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Measuring Network Configuration of the Yangtze River Middle Reaches Urban Agglomeration: Based on Modified Radiation Model

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Abstract: The objective of this study is to develop a framework for re-examining and re-defining the classical concepts of spatial interaction and reorganization in the urban system. We introduce a modified radiation model for spatial interactions, coupled with migration big data, transport accessibility algorithm, and city competitiveness assessment for efficient distribution of the inter-city flow through the network. The Yangtze River Middle Reaches (YRMR) urban agglomeration (UA) is chosen as the case study region to systematically identify and measure its spatial configuration and to gain insights for other UAs' sustainable development in China. The results are also compared with those computed by the classical gravity model to systematically discuss the applicability of spatial interaction laws and models, and related practical policies for regional sustainable development are discussed based on the findings as well. The conclusions are highlighted below: 1) Combining with the 'city network paradigm' and 'central place theory' can better express the spatial configurations of city systems in the context of 'space of flows'; 2) The results validate the potentialities of a multi-analysis framework to assess the spatial configurations of city network based on the improved radiation model and network analysis tools; 3) The applications of spatial interaction models should be considered according to the specific geographical entity and its spatial scale.

Keywords: spatial interaction; city network; radiation model; gravity model; urban agglomeration

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1 Introduction

With the development of information and communications technology (ICT) and transport infrastructure, urban agglomerations in China have been increasingly incorporated into synergetic regions. This city-region emphasizing the interdependency of cities that results from real and virtual flows across borders, and the influence that such fluxes have on the spatial and hierarchical configurations of urban systems (Fang and Yu, 2017). Parallel to the rise of the 'space of flows', the structure and organization of urban systems are understood through the concept of city network (Meijers, 2007; Batten, 1995; Neal, 2010). The form of urban regions has become ever polycentric composed of different kinds of centers, axis, and communities (Zhong et al., 2014). In particular, the importance of network patterns has often been highlighted, as it has not only been regarded as an ideal form for measuring the urbanization process (Liu et al., 2016), but is also linked to regional economy (van Meeteren et al., 2016; Zhang et al., 2017), and sustainable development (Cao et al., 2018).

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The importance of spatial centrality in hierarchical space has given way to cross-border networks: nodes linked by spatial and/or functional connections, rather than simply a form of ranking (Sassen, 2002; Neal, 2010). Consequently, given the contemporary arrangement of urban regions with a spatial logic of the 'space of flows' (Castells, 1989), these transformations raise serious questions: what are the spatial configurations of urban agglomeration in geographic space? How to re-examine the traditional hierarchical-competitive approach and to develop a new perspective highlighting horizontal, network-like relationships to accurately understand spatial interactions? What kind of policy enlightenment could provide based on the spatial interaction for regional sustainable development?

Existing studies have investigated city networks formed by a variety of spatial flows, including economic linkages (Lao et al., 2016), passenger movements (Yang et al., 2019), and firm connections (Taylor et al., 2014). Among these, each network captures the relevant characteristics of city connections and deepens our understanding of city systems in different dimensions. However, the economic flows, in particular, are relatively subjective, and it is impractical to simulate the actual volume of economic relationships between cities (Lao et al., 2016). Instead, several studies, such as Hou et al. (2015) and Lao et al. (2016), have employed different modelling methods to measure economic linkages, using the attribute data, rather than the relational data.

Traditionally, one method that has been widely used in the spatial interaction literature is the gravity model (Camagni and Salone, 1993; McArthur et al., 2011; Lao et al., 2016; Zheng et al., 2016). Inspired by Newton's laws of physics, the gravity model is a subjective generalization of experience (Li et al., 2017), assuming that the strength of inter-city connections is proportional to the mass of each geographic unit, decaying with distance (Zipf, 1946). However, the classical gravity model has difficulties in assessing the intercity relationships with particular reference to the reorganization in the urban system from the well-known hierarchy paradigm to the network-based one, as it is usually seen as related to a marked hierarchical order (Camagni and Salone, 1993). Additionally, from a theoretical perspective, the gravity model assumed that the connections between each origin-destination pair are established independently of other cities. In fact, there is a competitive effect between destinations within a certain region, for example, when other destinations are less attractive, it will intensify the connection between these two cities. On the contrary, it will weaken the strength of spatial interaction between the original city pairs. Furthermore, it estimates the spatial interactions in an asymmetric way, which means that the outward flow is equivalent to the inward flow. Obviously, the attraction of a big city to a small city must be greater than that of a small city to a big city. From a practical standpoint, the validity of gravity models varies significantly from region to region due to their adjustable parameters (Mikkonen and Luoma, 1999; Anderson and van Wincoop, 2003; McArthur et al., 2011).

Recently, Simini et al. (2012) introduced a sociodemographic model, the radiation model, that allows calculation of the directional migration flows, reflecting and reinforcing the heterogeneity of interdependencies between any two regions. As an analogue to the traditional gravity model, the radiation model determines the complex topological features observed in networks by a stochastic process of job selection within a certain heterogeneous region in which a person is inclined to search for destinations, with opportunities proportional to populations. Thus, the radiation model considers the spatial distribution of places of interest more important than pure physical distance and scale of origins. As a socio-demographic model originally, the radiation model has been used in studies on population mobility (Kang et al., 2015), transport process (Ren et al., 2014), and epidemiology spreading (Wesolowski et al., 2015). The results were also compared with the gravity model (Kang et al., 2015; Lenormand et al., 2016; Stefanouli and Polyzos, 2017), which proved the superiority of the radiation model, and improved the predictive accuracy in the areas involved in migration and transport processes. Additionally, some works (Masucci et al., 2013; Ren et al., 2014; Wesolowski et al., 2015) have shown that the radiation model can be implemented successfully at macroscopic scales, i.e. national, metropolitan, cities. In China, Hou et al. (2015) simulated the inter-town migrations based on the radiation model and transport accessibility, providing illuminations for concrete city system planning. Li et al. (2017) applied the radiation model to analyze the migration pattern among 337 cities in China. To summarize, existing empirical studies focus on judging the validity and accuracy of the model for the evaluation of factor flow itself, but fall to shed light on the spatial information and connotation of elements flow, such as network structure, interaction density, and spatial difference, *etc*.

Furthermore, given the assumption of the random migration probability with a rigorous formula derivation, the radiation model can be associated to the flow of population in a relatively flat space, which makes it not only has the theoretical basis of sociology but also consists with the theoretical connotation of 'space of flows'. At the same time, we believe that the radiation model is two-dimensional model, because of its considerations of the role spatial competition and difference in dynamic regions. However, the traditional gravity model only considers the mass and distance of two cities, which is a one-dimensional model. Under the background of economic globalization, regionalization, and modern urbanization, node functions, transport corridors, and distribution of events jointly construct a new network space. We consider that, the radiation model, considering points, lines, and planes in space simultaneously, can be introduced to assess spatial interaction in the wake of network changes, which not only expands the application scope of the radiation model, but also breaks through some limitations of traditional models, and provides a new perspective for assisting and optimizing regional management efforts for coordinated and integrated development.

Thus, to further understand how inter-city relationships being operationalized in the era of city networks, and overcome the challenge for measuring the transitions of the urban system, we take the Yangtze River Middle Reaches (YRMR) urban agglomeration (UA) as a case study area. We introduce a generalized radiation model for spatial interactions, coupled with migration big data, transport accessibility algorithm, and city competitiveness assessment for efficient distribution of the inter-city flow through the network.

