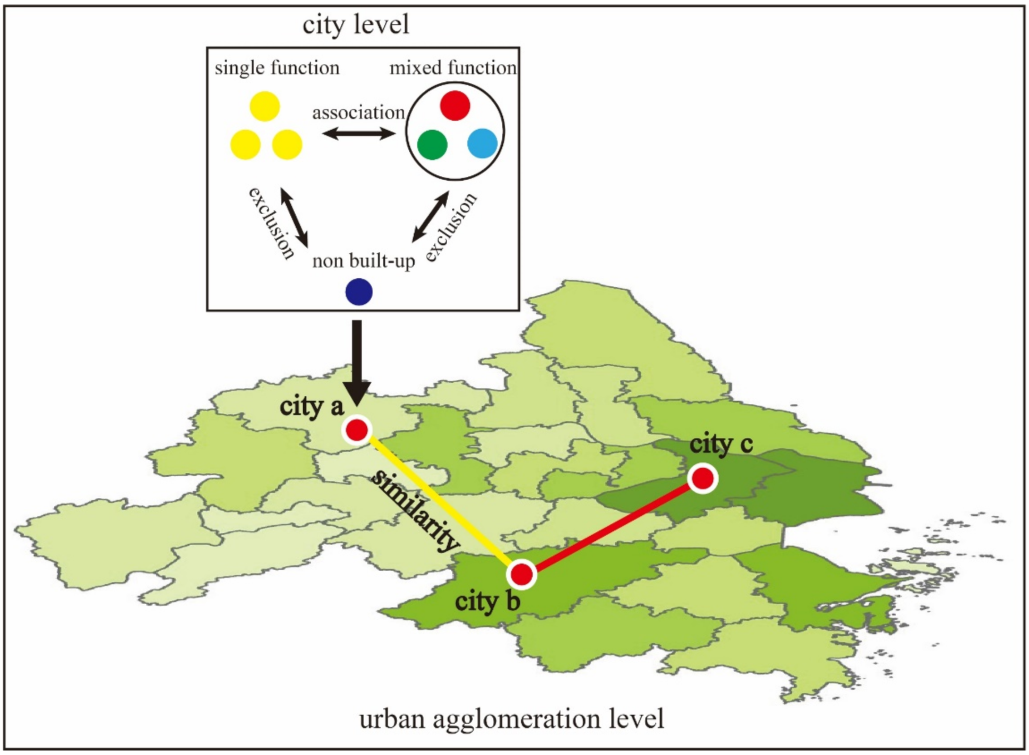

Figure 1. Two analytical levels for mining spatial correlation pattern.

Mining Spatial Correlation Pattern in a Single City

Considering that this idea requires a clear expression of the correlation between functional areas, we propose that 50 level2 functional areas should be randomly selected from each level2 types. Then, we made the buffer, whose center was the above functional areas, so that the proportion of the various functional areas in the buffer zone was counted, which is shown in Figure 2. Next, we needed to ensure that the buffer could extract as many functional types as possible and avoid the large buffer radius that cannot experience the local features of urban functional areas. After the experiments, 5 km was selected as the buffer radius. Then, OLS (ordinary least squares) linear regression was carried out between the proportion of each functional area type in each buffer zone, as shown in Equations (1) and (2). The results that passed the 5% significance test were screened, and the mean values of the regression results centered on each functional area were calculated, as shown in Equation (3). Finally, the spatial correlation pattern of the functional area was obtained for one single city.

$$Y_t = a + bX_t + u_t \quad (1)$$

$$R^2 = \sum_{t=1}^{T} \left(a + bX_t - \overline{Y}\right)^2 / \sum_{t=1}^{T} \left(Y_t - \overline{Y}\right)^2 \quad (2)$$

$$\overline{R^2} = \frac{\sum_{i=1}^{n} R_i^2}{n} \quad (3)$$

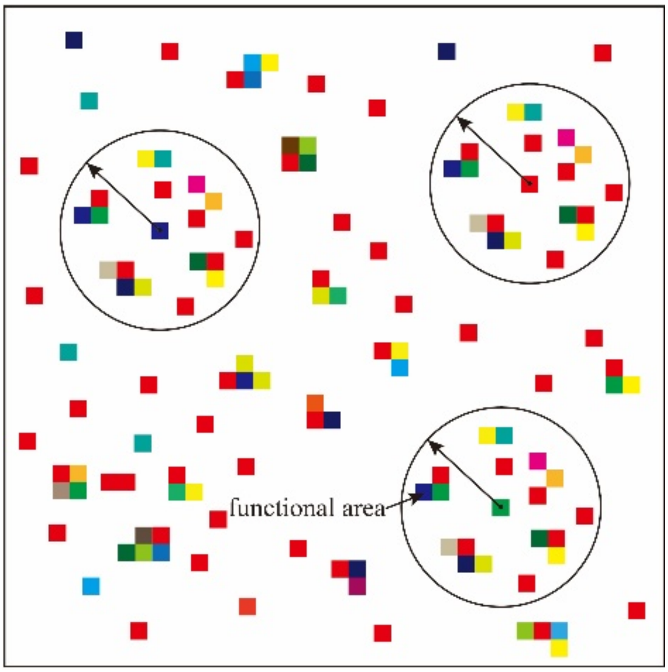

Figure 2. The buffer for statistic the spatial distribution of functional areas. (The different colored squares represent different types of functional areas).

Y_t is the proportion of a certain type of functional area in one buffer; X_t is the proportion of another type of functional area; t = 1, 2, ..., 50, the number of the buffer, T = 50; b is the slope; a is the intercept; u_t is the random error; n is the number of the level2 type of urban functional areas; i is the central functional area type of the buffer; R^2 is the correlation coefficient between the two types of functional areas for the proportion in one buffer; $\overline{R^2}$ is the mean of R^2 for the functional type of the buffer center.

