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Research article

Spatial relevancy of digital finance in the urban agglomeration of Pearl River Delta and the influence factors

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Abstract: At present, the rapid development of digital finance is closely related to the economic development of urban agglomerations. An urban agglomeration provides conditions for digital finance to form a spatial relevancy network. Exploring the development of digital finance in the urban agglomeration of the Pearl River Delta (PRD), which is the bellwether of China's economy, can provide important practical experience for the economic construction of coastal areas and even the whole country. In this study, using the urban digital finance index issued by the Guangzhou Institute of International Finance, we measured the intensity and direction of the spatial relevancy of digital finance in the PRD urban agglomeration by applying the gravity model, modified in the calculation of distance between cities. Then, we examined the influencing factors of the spatial network of digital finance through the quadratic assignment procedure (QAP) approach. The achieved results are as follows. First, although the overall density is low, the network is tightly connected and stable. Second, in terms of individual characteristics of the network, Guangzhou, Shenzhen, Foshan still play the leading roles in the spatial network of digital finance. Third, the digital finance network does not have bidirectional spillover block. The links between segments are relatively loose. Fourth, economic level, degree of opening up, Internet level and geographical location are important factors in driving the formation of spatial relevancy of digital finance in the PRD urban agglomeration.

Keywords: spatial relevancy; digital finance; PRD urban agglomeration; social network analysis; urban digital finance index

1. Introduction

The economy and finance should develop synergistically. A well-functioning economy often promotes a sound financial system, and in turn, the improvement of financial services also creates favorable conditions for the rapid growth of the economy [1]. Finance is underdeveloped in some areas, especially in the countryside, where there is even a lack of financial services [2, 3]. Also, middle and small-sized enterprises are usually encountering financing difficulties [4, 5]. Therefore, how can financial exclusion effectively be avoided? How can we extend the covering of financial services, increase their efficiencies and inclusion and then guide the rational allocation of financial resources? [6, 7] As a result, digital financial inclusion was born to address all these issues, which have been the focuses of the current era [8–15]. With information technology developing, the integration of digitalization and financial inclusion is deepening [16–20], which leads to a wider coverage of inclusive finance [21, 22].

Urban agglomeration, which is an evolutionary result of urban integration, creates an important platform for the development of digital finance, with the close economic connection of interior cities. Urban agglomerations are regarded as the superlative spatial structure formed by big cities. They take one or several cities as the cores and drive the coordinated development of surrounding cities to form a comprehensive urban group [23, 24]. Cities in urban agglomerations are closely connected in transportation, communication, industrial cooperation, population flow, capital exchange and so forth, which provides some fundamental conditions for digital finance to build a spatial network [25, 26]. The significant development of digital financial inclusion in China has benefited from the formation of urban agglomerations. There are several urban agglomerations playing vital roles in Chinese economy, like the Yangtze River Delta, the Pearl River Delta and the Beijing-Tianjin-Hebei Region. The urban agglomeration in the Pearl River Delta (PRD) consists of Guangzhou, Shenzhen, Foshan, Dongguan, Huizhou, Zhongshan, Zhuhai, Jiangmen, Zhaoqing, Shanwei, Yangjiang, Qingyuan, Yunfu and Heyuan*. It is one of the most energetic economic zones in the Asian-Pacific region. It is also an advanced manufacturing base and a modern service base with global influence. As the bellwether of the Chinese economy, exploring the past development of digital finance in the urban agglomeration of PRD will provide important practical experience for the economic construction of coastal areas and even the whole country. Accordingly, in this paper, we focus on the spatial relevancy of digital finance in the PRD urban agglomeration and then find its driving factors. Our results can deliver some useful information on the development of digital finance in PRD, relying on which one can derive some appropriate policies.

At present, most literature prefers to discuss the effects of digital financial inclusion on the economy; for instance, see Manyika et al. [27], Ji et al. [28], Deng et al. [29], Li et al. [30], Sun and Tang [31], Li and Ma [32] and so forth. Fewer studies discuss the spatial features of digital finance [33–37], as both Wang and Guan [33] and Shen et al. [34] revealed a geographical spatial aggregation distribution and clustered pattern in national income groups. Liu et al. [35] constructed the spatial association network of China's digital financial inclusion development directly using the simple correlation coefficients. Dong et al. [36] explored the regional disparity in digital finance inclusive development and its sources in the Yangtze River Delta economic cluster. Li et al. [37] examined the effects of digital financial inclusion on household consumption by applying spatial econometric models. For the present study, we selected the PRD urban agglomeration as the research object, due not only to its regional advantages but also to its significant economic development in recent years. Due to the distinct differences among the cities in PRD, we had to extend the technical links used in the existing literature. Most authors usually apply straight-line length to measure the distance between two cities, when improving the classical gravity model. However, in practice, the relevance between two cities depends on not only the

*Shanwei, Yangjiang, Qingyuan, Yunfu, Heyuan are involved after replanning, and the others are original.

straight-line distance in geography, but also the traffic convenience. Thus, using the traffic accessibility to measure the distance between two cities is more practical. Therefore, in this paper, according to the development of traffic networks and the change of passage ways like intercity high-speed rail, the authors improve the distance measurement in the gravity model from two dimensions, the highway distance and the minimum time cost. Then, it is the first time measuring the spatial relevancy of digital finance in PRD urban agglomeration by applying the improved model.