Notably, this is one of the first studies to measure the spatial structures at the urban agglomeration scale applying a modified radiation model and to systematically discuss the applicability of spatial interaction laws and models. We focus on the issues of extending more effective models and designing network analysis framework for better accuracy in the field, presenting a gap in the literature. On the one hand, an extended radiation model based on Big Data sets is developed: first, on the basis of full consideration of sustainability, we introduce a comprehensive evaluation system to identify city comprehensive competitiveness from many aspects, including economy, population, society, and environment, which represent the influence of elements' non-equilibrium on the spatial interactions. Second, Big Data sets (i.e., Tencent Location Big Data) are embedded into the radiation model, because such comparative and relational data may much more explicitly reflect the interactions between cities. Third, we assess transportation accessibility based on a reliable O-D travel time matrix, catching the influences of the comprehensive traffic network. On the other hand, we designing network analysis framework to analyze the topological attributes of nodes and edges, the community configurations, and the macroscopic connection patterns of city networks. We employ several newly developed network measures and propose a novel evaluation method—Global importance—for analyzing city position, which caters to the context of cities interdepending with each other within the city network.

In summary, the objectives of this paper are to reconsider the concept of spatial interaction and reorganization in urban system, with particular reference to the transformation from the well-known hierarchy paradigm to the network-based one. The framework for analyzing the relationships between cities and exploring regional disparities could lead the city development into a sustainable way and facilitate UAs' push for regional economic integration.

2 Study Area

Our study region is the Yangtze River Middle Reaches (YRMR) urban agglomeration (26°03′N–32°37′N, 110°15′E–118º29′E) in central China (Fig. 1). It includes three megacities (Wuhan, Changsha, and Nanchang) and 28 other prefecture-level cities in the provinces of Hubei, Hunan, and Jiangxi. In 2014, this region had a total population of 121 million in an area of about 317 000 km^2 (referenced from '*The Development Plan for the Urban Agglomeration of the Yangtze River Middle Reaches* (*2015–2030*)'). It is a complex urban system, with highly dense social and economic activities within its sub-agglomerations, including urban clusters around Wuhan, the Changsha-Zhuzhou-Xiangtan city group, and clusters around Poyang Lake. In recent

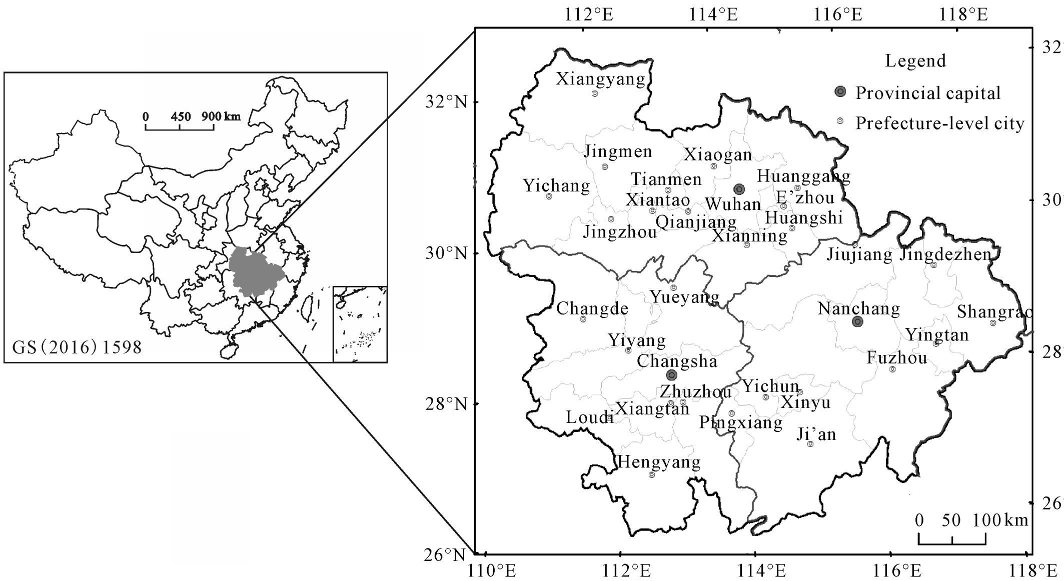


Fig. 1 Location and administrative divisions of the Yangtze River Middle Reaches (YRMR) urban agglomeration (UA)

years, the urban agglomeration has undergone a rapid process of urbanization, due especially to its significant role in the 'Rise of Central China' strategy. According to the plan, the gross domestic product (GDP) of the region reached 600 billion yuan (RMB), accounting for 8.8 percent of national GDP, and urbanization rate exceeded 55% in 2014. The well-balanced system with multiple centers makes the YRMR UA a useful study region for assessing the utility of our approach and framework.

3 Materials and Methods

3.1 Data resource

In addition to the traditional statistical data, such as China City Statistical Yearbook (Department of Urban Socio Economic Investigation, National Bureau of Statistics, 2017), Hubei Statistical Yearbook (Hubei Provincial Bureau of Statistics, 2017), Hunan Statistical Yearbook (Hunan Provincial Bureau of Statistics, 2017), and Jiangxi Statistics Yearbook (Jiangxi Provincial Bureau of Statistics, 2017), we innovatively introduced the real-time migration data and composite travel time data into the radiation model to analyze the spatial interaction between cities.

The migration data were obtained from the website of Tencent Location Big Data (https://heat.qq.com/qianxi.php). This website publishes the volume of migration based on user location information from several mobile applications, such as WeChat and QQ. As long as the user's phone is on, the travelling route could be tracked by these apps. In urban connection research, Ye et al. (2017) analyzed the migration data among Chinese cities from February 7, 2015, to May 15, 2015, and demonstrated that human migration in China shows a weekly movement pattern (except the Spring Festival, Qingming Festival, and other legal holidays). And thus to eliminate the influence of population explosion during the special period of holidays and festivals, scholars usually use the data of ordinary working and non-working days for the analysis of urban flows (Ye et al., 2017; Hui et al., 2018; Xia et al., 2019). For example, Hui et al. (2018) sampled a weekday (18 September 2017) and a weekday (23 September 2017) for the study of deciphering the spatial structure in Guangdong-Hong Kong-Macao Greater Bay Area, aiming to examine the regional integration and economic growth of the megacity region. Considering this, we selected data for one week (from November 4, 2016, to November 10, 2016) to characterize ordinary passenger flows.

For the transportation data, on the intra-province and inter-adjacent province scales in central China, like the Hunan-Hubei-Jiangxi region, highway and railway are the main means of transportations with little involving of the aviation and navigation. Checking the information on the numbers of airlines and shipping lines on the Ctrip.com, one of the largest travel websites in China, only four air transport lines are in operation within YRMR UA, namely, Changsha–Jinggangshan, Changsha–Xiangyang, Wuhan–Xiangyang, and Nanchang–Jinggangshan. In addition, the inland river navigation mainly serves for the outside regions. We thus considered the road and rail traffic accessibility to comprehensively calculate the O-D travel time matrix. Specifically, the dynamically updated road network dataset was obtained from the Baidu Maps Application Programming Interface (API) (https://map.baidu.com/). The daily schedule of the number of trains (including high-speed trains, ordinary trains, and inter-city rail) within YRMR UA was crawled from China's national online booking system (https://www.12306.cn/index/). Such datasets, compared with those computed by the ArcGIS Network Analyst module using traffic vector data, capture the highly reliable travel time, and have a fine resolution (Wang and Xu, 2011).