When the R^2 between the nonbuilt-up and another functional type is larger (the premise is to pass the 5% significance test), the stronger the mutually exclusive relationship between the functional area and nonbuilt-up is (the slope of regression between other functions and nonbuilt-up is negative). Since the nonbuilt-up mainly appears in the area far from the city center, we suppose that the stronger the exclusion relationship between certain functional areas and the nonbuilt-up, the more likely such functions are to appear in the city center. Similarly, when the R^2 between two other functional types, except the nonbuilt-up, is larger, the associated relationship between these two functional types is considered to be stronger (the slopes of regression between any two functional types except the nonbuilt-up is positive).

Calculating the Similarity of Spatial Correlation of Functional Area between Different Cities in One Urban Agglomeration

At the level of urban agglomeration, on the basis of the spatial correlation between the internal functional areas of each city, we further use the vector space model (VSM) to calculate the similarity of the spatial correlation of the functional areas between two cities in one urban agglomeration.

Firstly, the types of functional areas with strongly associated (or exclusive) relationships ($\overline{R^2} > 0.8$) as the correlation pair in each city and the number of relationships between these functional types were summarized and analyzed. Then, it was mapped to the vector space to calculate the similarity between two cities. Since we mainly focus on the emerging correlation pair (e.g., shopping–catering), we suppose that the emergence of a new pair will have a greater impact on the functional correlation pattern than the change in the number of existing pairs. Based on this situation, we set the weight of the new functional type in the emerging pairs (that is, the functional type of city A has it, but city B does not) to 10 when calculating the similarity, and to 1 in other cases. The similarity between two cities is calculated, as shown in Equation (4):

$$similarity_{vz} = \sqrt{\sum_{i=1}^{n} (w_{vi} \times c_{vi} - w_{zi} \times c_{zi})^2} \quad (4)$$

where v, z is the city name, $similarity_{vz}$ is the similarity of the spatial correlation pattern between city v, z, w_{vi} is the weight of the functional type i of city v, c_{vi} is the correlation pairs number of the functional type i of city v, and n is the set of functional types which is in correlation to the pairs of city v, w.

3. Results

3.1. Statistical Analysis of Functional Areas in Urban Agglomeration

As the mixed-function area is a deep fusion of a single-functional area, based on this idea, and the functional area calculated by place2vec deep learning model, we conduct a statistical analysis on the identified urban functional area, types, and area proportion of the mixed-function area, as shown in Figure 3.

It is found that there are generally significant step faults in the urban built-up area from top to bottom in the urban agglomerations; that is to say, the step faults decline slowly within a rank and sharply between different ranks. The city rank is generally consistent with the development level of the city. The relatively lower rank often contains more cities, indicating that when these urban agglomerations form a development group, the member composition of all the development groups is still relatively close to the pyramid. The Yangtze River Delta, the Pearl River Delta, and the Beijing–Tianjin–Hebei have more ranks. Although Chengdu–Chongqing can only be divided into two ranks, there are the most gaps between the two ranks. This shows that there are great differences in the radiation ability of cities with higher development levels in different urban agglomerations. The variation range of the urban built-up areas of rank1 is 1890.53–3314.47 km^2, which is a large interval. The lowest rank of the urban built-up areas varies from 170.86–562.08 km^2, whereby the range of change is much smaller than that of rank1. This shows that, although there are large differences among cities with a higher development level, there are small differences among cities with a lower development level.