With regard to the measurement of urban digital finance, rather than using the index of digital financial inclusion developed by Peking University, which has been widely analyzed in academia and practice but is inclined to measure the financial inclusion, in this paper, the index of urban digital finance developed by the team of Guangzhou Institute of International Finance (GIIF), issued in the Seventh Forum on Risk Management and Financial Statistics (2022)[†], is used to attain our research objective [38]. There are some other indexes of digital financial inclusion constructed in the existing literature [39–44], all of which mainly focus on the financial inclusion, lacking some digital elements. This index of urban digital finance issued by GIIF was compiled from three dimensions, including the digital finance service, the digital finance technology and the digital finance environment [45], so that it is more inclined to measure the digitization level of financial development, which is different from the existing indexes of digital financial inclusion. In addition, we further applied the analytic network process (ANP) and quadratic assignment procedure (QAP) to study the network structure and location characteristics of digital finance in the PRD urban agglomeration, and explored the driving factors of urban digital finance, such that some common problems like multicollinearity, caused by conventional statistical approaches, can be avoided.

This paper first explores the spatial relevancy of digital finance in the PRD urban agglomerations based on social network analysis and financial spatial spillover theory, which enriches the theoretical research on both digital finance and regional economy. It provides some facts on the reginal development of digital finance in the PRD urban agglomeration, from which we can analyze the current status and existing problems of digital finance in the PRD urban agglomeration. Furthermore, we examine various influencing factors for the spacial relevancy of digital finance in the PRD urban agglomeration. By analyzing the empirical results, we propose some specific policy recommendations to improve the network structure of digital finance among cities and promote the effective allocation of financial resources in the PRD. The findings of this paper can help policy makers expand the depth and breadth of digital finance and promote its development in the PRD urban agglomeration.

The rest of the paper is organized as follows. In Section 2, we have feature analysis on the spatial relevancy of digital finance in the PRD urban agglomeration by using social network approach. In Section 3, we examine the influencing factors in the formation of the spatial network structure of digital finance in the PRD urban agglomeration. In Section 4, we conclude the paper.

2. Feature analysis on spatial relevancy of digital finance

In this section, we first have analysis on the whole and individual features of the spacial network structure of digital finance in the PRD urban agglomeration, with reference to the indicators commonly used in social network analysis; then, we cluster 14 cities therein and explore the relations between blocks by applying the block model.

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2.1. Measuring the spatial relevancy of digital finance

As the current analysis on spatial relevancy is relatively mature, mostly using social network analysis and the block model, this section also follows this approach to portray the network structure of spatial relevancy of digital finance in the PRD urban agglomeration.

2.1.1. The modified gravity model

The gravity model, based on the formula of gravitation in physics, has been widely employed to measure the spacial relevancy. The formula of gravitation, shown as (2.1), measures the interaction between two objects,

$$Y = \frac{Gm_1m_2}{r^2}, \tag{2.1}$$

where G represents the gravitational constant, m_1 and m_2 represent the masses of the two objects, and r measures the distance between them. Subsequently, the gravity model was commonly used to measure the relevancy between cities and modified to various versions according to different understandings on the spacial relevancy theory. In this paper, in order to measure the relevancy of digital finance between cities in the PRD urban agglomeration in a proper way, the authors modify the gravity model by considering that gravity is proportional to the "quality" of the city and inversely proportional to the economic distance between cities. The so-called economic distance, which is the distance between two places expressed in terms of freight, time, and convenience, varies mainly due to technological advances in transportation and improvements in facilities.

In our context, the "Mass" of a city is represented by its financial size. On the one hand, the population, as the core of a city, is a primary element of financial services, which can be regarded as an important indictor measuring the "Mass" of a city; on the other hand, the total deposits and loans at the end of the year is a natural indicator reflecting the financial size of a city. Thus, we determine the proxy variable of the "Mass" of a city as the product of the urban population and the total deposits and loans at the end of the year. With regard to the distance between two cities, the spatial distance alone cannot well reflect the practical distance between them. In this paper, we integrate the spatial distance and time cost between two cities to measure the their distance, by fully considering the traffic and geographical conditions.

Thus, this paper characterizes the relevancy of digital finance in the PRD urban agglomeration with the modified gravity model, which is written as follows:

$$R_{ij} = \frac{K_{ij}\sqrt{P_iM_i}\sqrt{P_jM_j}}{D_{ij}T_{ij}}, K_{ij} = \frac{I_i}{I_i + I_j}, \tag{2.2}$$

where, i and j denote the cities in the PRD urban agglomeration, and R_{ij} is the index that we need to measure, which reflects the relevancy intensity between the digital finance of city i and that of city j. P_i and P_j respectively represent the permanent populations of city i and city j, and M_i and M_j respectively represent the total amount of year-end deposits and loans of city i and city j. The product of the population size P_i and the year-end deposits and loans M_i represents the "mass" of city i, that is, the urban financial scale. I_i and I_j respectively represent the digital finance indexes of city i and that of city j. Due to the asymmetric relevancy of the urban digital finance, in order to reflect the direction of the spacial network, the proportion of city i's digital finance level to the sum of both city i's and city j's digital finance levels is used to represent the modified empirical constant K_{ij}, denoting the contribution degree of city i in the joint development of digital finance of city i and city j.