3.2 Network construction

We establish a directed weighted network, whose nodes are 31 cities in the YRMR UA and whose link weights are the strength of inter-city interactions calculated in the radiation model. According to Simini et al. (2012), the simple diffusion model is expressed as:

$$T_{ij} = T_i \frac{m_i n_j}{(m_i + s_{ij})(m_i + n_j + s_{ij})} \tag{1}$$

where T_{ij} is the commuting flux from locations i to j; m_i is the city size of origin i, n_j is the city size of destination j; s_{ij} is a totality (excluding origin and destination) in an intervening space delimited by a circle of radius r_{ij} and centered at location i; and T_i is the total fluxes moving out from i to other places. Based on this simple form, we make several changes, as follows.

Calculation of m_i and n_j: city development capacity is a systematic concept (Zhen et al., 2019), especially in the context of sustainable urbanization, the attractiveness of a city depends not only on its economic performance, but also on people's livelihood, cultural reconstruction, and eco-environmental sustainability (Tan et al., 2016). These dimensions are integrated into the process of new-type urbanization in China, and thus affect urban interactive influence ability (He et al., 2017). Thus, we argue that the city comprehensive development capacity can represent cities' radiation ability. Considering the comparability, data availability, and representativeness, we apportion 25 indicators to measure various aspects of urban developmental level across four dimensions, including economic profile, people-orientedness, culture and education, and ecological sustainability. We measured the economic performance in both agglomeration and efficiency terms. Indicators related to the regional GDP and industrial structure were used to represent economic development level. To capture the presence of the people-oriented urbanization, we focused on four criterion indicators: the demographic profile, living standard, infrastructure construction, and urban-rural integration. As the levels of culture and education in a city are an important factor in its attractiveness, we suggested using indicators on infrastructure construction and government investment to indirectly represent the cultural and education capacity of cities. The environment quality was considered based on urban land utilization and industrial disposal. Based on previous studies (Jiang and Shen, 2010; Zhou et al., 2015; Tan et al., 2016; He et al., 2017; Zhen et al., 2019), relevant indicators were selected, and consequently formed a three-level index system consisting of four target level indicators, 10 criterion level indicators, and 25 basic level indicators (Table 1) to evaluate the comprehensive competitiveness of cities. Finally, we combined the analytic hierarchy process (AHP) method (which is relatively subjective) and the entropy weight (EW) method (which is relatively objective) to calculate the weight of each indicator：

$$\omega_j = \frac{\sqrt{\omega_{aj}\omega_{bj}}}{\sum_{j=1}^{n}\sqrt{\omega_{aj}\omega_{bj}}} \tag{2}$$

where ω_j is the synthetic weight, ω_{aj} is the subjective weight of indicator k calculated by AHP method (Thapa and Murayama, 2010); ω_{bj} is the objective weight of indicator k calculated by EW method (Xia et al. 2019).

Calculation of T_i: The real-time migration data was introduced into the radiation model. T_i can be expressed as:

$$T_i = \sum_{j=1}^{l}\sqrt{e_{ij}} \tag{3}$$

where l is 10, and e_{ij} is the migration data for people moving from i to j.

Calculation of s_{ij}: in heterogeneous environments, people usually move following road networks instead of straight lines, we applied an O-D travel time matrix, determined by a comprehensive travel time calculation

Table 1 City comprehensive development capacity evaluation index system

Target	Criterion	Index	Weight	Attribution
Economic profile	Intensive development	Regional GDP	0.079	Positive
		Proportion of secondary industry in GDP	0.012	Positive
		Proportion of tertiary industry in GDP	0.033	Positive
	Efficient development	Local government revenues	0.074	Positive
		GDP per capita	0.042	Positive
		GDP per area	0.020	Positive
People-orientedness	Population profile	Urbanization rate (permanent residents)	0.025	Positive
		Number of residents at year end	0.046	Positive
	Living standard	Total retail sales of consumer goods	0.067	Positive
		Resident savings deposits	0.057	Positive
	Infrastructure construction	Per capita urban road area	0.027	Positive
		Gas penetration	0.029	Positive
		Number of medical beds per 10000 people	0.013	Positive
	Urban-rural integration	Ratio of urban and rural per capita disposable income	0.012	Negative
		Ratio of urban and rural per capita consumption expenditure	0.016	Negative
Culture and education	Cultural development	Number of books per 100 people in the public library	0.044	Positive
		Science and technology expenditure	0.098	Positive
	Education development	Number of full-time primary and secondary school teachers per 10000 people	0.042	Positive
		Education expenditure	0.063	Positive
Ecological sustainability	Land utilization	Area of built-up area	0.096	Positive
		Area of public green space in built-up area	0.076	Positive
	Industrial disposal	General comprehensive utilization of industrial solid waste	0.016	Positive
		Sewage treatment plant concentration treatment rate	0.015	Positive

Notes: Data source, China City Statistical Yearbook (2017); Hubei Statistical Yearbook (2017); Hunan Statistical Yearbook (2017); Jiangxi Statistical Yearbook (2017). GDP, gross domestic product

process, into the radiation model; thus, an irregular intervening space based on the road and rail accessibility replace circles centered at the origin.

$$D_{ij} = Min(R,G) \quad (4)$$

where D_{ij} is the shortest travel time from i to j; G is the time required for an optimal route through highways, obtained from the Baidu Maps Application Programming Interface (API); and R is the shortest time calculated based on the railway traffic dataset. Note that if direct travel by train from i to j is not possible, D_{ij} is the driving time required on highways.

3.3 Network structure measures

Evaluating the complex configurations of spatial interaction plays an important role in making policies for concrete regional management. As such, we aim to identify three essential features of the network, including:

(1) What the connection pattern of the entire system is?

(2) How communities and their hidden local organization present?

(3) What role each city plays in the network?

With these aims, we apply a variety of novel network analysis methods for further analysis, introduced as follows.

3.3.1 City-size distribution

Regressing the 'importance' of cities onto a rank-size distribution is a major route in regional research, which not only informs the hierarchical organization of cities but also provides a comprehensible statistical benchmark (Batty, 2013). In this paper, based on the degree of external functional linkages—the capacity for one city to connect others—city-size distribution is used to examine the hierarchical structure of the study region. The degree of a city's external linkages or local importance can be expressed as:

$$I_i = \sum_{j=1, j\neq i}^{n} (T_{ij} + T_{ji}) \tag{5}$$

where T_{ij} represents migration flows from i to j, T_{ji} represents migration flows from j to i, and n is the number of cities in the study region.

3.3.2 Chordal graph

The volume and properties of inter-city relationships are characterized by chordal graphs. As illustrated in Fig. 2, arcs represent the city's degree of external linkages. The longer the arc, the greater the external linkage degree. The width of the chord represents the intensity of connections between cities. This helps us to understand the topological patterns of a city network and measure its polycentric structure. For example, the width of chord l indicates that the connection strength between city A and B is 11, while the length of arc m indicates that the total external linkages degree of city A is 31.