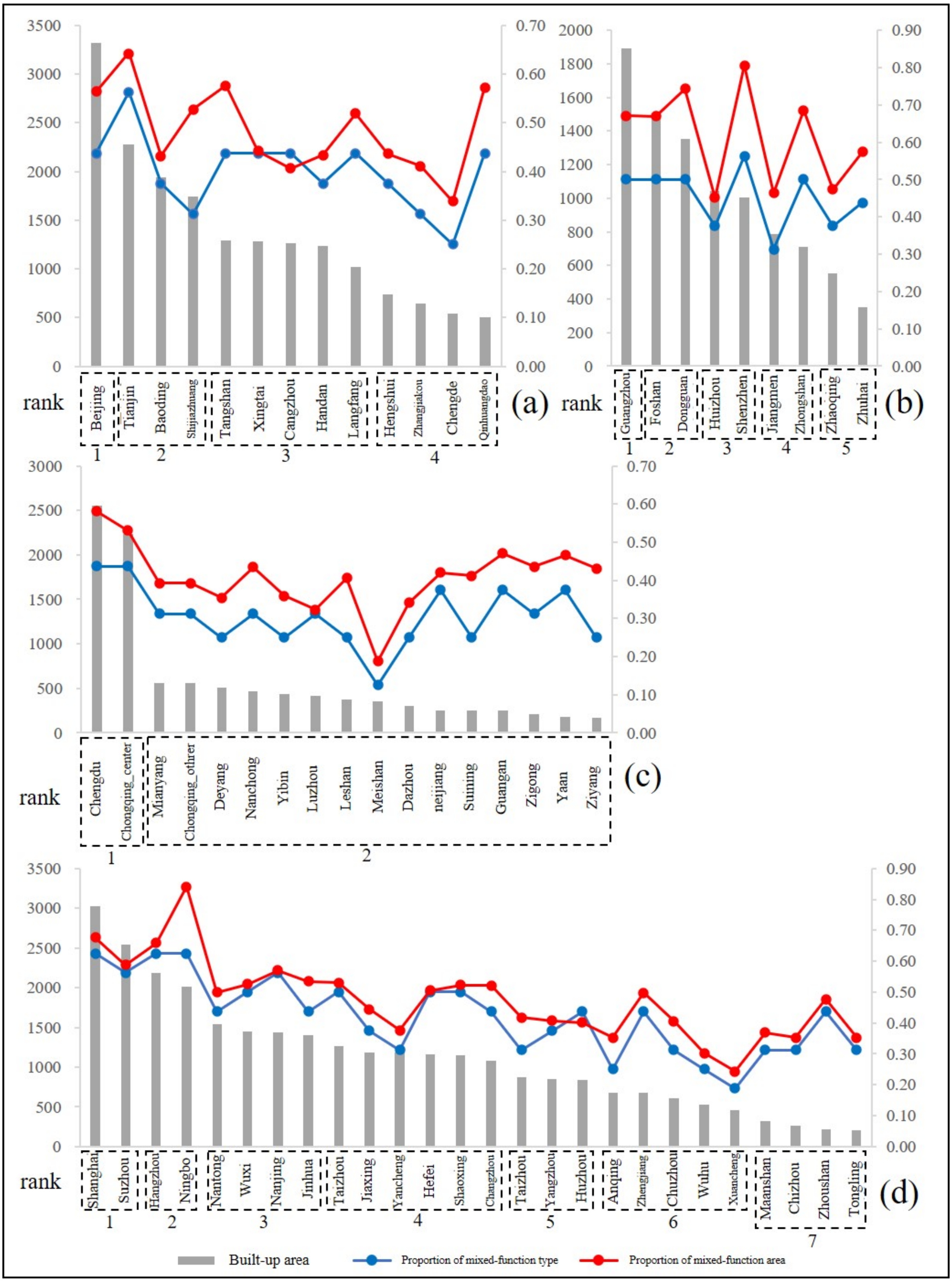

Figure 3. Statistical graph of urban functional area, (**a**): Beijing–Tianjin–Hebei, (**b**): The Yangtze River Delta, (**c**): Chengdu–Chongqing, (**d**): The Pearl River Delta.

The variation characteristics of the proportion of mixed-function types in all urban agglomerations are similar and fluctuate between about 0.2 and 0.6. This shows that the deep fusion level of the urban functions has little difference among the urban agglomerations. However, there are some differences in the proportion of the mixed-function types in the different cities of one urban agglomeration. This does not mean that the higher the city rank, the greater the proportion of mixed-function types. The proportion of mixed-function areas also fluctuates between about 0.2 and 0.6. However, this proportion is mostly higher than the proportion of mixed-function types, indicating that the scale development degree of the mixed-function area in various urban agglomerations exceeds the diversification development degree. However, similar to the proportion of mixed-function areas, there is also a large fluctuation in urban agglomerations, representing that the richness of the mixed-function types is also less affected by the city rank; that is, the level of urban development has less influence on it. It is worth noting that the fluctuation trend of both types and areas of mixed function is highly consistent on the whole. That is to say, the mixed-function area of the city with a high variety of mixed-function types is relatively large.

3.2. Analysis of Spatial Correlation of Functional Area

3.2.1. Feature of Rank1 Cities

As the core cities of urban agglomerations, the rank1 cities in urban agglomerations often have great influence on the whole of urban agglomerations. Therefore, we first make a comparative analysis on the feature of urban functional areas in spatial correlations.

As shown in Figure 4, the color of the line between functional types expresses the intensity of the associated relationships between the different functional types. These rank1 urban functional areas generally have an associated relationship with each other. However, the associated relationships between some single-functional types and other functional types are weak, and they are very diverse. It includes commercial, industry, residential, public service, green space, and square; that is, all level1 types. However, the mixed-function types, including life service, shopping, catering, industry, and transportation hub, which are composed of industry, business, and public service (level1 types), are closely associated with each other. In addition, the components of these mixed-functional types are relatively similar, mostly containing three businesses, namely, shopping, life service, and catering service. Therefore, it is not difficult to understand why there is a strongly associated relationship between them, which is the performance of the deep fusion of various components in the mixed-functional area.

In Figure 4, the color of the dots expresses the intensity of the exclusive relationship between each functional type and the nonbuilt-up area. It can be found that in these rank1 cities, most types of functional areas have a certain exclusion relationship with the nonbuilt-up areas. However, most of the functional types with single types of functions have weak or even no significant exclusive relationship with the nonbuilt-up areas. They are mainly the transportation hub, science, education and culture, administrative office, sports and leisure, catering, and so on. In terms of level1 types, they mainly have public service, industry, residential area, and also have a few businesses. It is worth noting that most mixed-function types have a strong exclusive relationship with the nonbuilt-up areas; that is, these functions are more likely to appear in the city center. The components of these mixed-function areas mainly include shopping, catering, life service, industry, and transportation hub, among which there are many businesses (level1 type). It can be seen that the transportation hub is one of the supporting functions of the rank1 urban center in Chinese urban agglomerations.

It can be found that the features of the spatial correlations in rank1 urban functional areas are highly similar. Moreover, as can be seen, although Beijing–Tianjin–Hebei are mainly driven by policy, the Yangtze River Delta and the Pearl River Delta are more developed and have a long history, and Chengdu–Chongqing is the platform of western development strategy, wherein they all have many single functions which have weakly associated relationships with each other, whereby the main one is relatively close between the mixed-function types.

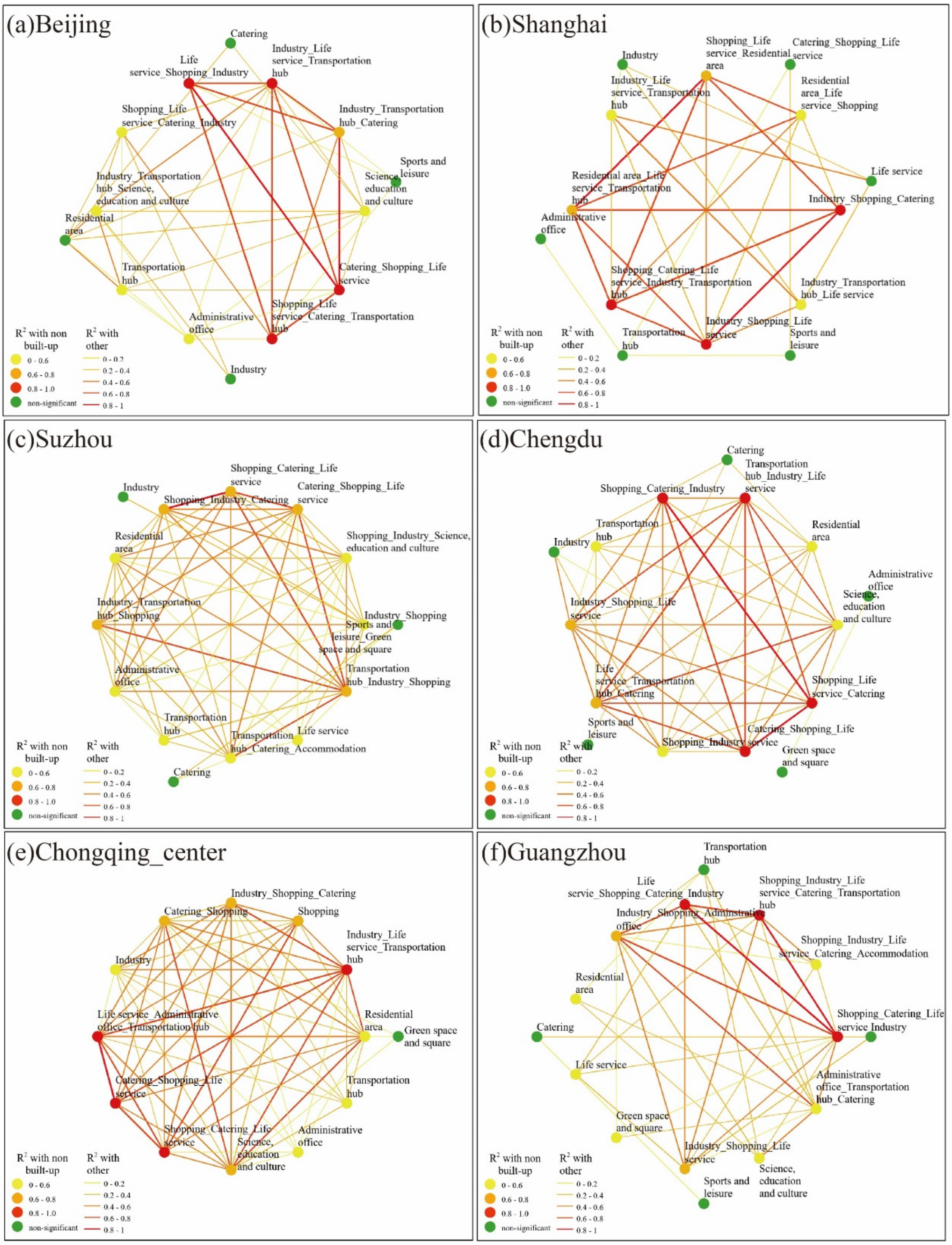

Figure 4. Functional correlation diagram for rank1 city. (**a**): Beijing—Tianjin—Hebei, (**b**,**c**): the Yangtze River Delta, (**d**,**e**): Chengdu—Chongqing, (**f**): the Pearl River Delta.

3.2.2. Summary of Cities in All Ranks

As shown in Figure 5, the types of functional areas with strongly associated (or exclusive, $\overline{R^2} > 0.8$) relationships in cities at each rank are summarized. In Figure 5(a1), it can be found that in the Beijing–Tianjin–Hebei, from rank1 to rank4, shopping, life service, catering, and industry components in the mixed-function areas are closely associated with each other, and as components of the mixed-function areas, the fusion degree of these four components is deep. These four types of functions are the basic functions of the Beijing–Tianjin–Hebei urban agglomeration. In addition, public service, such as transportation hub, appeared in the rank1, and then public service, administrative office, science, and education and culture appeared in rank2–rank4, indicating that public service has a deep fusion with these four basic functions in the Beijing–Tianjin–Hebei. In Figure 5(b1), it can be seen that the components of shopping, industry, life service, and catering in the mixed-functional areas are in significant fusion with each other. These four components of mixed function are also the basic elements of urban functions in the Yangtze River Delta urban agglomeration, no matter whether in cities of higher rank or cities of lower rank. In addition, residential areas are more associated with other functions. With the decrease of the city rank, more public services, such as administrative office, transportation hub, science, education and culture, and healthcare services appear in the form of mixed-function components. In Figure 5(c1), the Chengdu–Chongqing urban agglomeration has few ranks, but the overall features are similar to other urban agglomerations. The basic functions of the city on rank1 are still the mixed-function areas of shopping, industry, life service, and catering. Moreover, in the lower rank, more public service functions and other types of urban functions in single-function form are strongly associated with each other. In Figure 5(d1), the associated relationships of the functional areas are relatively simple. The basic complementary functional area is still the mixed-function area in the form of shopping, industry, life service, and catering, which is similar from rank1 to rank3. However, there are more public service components and single-functional areas in rank4.