3.3.3 Infomap algorithm

Community detection disintegrates networks into sub-units or communities comprised sets of highly interdependent nodes (Blondel et al., 2008). Given the asymmetric connections in the radiation model, the Infomap algorithm is employed. This algorithm uses random walks to identify the hierarchy of links and nodes in the network and detects communities using an entropy decomposition method (Zhong et al., 2014). It has significant adaptability for network community detection with full consideration of vector characteristics, including node features, edge weights, and connection directions.

3.3.4 Global importance

Given the context of the city network, the importance of a node depends on its own attributes as well as its functional connections with other nodes, both adjacent and nonadjacent. A novel evaluation method based on an efficiency matrix is introduced to thoroughly analyze node position. The technical details of this method are shown as follows.

First, we introduce two concepts, node efficiency and transition efficiency. Node efficiency e_i describes the convenience of reaching other nodes, whereas transition efficiency e_{ij} represents accessibility from i to j and is inversely proportional to the length of the shortest path between them:

$$e_i = \frac{1}{n-1} \sum_{j=1, j\neq i}^{n} \frac{1}{d_{ij}} \tag{6}$$

$$e_{ij} = \frac{1}{d_{ij}} \tag{7}$$

In both Equation (6) and Equation (7), d_{ij} is the travel time from i to j, and n represents the number of cities in the study area. The larger the value of e_i, the more likely the node is to be in the center of the network, and the greater role it plays in the transfer process.

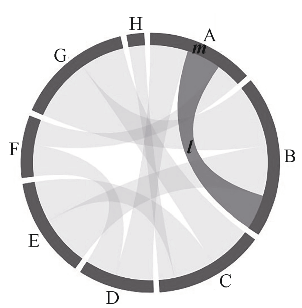
Second, we construct a transmission efficiency matrix to explain the interdependence among cities:

$$H = \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_n \end{bmatrix} = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix} \tag{8}$$

Thus h_i, city's relative importance, can be expressed as:

$$h_i = \sum_{j=1, j\neq i}^{n} h_{ij} = \sum_{j=1, j\neq i}^{n} e_{ij} e_j \tag{9}$$

Third, combining with the degree of local importance in Equation (5), the importance contribution matrix of cities can be defined as:



City	City	Linkages
A	B	11
A	D	12
A	F	8
B	G	20
…	…	…

Fig. 2 Chordal graph schematic

$$D=\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix}=\begin{bmatrix} I_1h_1 \\ I_2h_2 \\ \vdots \\ I_nh_n \end{bmatrix}=\begin{bmatrix} I_1\sum_{j=2}^{n}e_{1j} \\ I_2\sum_{j=1,j\neq 2}^{n}e_{2j} \\ \vdots \\ I_n\sum_{j=1}^{n-1}e_{nj} \end{bmatrix} \tag{10}$$

Finally, after normalization, the global importance of a city d_i' can be expressed as:

$$d_i'=\frac{I_i\sum_{j\neq i}^{n}(e_{ij}e_j)}{\sum_{l=1}^{n}(I_l\sum_{m\neq l}^{n}(e_{lm}e_m))} \tag{11}$$

3.3.5 Centrality and power

Based on the works of Neal (2011a) and Zhao et al. (2017), the directed alternative centrality (DAC) and power (DAP) are used to explore the functions of the city. The *DAC* can be expressed as:

$$DAC_i=\sum_{j=1}^{n}\left[T_{ij}\ln(T_j^+)-T_{ij}\ln(T_j^-)\right] \tag{12}$$

where T_j^+ and T_j^- stand for the in-degree (total number of links coming in) and out-degree (total number of links going out) of city *i*. If the DAC is positive, the city is agglomerative; otherwise, it is diffusive.

In comparison, the *DAP* reflects cities' ability to control or affect the fluxes of resources, which takes the following form:

$$DAP_i=\sum_{j=1}^{n}\frac{T_{\vec{ji}}}{T_j^-}ln(T_j^+) \tag{13}$$

According to the DAC and DAP values, four types of cities can be identified: 1) quintessential cities, both central and powerful, 2) hub cities, central but not powerful, 3) gateway cities, powerful but not central, and 4) peripheral cities, neither central nor powerful.

3.4 Comparison with the gravity model

To systematically discuss the applicability of spatial interaction laws and models, we perform a comparison with the gravity model, whose general form can be specified as:

$$T_{ij}=\frac{m_i^{\alpha}n_j^{\beta}}{f(r_{ij})} \tag{14}$$

where T_{ij} denotes the probability of interplay between locations *i* and *j*, with masses (sizes) m_i and n_j, respectively, at a distance of r_{ij}, and all of them are the same as that in radiation model to ensure the effectiveness of comparison. Additionally, two adjustable exponents, α and β, represent the scale elasticity of locations *i* and *j*. The function $f(r_{ij})$ is introduced to adjust the degree of distance decay. Here, we employ the most conventional gravity model with $\alpha = \beta = 1$, and $f(r_{ij})$ as a power-law function of distance whose power exponent is 2.

4 Results

4.1 Hierarchical and distribution features

Fig. 3 shows the relationship between the original rankings and the strength of external linkages. First, the strength distributions present power-law behaviors with exponent of 0.56, meaning that the city network of the YRMR demonstrates a small-world pattern with scale-free and hierarchical organization (Watts and Strogatz, 1998); namely, there is a hub-like hierarchy in YRMR UA that a few big cities play the role of central hubs and control the most connections. Second, we take the logarithm of rank as the independent variable and the logarithm of corresponding external linkages as the dependent variable to run a linear regression. As R^2 exceeds 0.90, the strength distribution seems to highly satisfy Zipf's law. At the same time, the value of Zipf's index (0.56) shows a relatively flat pattern with small regional differences within the entire UA.

Furthermore, Fig. 4 visualizes the topological structure of the network using chordal graphs. Taken as a whole, it shows a polycentric network form with Wuhan,

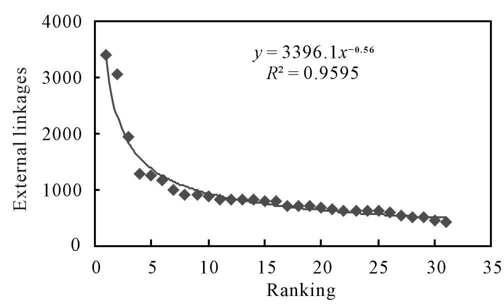


Fig. 3 City-size distributions within the Yangtze River Middle Reaches (YRMR) urban agglomeration (UA)

Changsha, and Nanchang as core cities in YRMR UA. As shown in Table 2, Wuhan holds the most external linkages (11.51%) with little differences with the second city, Changsha (10.28%). Besides, there are significant regional differences because of the heterogeneous city network. Considering the differences in three provinces, there is a single monocentric sub-network in Hubei Province with Wuhan as the center. More specifically, Wuhan accounts for 11.51% of interaction flows, followed by Yichang (3.07%), resulting in a high urban primacy ratio of 3.74 (i.e., 11.51%/3.07% = 3.74). In contrast, due to the polycentric construction of the Changsha-Zhuzhou-Xiangtan Metropolis, the urban primacy ratio of Changsha in Hunan Province is 2.44, lower than that of Wuhan in Hubei Province. Jiangxi Province also contains a monocentric region, but with a low urban primacy ratio (1.50). The proportion of Nanchang's interaction flows (6.59%) is inferior to that of both Wuhan (11.51%) and Changsha (10.28%).