As for the relationship between the functional areas and the nonbuilt-up areas, as shown in Figure 5(a2), the Beijing–Tianjin–Hebei urban agglomeration also has a strong exclusive relationship between the four components of the mixed-function (shopping, catering industry, life service) and the nonbuilt-up areas; that is, these functions are often distributed in the city center. Moreover, as the city rank decreases, the public service of the mixed-function begins to show a strong exclusive relationship with the nonbuilt-up areas; that is, these functions begin to appear more and more in the core area. There are also some public service functions in the form of single-functional areas (shopping, science, education and culture) in the city center, showing that these functions are not in a deep fusion with other functions in the core of lower-rank cities. In Figure 5(b2), the overall features of the Yangtze River Delta are similar to that of Figure 5(b1), indicating that with the reduction of city rank, more public service functions appear in city center in the form of mixed-functions. Moreover, with the further reduction of the city rank, some single-functions, such as residential area, life service, and shopping, appear in the city center. In Figure 5(c2), Chengdu–Chongqing expresses the exclusive relationship between various functions and nonbuilt-up areas. It can be found that the urban center is still composed of mixed-function areas consisting of shopping, catering, life service, and industry. However, the functional combination of the lower-rank cities is more complex. Additionally, in the above four functions, there are many types of public services as mixed-functional components and various single types of functional areas. As shown in Figure 5(d2), the exclusive relationship between the various functional areas and the nonbuilt-up areas in the Pearl River Delta mainly includes mixed-functional forms of shopping, industry, life service, and catering, and other ranks are similar, except for occasional public service functions.

Based on above analysis, the core urban functions of all ranks in these four urban agglomerations are mainly business and industry (shopping, catering, industry, and life service) with mixed forms, that is, deep fusion. With the decrease of the rank, public service of various types of mixed-functional areas and various single-functional areas appear more and more in the city center, and these functions are closely associated with each other.

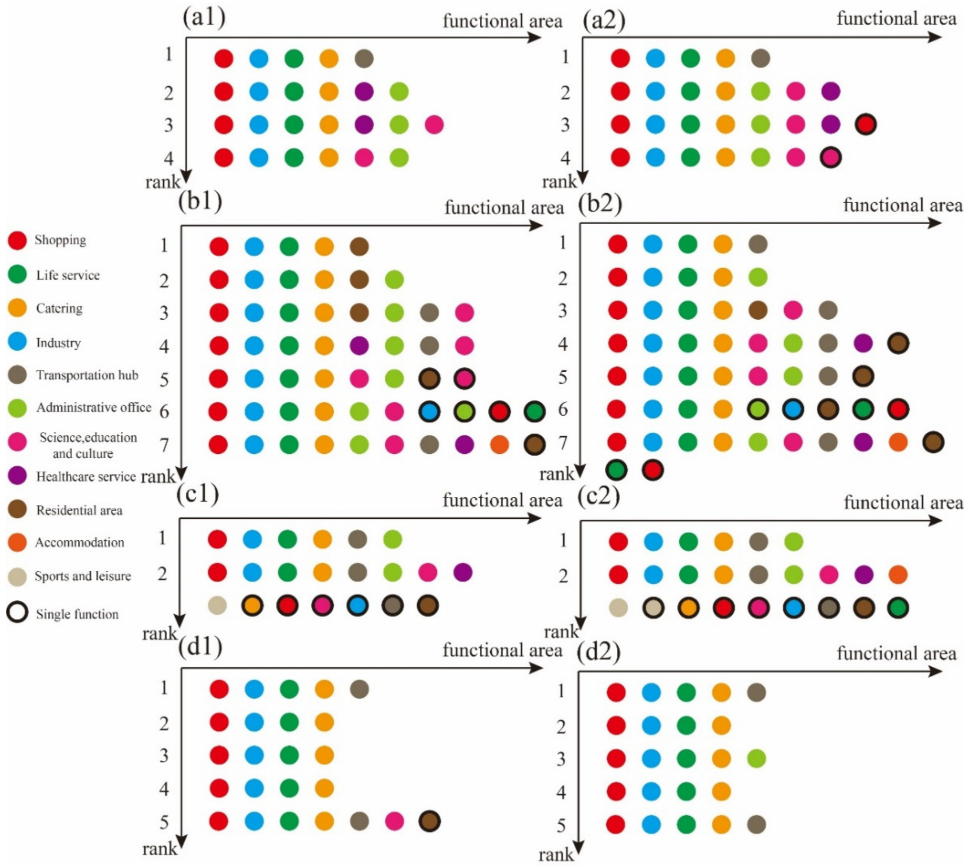

Figure 5. Statistical diagram of correlation characteristics for different ranks. (**a1**): Beijing–Tianjin–Hebei, correlation with other functional areas; (**a2**): Beijing–Tianjin–Hebei, correlation with nonbuilt-up area; (**b1**): the Yangtze River Delta, correlation with other functional areas; (**b2**): the Yangtze River Delta, correlation with nonbuilt-up area; (**c1**): Chengdu–Chongqing, correlation with other functional areas; (**c2**): Chengdu–Chongqing, correlation with nonbuilt-up area; (**d1**): the Pearl River Delta, correlation with other functional areas; (**d2**): the Pearl River Delta, correlation with nonbuilt-up area.

3.2.3. Analysis of Similarity of Functional Correlation between Cities in Urban Agglomeration

Through calculating the similarity of functional correlations between cities in each urban agglomeration, we screened the top 20 similarity pairs for visual expression, whereby Figure 6 is obtained.

In Figure 6(a1), it can be found that in the Beijing–Tianjin–Hebei urban agglomeration, there is a certain similarity in the functional correlation pattern between cities at rank2, 3, and 4. However, the relatively strong similarity is mainly concentrated in the diamond-shaped zone composed of rank2 and 3. As shown in Figure 6(a2), in terms of the relationship between the functional areas and the nonbuilt-up areas, there is certain degree of similarity between the southern cities of urban agglomeration and the northern cities of central cities, but the overall similarity is weaker than that of the correlation relationship between functional areas.

In Figure 6(b1), the Yangtze River Delta forms a diamond-shaped area around rank1 cities on the degree of similarity of the correlation relationship between the functional areas, in which the similarity of the functional relationship between cities is high. Moreover, the similarity of the functional relationship between the rank1 city and other surrounding cities is high. As shown in Figure 6(b2), we can see that in terms of the similarity of the relationship between various functions and nonbuilt-up areas, the higher are mainly concentrated near the rank1 cities, around which there are three closely related cities in the Yangtze River Delta urban agglomeration, and there is also a high similarity in the relationship between functional areas and nonbuilt-up areas. However, whether b1 or b2, the cities with strong similarity of association relationships are mainly close to the rank1, while the similarity of functional relationships between the cities far away from these two cities are not high.

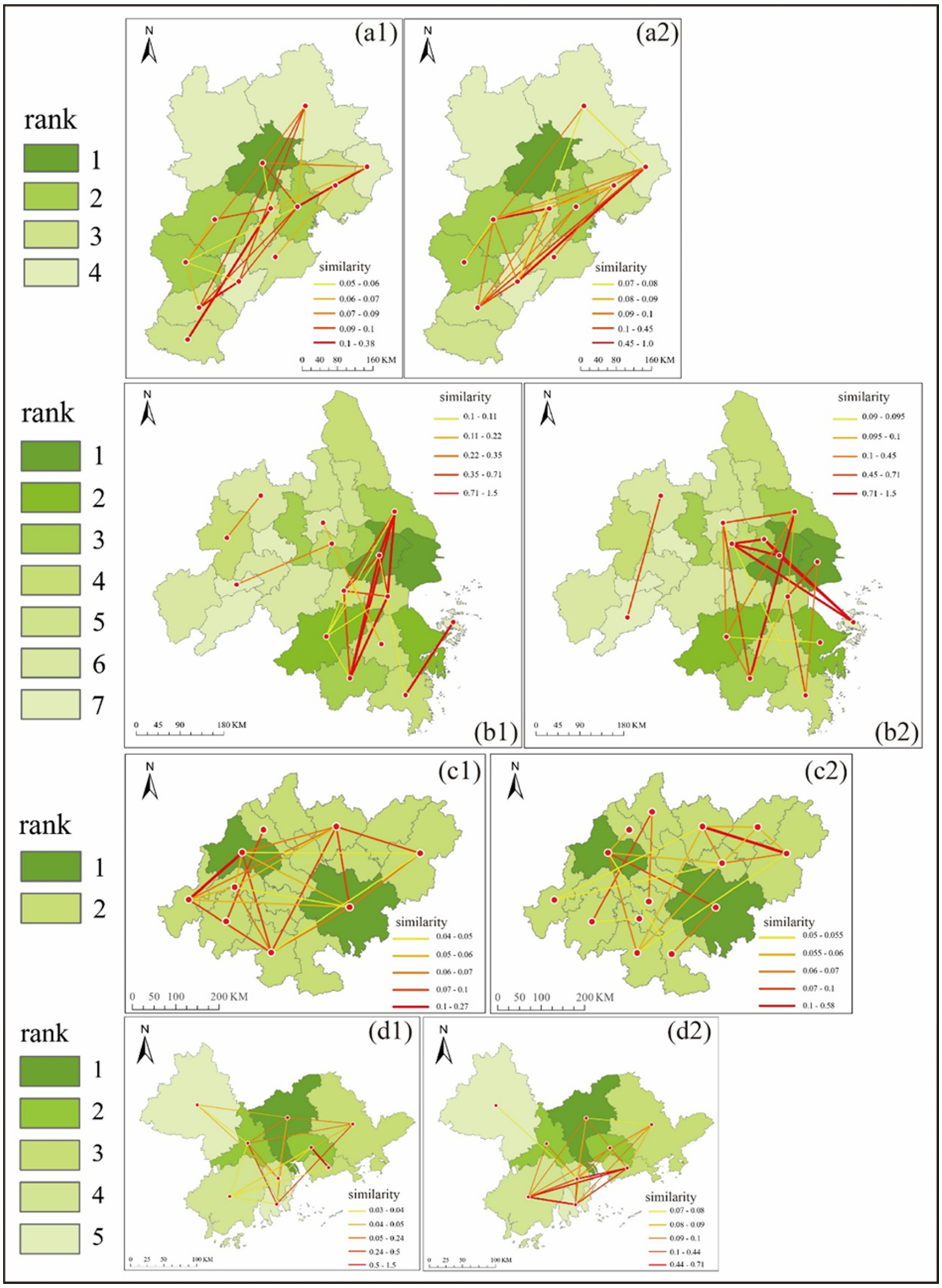

Figure 6. Similarity degree diagram of spatial correlation in functional areas. (**a1**): Beijing–Tianjin–Hebei, correlation with other functional areas; (**a2**): Beijing–Tianjin–Hebei, correlation with nonbuilt-up area; (**b1**): the Yangtze River Delta, correlation with other functional areas; (**b2**): the Yangtze River Delta, correlation with nonbuilt-up area; (**c1**): Chengdu–Chongqing, correlation with other functional areas; (**c2**): Chengdu–Chongqing, correlation with nonbuilt-up area; (**d1**): the Pearl River Delta, correlation with other functional areas; (**d2**): the Pearl River Delta, correlation with nonbuilt-up area.

In Figure 6(c1), the similarity between the two rank1 cities and other cities in Chengdu–Chongqing urban agglomeration is relatively high in terms of the associated relationship between functional areas. Moreover, some rank2 cities are the key nodes, that is, the similarity of the functional area relationship between these cities is higher than that of other cities. As can be seen from Figure 6(c2), the similarity degree is lower than the other three urban agglomerations on the whole, and the core of the similarity relationship is not the two regional core cities of rank1, although there are certain similarities between them.