Judging from the spatial distribution, Fig. 5 represent the distribution features of relationship intensity in YRMR UA. Generally, there are dense and extensive interactions among cities, but the intensity is unbalanced. Strong connections are distributed not only in the megacities and their surroundings like Wuhan, Changsha, and Nanchang, but also in the periphery of the study area, such as the Yichang-Jingzhou-Jingmen group, Dongting Lake Region, and Xinjiang River Valley Region. Meanwhile, links are also extensive between non-central cities across provincial administrative boundaries, such as Xianning-Yueyang, Changsha- Pingxiang, Changde-Jingzhou, and other city pairs. However, the core cities (Wuhan, Changsha, and Nanchang) are not closely linked. In summary, these complex horizontal and vertical connections together constitute an interwoven network structure.

4.2 Community structure

The results of community detection are shown in Fig. 6. Cities are divided into five communities that are organized by sets of highly interconnected nodes. Overall, the generated community borders are established based on regional agglomerations boundaries and provincial administrative divisions. The community results are consistent with the reality that the spatial structure planned by the government. However, some cities are separated from the political sub-urban agglomeration framework into adjacent communities. For example, Qianjiang,

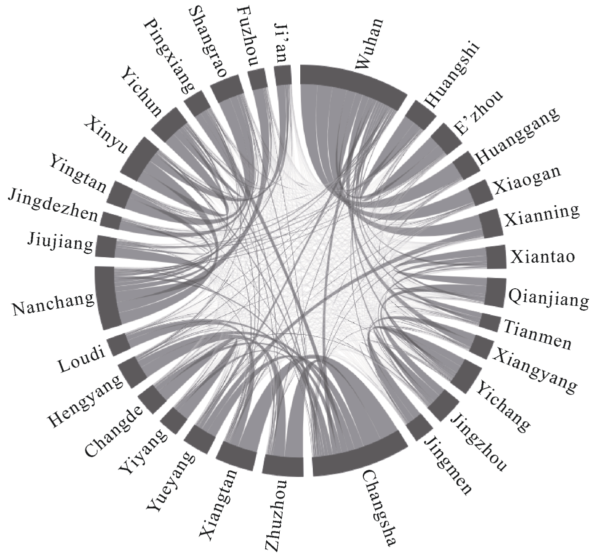


Fig. 4 Chordal graphs within the Yangtze River Middle Reaches (YRMR) urban agglomeration (UA)

Table 2 Percent of cities for the strength of external links

Province	City	Percent (%)
Hubei	Wuhan	11.51
	Yichang	3.07
	Qianjiang	2.98
	Jingzhou	2.8
	E'zhou	2.77
	Xianning	2.76
	Huangshi	2.66
	Xiantao	2.37
	Huanggang	2.34
	Xiaogan	2.18
	Jingmen	2.11
	Xiangyang	1.97
	Tianmen	1.52
Hunan	Changsha	10.28
	Zhuzhou	4.22
	Xiangtan	3.94
	Hengyang	2.75
	Yueyang	2.72
	Changde	2.37
	Yiyang	2.09
	Loudi	1.81
Jiangxi	Nanchang	6.59
	Xinyu	4.37
	Yichun	3.4
	Shangrao	3.05
	Yingtan	2.34
	Jiujiang	2.15
	Pingxiang	2.08
	Fuzhou	1.71
	Ji'an	1.67
	Jingdezhen	1.42

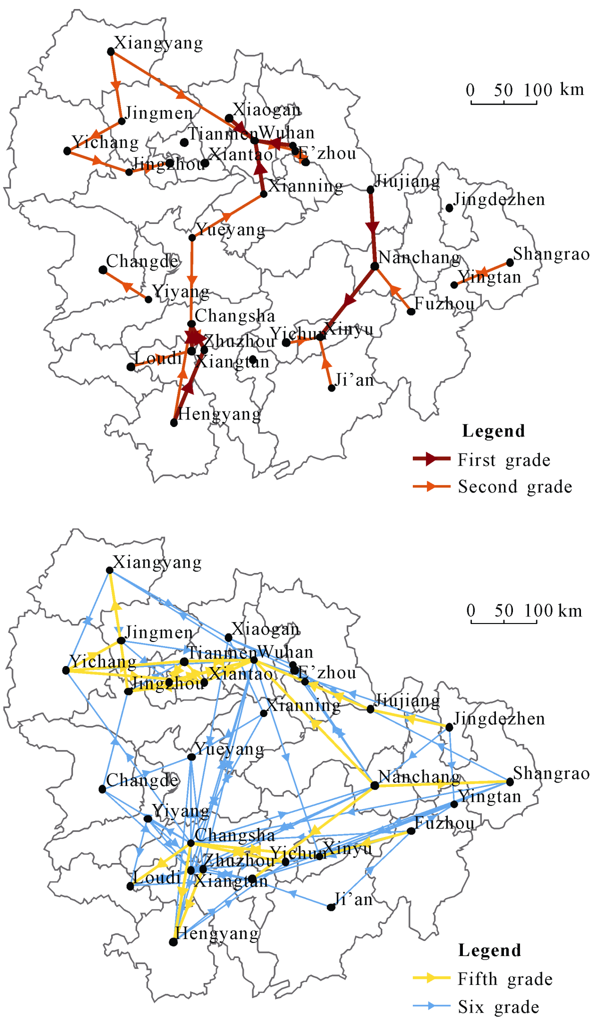


Fig. 5 Linkage distribution in different grades within the Yangtze River Middle Reaches (YRMR) urban agglomeration (UA) calculated by improved radiation model

Tianmen, and Xiantao, which belong politically to the Wuhan metropolitan area, are categorized into the Yichang-Jingzhou-Jingmen cluster. Changde and Yiyang are separated from the Changsha-Zhuzhou-Xiangtan city group. By contrast, all the cities in Jiangxi Province form a community. This shows that factors are well used and relatively flexible in Hubei and Hunan provinces, which also further verifies the findings of the polycentric structure analysis mentioned above. Besides Wuhan, Changsha and Nanchang, Yichang, Changde and other cities on the edge of the region are developing rapidly.

Table 3 shows the corresponding statistical results of interregional relations among different groups in YRMR UA, reflecting the regional heterogeneity. First, Changsha Group have the largest out and in-degree, which has intensive interactions with other regions, especially with

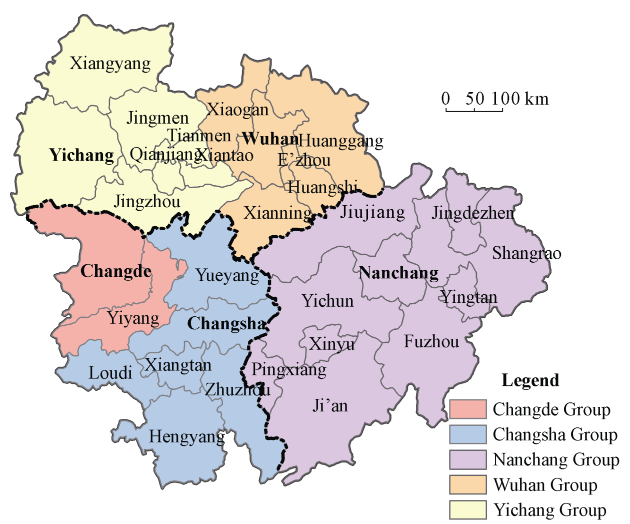


Fig. 6 Community structure within the The Yangtze River Middle Reaches (YRMR) urban agglomeration (UA)

Table 3 Interconnection between communities in the radiation model

	Wuhan Group	Changsha Group	Nanchang Group	Yichang Group	Changde Group	Out-degree
Wuhan Group		10.87	5.44	12.13	0.34	28.78
Changsha Group	9.20		10.46	1.97	7.95	29.57
Nanchang Group	6.69	9.62		1.63	0.67	18.61
Yichang Group	9.20	3.26	2.09		1.67	16.23
Changde Group	1.00	3.60	0.84	1.38		6.82
In-degree	26.10	27.35	18.82	17.11	10.63	

Wuhan and Nanchang Groups. Second, in the whole UA, the spatial interaction between Yichang Group and Wuhan Group is the strongest, while the marginal area, Changde Group, lack of connections with others.