The situation of the Pearl River Delta urban agglomeration is shown in Figure 6d. In d1, the similarity of the correlation between other functional areas is the diamond-shaped area composed of cities at all ranks, and the similarity between these cities is relatively high. As shown in d2, in terms of the correlation between various functions and nonbuilt-up areas, the diamond area with rank4 as the core appears, and the correlation between surrounding cities are relatively similar. However, on the whole, the similarity between cities at all ranks is relatively high, no matter whether d1 or d2, indicating that the functional correlation features in the Pearl River Delta urban agglomeration tend to be homogeneous.

Through the analysis of the above, we can see Sections 3.2.1 and 3.2.2 show similar functional correlation patterns. However, Section 3.2.3 is different from them: there is a large gap between cities in different urban agglomerations in the similarity of the spatial correlation patterns of the functional areas, and the similarity relationship does not necessarily revolve around the most developed cities in one urban agglomeration. Among them, the Yangtze River Delta and the Pearl River Delta have strong overall similarity between their cities, while the other two have relatively low. It is worth noting that the strongly correlated relationship in the Yangtze River Delta is mainly concentrated in the center of rank1 cities. This is significantly different from the other three urban agglomerations, where all the cities have relatively strong similarity degree in the entire urban agglomerations.

3.3. Spatial Correlation Pattern of Functional Area in Chinese Urban Agglomeration

By comparing the functional features in different urban agglomerations in Section 3.2, we find that:

1. Mixed-function areas are strongly excluded from the nonbuilt-up areas, and they are mainly composed of business (shopping, catering, life service) and industry, and there is a strongly associated relationship between the mixed-function areas.
2. As the rank is lowered (along with the step down of the urban built-up area), some functional components (science, education and culture, healthcare service, and administrative office) will gradually appear in the mixed-function area mentioned in (1).
3. With the further reduction of the city rank, some single-functional areas in the city begin to have a strong exclusion relationship with the nonbuilt-up areas, and have a strongly associated relationship with each other and the mixed-function areas shown in (1).
4. In all cities, the functional areas that do not have a significant exclusion relationship with the nonbuilt-up areas are mostly single-functional areas, and these functional areas have a small number of associated relationships with other urban functional areas that have a strong or weak exclusion relationship with the nonbuilt-up areas.
5. Generally speaking, the lower the rank of a city is, the more complex the correlation relationship between urban functional areas is. Cities in rank1 often have a relatively simple functional correlation relationship.

To sum up, the overall spatial correlation pattern is shown in Figure 7. It can be seen that in cities with higher ranks, the city center is often a variety of mixed-function areas composed of shopping, life service, catering, and industry. It shows that production and commercial activities in these city centers are a deep fusion to support the high intensity of human activities in city centers. Other single-functional areas are distributed from the center to the edge, indicating that the fusion degree of the urban functional areas in the outer layer of the city is still not high, and the functional characteristics of the various functional area units are relatively single, with obvious boundaries. However, with the lower rank of the city, the composition of the mixed-function areas in the city center are diversified, mainly manifested in the emergence of more public services, such as administrative office, science, education and culture, and healthcare service. With the further reduction of the city rank, some single functions, such as residential area, industry, and business, begin to appear in the city center, presenting the pattern that mixed-function areas are associated with single-function areas. Therefore, we can see that with the lowering of the city rank, the relationship between the functional areas in the city center tends to be complicated. This shows that, with the gradual development of the city, the pattern of the central functional areas has gradually changed from the combination of various types of functional areas into a high fusion degree of a few types of functions, so as to facilitate the efficient operation of the city.

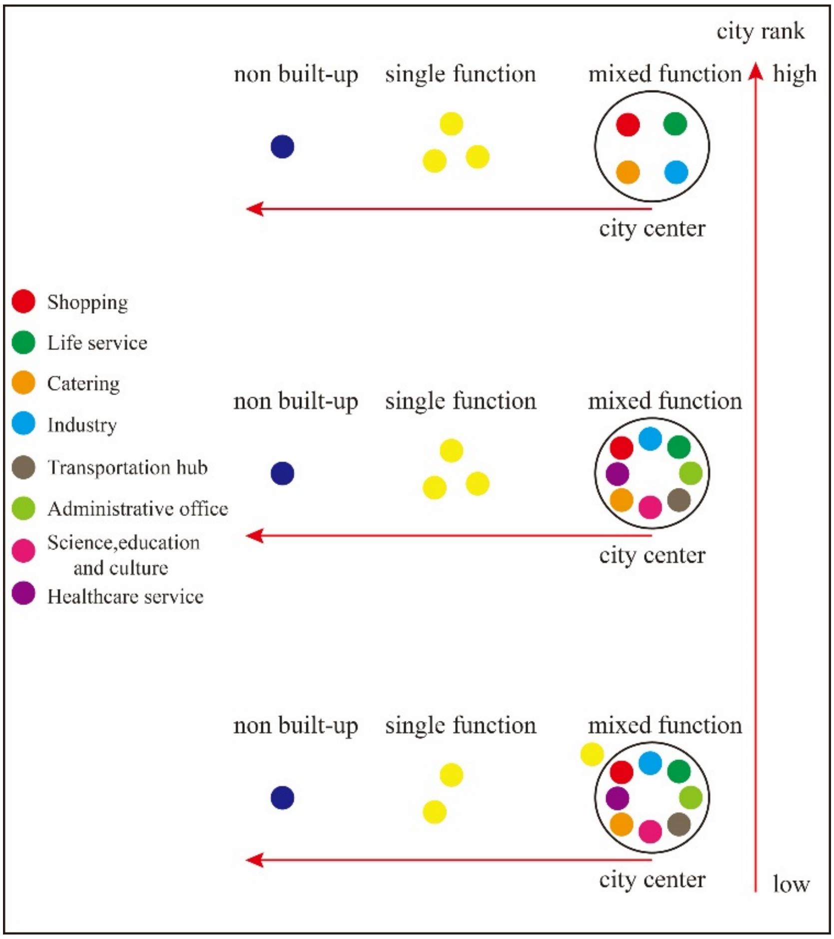

Figure 7. Spatial correlation pattern in Chinese urban agglomeration.