4.3 Position and functions of cities

We explore the role of each city plays in the network, visualize the global importance based on their external relations in Fig. 7, and then divided cities into four categories according to their functions in Fig. 8. For the global importance, the spatial distribution reveals to be three remarkable core-peripheral structures. Wuhan, Changsha, and Nanchang are the most important cities in YRMR UA, around which the global importance decline from their surrounding areas to the further periphery cities. Specific to the provinces, Wuhan plays a vital role in Hubei Province, where the distance-decay effect is steeper than other regions; in Hunan Province, Changsha, Zhuzhou, and Xiangtan are three pillars, but the importance value of other cities are really low; and in Jiangxi Province, the two pillars are Nanchang and Xinyu, both of which do not play significant importance roles in the entire UA.

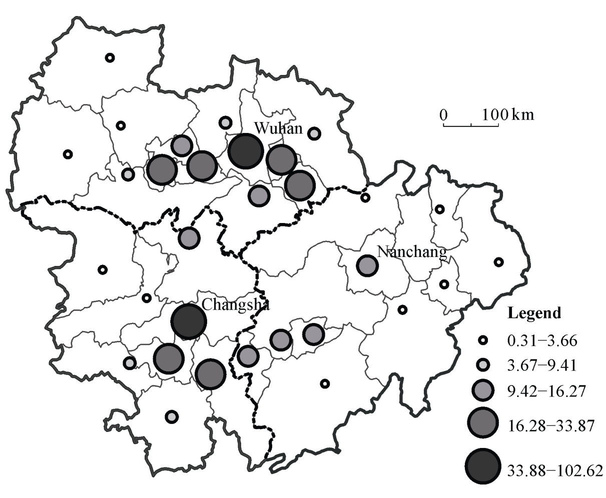


Fig. 7 Global importance within the Yangtze River Middle Reaches (YRMR) urban agglomeration (UA)

Fig. 8 shows a scatterplot composed by the DAC and DAP values. On the one hand, the DAC distribution indicates that: 1) only a limited number of cities, like Wuhan and Changsha, belong to agglomerations; and 2) most cities in YRMR UA are diffusion ones, whose diffusion intensity are concentrated in the range of −2000 to 0. In particular, cities at the edge of the study region, such as Hengyang, Xiangyang, and Ji'an, have strong ability to spread. On the other hand, four types of cities are identified by combining the results of DAC and DAP: first, Wuhan and Changsha are quintessential cities, with high DAC and DAP values, characterized by large economies of scale and high levels of urbanization.

Second, Nanchang is a gateway city, powerful but not central. Some cities adjacent to Wuhan and Changsha, such as Yichun and Xiantao, also fall into this category. Third, Qianjiang and Xinyu are typical hub cities, usually referred to as the most significant nodes for connecting spaces and acting as spatial bridges between different cities within the city network. Fourth, cities like Jingdezhen, Tianmen, and Jingmen are neither central nor powerful, and thus belong to the category of peripheral cities.

5 Discussion

The aims of this work are to 1) reconsider the conception of city network and 2) improve its measurement for delineating urban system. To fulfill these aims, we investigated three issues those are directly derived from the city network research: first, based on our empirical analysis, we summarized the spatial structure characteristics of UA in the network age. Second, adding a

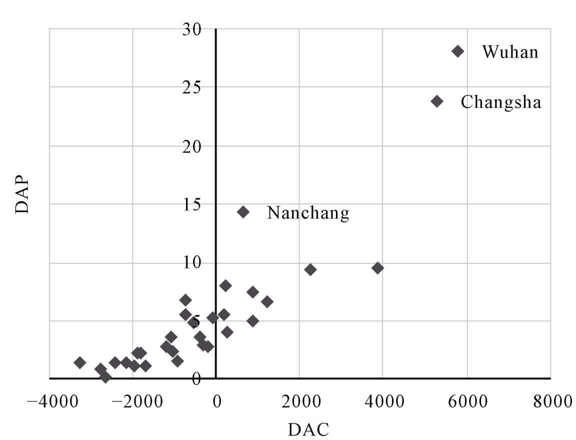


Fig. 8 Scatter plot of directed alternative centrality (DAC) and power (DAP)

comparative study on spatial interaction models, the models' applicability and their linkages between spatial interaction laws have been also discussed deeply. After that, we put forward several policy recommendations related to the healthy development of YRMR UA.

5.1 Network configurations of urban agglomeration

Theoretically, spatial structure transformation is a fundamental dimension of urban and regional planning. Especially for UA, a dense and urbanized region, 'is not only a geographically continuous entity but also a closely integrated spatial existence of networks' (Fang and Yu, 2017). Analyzing the unbalanced interactions between cities and the structure of city networks provides practical guidance in revealing regional differences, formulating spatial planning policies, and thus achieving sustainable development of social-economic (He et al., 2017; Tian and Wang, 2019). From this empirical analysis of the YRMR UA, the proposed framework yields satisfactory results in assessing the complicated nature of inter-city relationships and the existence of various configurations of the city network. The results demonstrate that, the spatial structures of the urban system referred to a network-like pattern characterized by multicentricity, complexity, and coordination, on the urban agglomeration level.

The flat characteristic of city size distribution, rather than a prominent pyramid one, macroscopically presents a network structure of the urban system. This finding is closely related to the spatial structure of urban systems from different dimensions. In terms of connection pattern of the entire system, the regional differences in the intensity of connection are narrowed, as non-hierarchical relationships replace partial vertical linkages. That is, the peripheral cities make direct interrelationships with hub and gateway cities in functional regions rather than only with core cities, which reduce core cities' dominance of regional cities and improves other nodes' important roles playing in the whole urban system. As a result, cities' centralities or positionalities include more than just size and distance. Additionally, the significant connections between peripheral and regional cities affect the spatial structure on communities, result in forming much more city groups with no restrictions on central cities, and involve a more polycentric configuration. These network performances, together with the evidence that regional centers, hub or gateway cities, have strong connections with core cities, forms a flat multi-level organization with the centrality of core cities at the primary grade and the centrality of regional cities at a secondary grade.

5.2 Re-thinking of city network and spatial interaction models

Noticeably, existing research has shown that the traditional gravity model in measuring the spatial structure of the urban system, usually relates to a marked hierarchical order (Camagni and Salone, 1993). Therefore, we apply the same network analysis framework and use the gravity model to measure the spatial structure of urban agglomeration, to 1) explore the characteristics of hierarchical spatial organization, 2) discuss the evolution of conceptual and theoretical issues on urban system, and 3) verify the applicability and validity of spatial interaction laws and models. Some useful conclusions are presented as follows:

First, the statistical-data-based gravity model was the basic rationale for understanding and analyzing economic activity and spatial interaction, however, comparative analysis shows that the place-based characteristics such as distance and size play a more important role in the gravity model, and the spatial configuration does order in a hierarchy organization. The Zipf's index (1.20), compared with the results in radiation model (0.56), indicates larger regional differences than seen in the above network system which forms a slender hierarchy structure. As shown in Fig. 9, the diffusion of interactions downward in a hierarchical manner due to the underestimation of horizontal relationships and overestimation of vertical relationships, especially the connections between two cities those are geographically close. As such, the centrality of core cities is exaggerated, while in other cities the centrality is underestimated. This widens the regional differences and presents an insignificant polycentric structure composed of fewer communities. All in all, a pattern of individual multi-group competition, remarkable regional imbalance, and the marginalization characteristics are intensified in the hierarchy system.

Second, through the comparison and analysis, we re-view and re-think the evolution of the conceptual and theoretical issues about the urban system. Obviously, it is the work of Christaller (1966) and Ullman (1941), the

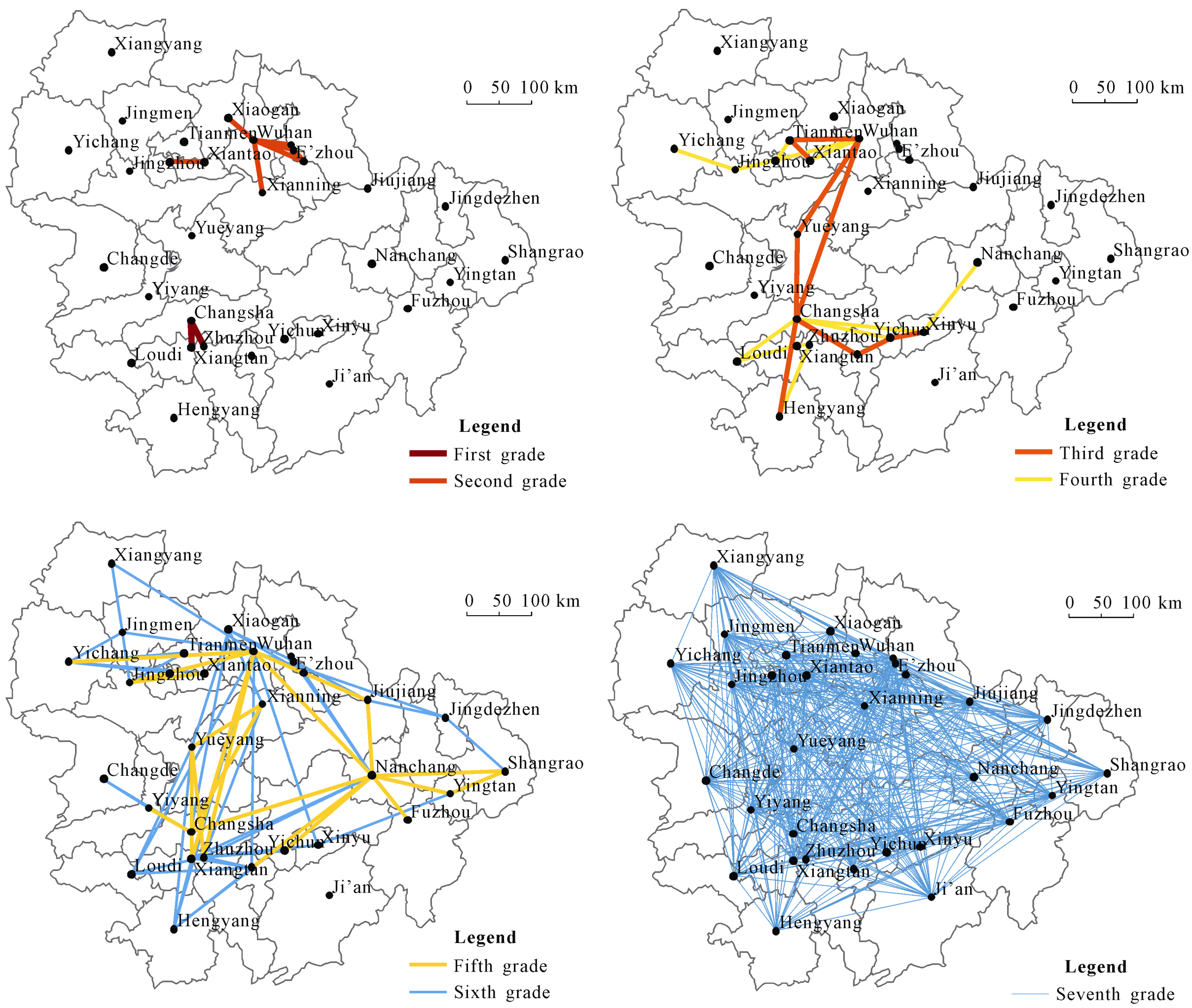


Fig. 9 Linkage distribution in different grades within the Yangtze River Middle Reaches (YRMR) urban agglomeration (UA) calculated by traditional gravity model

central place theory, that launched this field of research and have been the traditional base for understanding external functional relationships (Taylor et al., 2010; Mulligan et al., 2012). The urban system, first defined by Berry (1964), is a set of physical instances of interdependent urban nodes that linked with each other but limited by the scale and distance effects. That is, the one-way flow (vertical relationship) is established from higher to lower classes of cities, which prompts the spatial structure of urban system to be organized in a hierarchy way, presents a prominently unbalanced distribution, and yields monocentric urban system (Batten, 1995; Dennis et al., 2002; Burger et al., 2014). However, many researchers (Meijers, 2007; Neal, 2011b; Dadashpoor et al., 2017) suggested that a size-based hierarchy had been replaced or augmented with a network-based hierarchy during the twentieth century. Cities are more than isolated systems consisted of individual cities in 'spaces of places' (Dadashpoor et al., 2017), but linked together within and outside the network nested with each other, collectively and cooperatively. Their position and centrality can be explained to the functional differentiation or integration into the outer regions of a complex network, more than the distribution regularity of something fixed within them (Neal, 2011b). The changes of the integrate and incorporate region are caused by the two-way flows, within (horizontal) and across (vertical) different classes of cities (Taylor et al., 2010). Furthermore, the horizontal relationships, or complementarity, which further explain the attributions of nodality, size neutrality, and multicentricity in city network (Meijers et al., 2018).

Many argue that there is a 'paradigm change' or 'shift' with the 'network paradigm' superseding the 'central place theory' (Batten, 1995; Meijers, 2007; Malý, 2016); they are regarded as being in opposition to each other. However, both the 'spaces of places' and 'spaces of flows' are running parallel in the world (Taylor et al., 2010), that is, central-place features—locational fix—still valid (Hesse, 2010). Taylor et al. (2010) describe them as two general processes of external urban relations, namely, central place theory interprets the hierarchical relationships between an urban place and its hinterland at "local" scale, while the network paradigm primarily reveals horizontal spatial structures at 'non-local' scale. Therefore, theories should be complemented with each other to support and cope with the complex and changing urban system.