4. Discussion

4.1. Applicability of the Mining Method

The functional areas identified by the mature place2vec deep learning model are used as the basic data of the study, which makes the pattern of model mining more reliable. At present, there are mainly the spatial autocorrelation method [32], the kernel density method [33,34], the gravity model [35], and so on, to mine the relationships between spatial units. However, functional areas may have certain mutual relations at various scales, and mixed-function areas commonly found in urban functional areas are the deep fusion of various functions at a certain spatial scale. Therefore, a new spatial pattern mining method is proposed in this study, and the correlation graph for the functional areas is adopted to express the correlation relationship between the functions, which can intuitively express the spatial correlation patterns of different functional types in a city. Additionally, the random selection of functional areas for the buffer also ensures the objectivity of the results. Our results also show that our method is stable in most cities of these urban agglomerations and does not have a great influence on the results due to the change of urban form. Moreover, the deep fusion of the mixed-function components concerning the spatial correlation relationships can be well expressed. The spatial correlation pattern was mined and is also confirmed to some extent by the relevant research and the history of urban development. For example, Beijing moved the city administrative office from the city center to the Tongzhou District, which is far away from the city center, indicating that some public service may be withdrawn from the city center with the development of the city. Additionally, studies have also shown that some urban centers are mainly mixed-function areas [36,37].

4.2. The Practical Significance of the Overall Pattern of Functional Correlation

Cities with a higher rank, such as Beijing and Guangzhou, have simpler pattern in the mixed-function areas in city the centers, indicating that the functional development of these cities has been relatively mature [38]. Some residential areas and public services have a relatively low utilization efficiency of limited land in central urban areas, and are forced to move away. Some functional areas that occupy a large area, but which are not well integrated with other functional areas (such as some single shopping service areas consisting of wholesale markets), can only go to places farther away from the city. This makes sense for the distribution of single-functional areas at a certain distance from the center. However, the composition of mixed-function areas tends to be complicated in lower-rank cities. The situation reflects that these cities still have some original spatial correlation of functional areas in the city center due to their relatively backward development level. For example, public services are located in the city center, and even some single functions also appear in the city center. Therefore, lower-rank cities should update their own planning system in time, lay out more advanced industries in the city center, and promote the deep fusion of functional areas to improve land use efficiency and promote high-quality urban development.

4.3. Some Differences Still Exist in Function among Urban Agglomerations

The big gap between ranks in Chengdu–Chongqing may reflect that there is a big gap between the development of rank1 cities and other cities, and that these two cities have a poor radiation influence on the surrounding areas. This shows that the maturity of this urban agglomeration is quite different from that of the Yangtze River Delta, the Pearl River Delta, and Beijing–Tianjin–Hebei. It is worth noting that the Pearl River Delta may be better developed [39], with the result that the rank1 functional feature still exists with the decrease of the city rank. However, with the gradual decrease of the city rank, some lower-rank features still appear to some extent, which on the whole is consistent with our spatial correlation pattern. The above shows that the driving effect of cities at a higher rank on those with a lower rank needs to be further strengthened. In addition, when there are great differences in similarity patterns between urban agglomerations, the rank1 cities have similar correlation patterns, but there are certain differences in the lower ranks. This may indicate that there are certain differences in the driving factors of the development of different urban agglomerations, leading to certain differences in the interaction mechanism of urban functional development, which may be worth exploring in future studies.

5. Conclusions

In view of the problem that current research mainly focuses on the identification of urban functional areas, but few on the functional correlation pattern, this study selected four typical urban agglomerations in China as research areas and proposed a new method for mining the spatial correlation pattern of the functional areas. This method aimed to explore the spatial patterns from a city level and an urban agglomeration level for Chinese urban agglomerations so as to provide a key reference for the high-quality development of cities at different degrees of development.

In this paper, we found that the city hierarchy can be divided in one urban agglomeration according to the urban built-up area. Different urban agglomerations have two to seven ranks, which is helpful for us to explore the spatial correlation patterns of urban functional areas. The differences in the richness and size (area ratio) of the mixed-function areas among the urban agglomerations are similar, with the overall floating between 0.2 and 0.6. However, there may be cities with a higher richness and scale of mixed-function areas (about 0.8) and cities with a lower richness and scale of mixed-function areas (about 0.1). Through the closely functional area types of cities at all ranks, it can be seen that the urban core area is mainly composed of mixed-function areas consisting of shopping, catering, life service, and industry. Moreover, the associated relationship between these four types is also strong, and there is a deep fusion characteristic, which forms the basis of the functional correlation pattern in Chinese urban agglomerations. Although the overall spatial correlation pattern exists, there is a difference in its spatial similarity pattern between urban agglomerations, with the gap floating from 0.5 to 1 in terms of the similarity value, as shown in Figure 6, which indicates that different urban agglomerations still have their own characteristics of development and policy orientation.

Additionally, this study uses POI big data and a deep learning model to identify urban functional areas and mine the spatial correlation patterns. This shows that POI data still has great potential in the future. These graphs, which can express spatial correlation relationships, clearly have great value for mining the characteristics of spatial and temporal distributions of urban functional areas in the future. Moreover, the correlation between the functional areas also provides support for the spatial and temporal prediction of the spatial structures of urban functional areas in some interesting situations.

In order to compare cities, this paper still takes cities as the basic unit of functional area analysis. However, we did not consider that many urban built-up areas have broken through the original administrative boundaries, so the next step should be to draw more valuable conclusions about some of the changed basic units for analysis. In addition, the spatial distribution of the urban population is closely related to the pattern of functional areas [40]. Therefore, multilayer mining of human–land–industry spatial patterns using multisource data may be a valuable research topic.

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