Third, for the application potential of spatial interaction models, we draw two main conclusions. On the one hand, the comparison results indicate that the improved radiation model, integrating both interaction data (passenger flow data) and node-attribute data (socioeconomic statistics), is a highly suitable spatial interaction model, consistent with the contemporary trend of network-based economic development in urban regions. On the other hand, as the radiation model measures the spatial interactions in an anisotropic way, it is illuminating for accurately measuring other characteristics of the city networks, like the functions of cities, heterogeneity of asymmetric connectivity, and robustness and resilience of the urban system. By comparison, the results calculated by the gravity model refer to more obvious hierarchical rules, which emphasizes the placed-based attributes and physical proximity on spatial interaction between cities. The gravity model could be an appropriate model to assess the radiation potential or supply capacity at local scales. For example, the potential model and retail model (Reilly, 1929; Huff and Jenks, 1968) derived from the traditional gravity model are classic models for analyzing the market area and defining urban hinterland.

In summary, our empirical analysis demonstrates the improved radiational model's validity and advantages in assessing the complicated nature of inter-city relationships at the urban agglomeration scale. However, the gravity model may perform better in assessing the urban-hinterland (hierarchical) relations at local scales.

5.3 Policy implications

Based on the features of complex and strong inter-city relationships, several points that have significant influence for policy-making in the integrated development of UA are discussed as follows.

First, corresponding policies should be formulated to dwindle regional differences and enhance regional competitiveness in the future. Our research founded out that, Wuhan and Changsha have strong agglomeration effects, especially the Wuhan and its hinterland, which has formed a monocentric structure with Wuhan as the core; however, the central city of Nanchang does not fully realize its driving effect. Meijers (2005) pointed out that, polycentric spatial structures are often associated with the concept of integration. The flow of Wuhan is suggested to split into developing cities in order to coordinate the development and optimize the polycentric spatial structure across the entire urban agglomeration. However, it should be given full play to Nanchang's "leading role", promoting the economic development in Jiangxi Province. Potential nodes (such as Yichang, Changde, and Xinyu) can be pushed to become local development poles. Besides, the efficiency of traffic accessibility should be increased for the cities with a low degree of external linkages in peripheral regions (such as Loudi and Ji'an in Fig. 4), so as to strengthen the interaction between cities and reduce the regional differences.

Second, it is an urgent task to broken administrative borders whose exists reduce the advantages of spatial proximity (Capello et al., 2018). Since YRMR UA consists of three provincial capitals and other 28 cities in three provinces which represents obstacles to facilitate cross-border cooperation and integration across multiple administrative-level organizations. Regional administrative borders still impede the free flowing of various production factors. According to the spatial distribution analysis, capital cities not sufficiently link with each other (Fig. 5); while in the community detection analysis, the generated community borders are established based on provincial administrative divisions (Fig. 6). To address the challenges, coordinating the very provincial intergovernmental relation is the key to realizing the integration of regional economies (Han and Liu, 2018). Specifically, we suggest that, city governments designed at the top level should work together and make their decisions effective for the UA as a whole. Additionally, there is a serious unbalance among these communities, however, regarding to hub and gateway cities having an important significance to local and global development (Neal, 2011a), connecting these cities (such as Qianjiang and Xinyu in Fig. 8) with quintessential (Wuhan and Changsha) and peripheral cities (Jingdezhen, Tianmen, and Jingmen) through express transportation and business corridors would support to boost the economic development of sub-group (especially Changde and Yichang Groups in Fig. 6).

Third, the status of the core-peripheral structure, as shown in section 4.3, should be appropriately weakened. According to the borrow size theory in the city network externalities field, city size can be borrowed no longer relying on geographical proximity, but on the embeddedness in networks (Hesse, 2016). Cities should participate in the division of labor and cooperate with others within the whole UA rather than independently. An effective solution is expanding the industrial cooperation and implementing industry gradient strategy (Hou et al., 2015). We can relocate factories from center cities (Wuhan, Changsha, and Nanchang) to their surrounding developing regions (such as Huanggang, Zhuzhou, Jiujiang), thus providing opportunities for core cities to accomplish industrial upgrading and for developing cities to accelerate the industry transfer. Moreover, as Meijers and Burger (2017) suggested, there is an 'absence of connection between size and the presence of metropolitan functions', that is, each city plays an important role in the city system whatever its size may be. Quintessential cities (Wuhan and Changsha), as regional economic growth poles, give an impetus to the entire region, but should be cautious to avoid the shadow or competition effects of agglomeration on surrounding areas. Policy-makers should be possible to manage the benefits of big cities in a network of medium and small cities through the planning principle of 'borrowed size' (Meijers et al., 2016).

6 Conclusions

The research of spatial interaction can explore the external relations of cities and reveal regional disparities which are important for policy-making in the integrating and sustainable development of UAs. In this paper, with focuses on rethinking of the spatial interactions and developing a new perspective with network-like relationships highlight, we take the YRMR UA as the case study area and analyze its spatial configurations. The spatial logic of the urban system in the context of 'space of flows' have been discussed; the applicability and validity of spatial interaction models have been verified; and corresponding policies for regional sustainable development from an inter-city relationship perspective have been proposed.

The main conclusions are as follows. First, under the background of the 'space of flows', combining with the 'city network paradigm' and 'central place theory' can better express the spatial configurations of city systems. Second, the results validate the potentialities of a multi-analysis framework to assess the spatial configurations of the city network based on the improved radiation model and network analysis tools. The spatial structures of YRMR UA mainly manifest as network-like patterns, characterized by multicentricity, complexity, and coordination. Wuhan-Changsha-Nanchang has shaped a triangle structure leading the metropolitan to rise and maintaining interrelationships with their surroundings. Third, the applications of spatial interaction models should be considered according to specific conditions. The radiation model performs better in measuring the inter-city relationships at non-local scales, while the gravity model is suitable for analyzing the hierarchical spatial interactions between an urban place and its hinterland at 'local' scale. In summary, the methodological framework proposed for reconsidering, characterizing, and evaluating city system contribute to understanding the relationship among cities and offer a new perspective for regional sustainable development to guide integrated spatial planning for UAs, which can apply to other city regions.

However, this paper has several limitations, and future research should consider several directions. First, there are two defects in the process of city network construction: 1) The construction of index system about comprehensive competitiveness involves the selection of each index and the determination of the weight, which is subjective and difficult to comprehensively consider all factors. 2) The estimate of transport accessibility is not comprehensive, since it only considers time cost, and takes no account of transfer time and money costs. Second, due to the limitation that the Tencent migration data is not available until 2015, we have not explored the long-term evolution of spatial configuration. Third, in addition to the physical space, the cyberspace that carries information flow plays an important role to the spatial interaction in the era of the network, applying the radiation model to explore the cyberspace and to find out its relation with physic space are worthy of attention in future studies. Furthermore, as illustrated in Lao et al. (2016) and Dadashpoor et al. (2017), spatial interactions among cities are highly dependent on the factors used to simulate it. Comparing economic networks based on the radiation model and other forms of networks (such as transportation and migration) is one of the interesting directions in the future. Finally, the intrinsic mechanism of spatial interaction and topological properties of city network are only parts of the research to be done; more importantly, the spatial process mechanism of spatial interaction to promote the sustainable development of urban system must be investigated.

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