With regard to the denominator in Eq (2.2), the distance index between two cities in the gravity model is modified from two dimensions: the optimal road distance and the time cost of passage between two cities. This paper uses the product of D_{ij} (the shortest highway distance between two cities) and T_{ij} (the minimum time cost of passage between two cities) to measure the distance index. Finally, this paper calculates the relevancy intensity of digital finance from city i to city j, according to Eq (2.2), and constructs a directed matrix depicting the relevancy between any two cities in the PRD urban agglomeration.

In contrast to other papers that use the gravity model and modify it, the general gravity model usually measures the distance between two cities using the difference in GDP between the two cities. However, we believe that this approach is not appropriate enough because the economic distance that exists between cities cannot be fully described by the difference in GDP alone. As economic distance is mainly influenced by transportation and technological development, we measure the economic distance in terms of the geographical distance and minimum time cost between cities. In addition, as we focus on the spatial relevancy of digital finance in cities, the financial scale of cities is used to measure the "quality" of cities.

2.2. *Indexes for social network analysis*

After building the relevancy network, it is necessary to perform a structural analysis with the network. The social network analysis approach is utilized to analyze the network from three perspectives: overall network characteristics, individual characteristics and spatial clustering characteristics. The specific indicators are summarized in Table 1 below.

Table 1. Indicators in social network analysis.

Overall network characteristics	Individual network characteristics	Spatial clustering characteristics
Network density (D): tightness of contact	Degree centrality (De): whether the city is centrally located	Bidirectional spillover block
Network efficiency (E): connection efficiency of the network	Betweenness centrality (Be): the city's ability to be uncontrolled	Net beneficiary block
Network connectivity (C): network robustness	Closeness centrality (Ce): the city's ability to control other cities	Net outflow block
Network hierarchy (H): city status gap		Broker block

2.2.1. Indexes for overall network analysis

The overall characteristics of the network can be described by network density, network efficiency, network connectivity, and network hierarchy. Among them, network density (D) can reflect the closeness between cities in the digital finance network, usually expressed as the ratio of the actual connections in the network to the maximum potential connections. The more connections there are, the greater the network density, indicating a more significant impact of the spatial network structure of digital finance on individual cities. Assuming that the number of cities in the network is M, the maximum number of potential connections is $M \times (M-1)$. If the actual connections in the network is N, the network density can be calculated as

$$D = \frac{N}{M \times (M-1)}. \tag{2.3}$$

The network efficiency (E) represents the number of redundant lines that exist in the network, given the principal components within it. In other words, it reflects the connection efficiency between cities in the entire network, taking into account the indirect connections that exist besides the direct ones between nodes. This is a reverse indicator. The lower the network efficiency is, the more the indirect connections between cities, implying closer connection between them, and the more stable spatial structure of digital finance and capable of achieving balanced development in cities. In this paper, the network efficiency is used to measure the connection efficiency of the PRD urban agglomeration in the spatial network of digital finance. The lower the network efficiency is the more channels of communication and closer the connection, implying that the digital finance network is more stable and facilitating the balanced development of the cities in the PRD region. Denote the redundant connections in the network by W and the most probable maximum redundant connections by $\max W$. The network efficiency can be described as

$$E = 1 - \frac{W}{\max W}. \tag{2.4}$$

The network connectivity (C) primarily measures the robustness of the spatial relevancy network. The higher the network connectivity is the more paths exist between cities in the network, implying that the spatial network of digital finance is more robust and less dependent on specific cities, and it is less likely to cause the collapse of the spatial network. If the network shows strong dependencies on PRD urban agglomeration, it means that many of the network's connections are linked to their respective cities, and once a problem arises, it could cause network paralysis. The higher the network connectivity is the stronger its stability. Assuming the total cities in the network is M, and the quantity of cities without any links is S, the network connectivity C can be calculated as

$$C = 1 - \frac{S}{M \times \frac{M-1}{2}}. \tag{2.5}$$

The network hierarchy (H) represents the asymmetric reachability of cities within a spatial network. A higher H implies that fewer cities occupy a dominant position, with the majority being peripheral cities, which are more susceptible to being controlled and governed. This results in a wider gap in city status, forming a hierarchical structure. As denoted in Eq (2.6), the quantity of symmetric reachability (the connection between two nodes) is V, and the maximum possibly symmetric reachability is $\max V$. The ratio of V to $\max V$ represents the proportion of symmetric reachability:

$$H = 1 - \frac{V}{\max V}. \tag{2.6}$$

2.2.2. Indexes for individual analysis

For individual characteristics, the following three indicators are usually adopted: degree centrality (De), betweenness centrality (Be) and closeness centrality (Ce). Among them, degree centrality is determined by the quantity of direct links between a node city and other node cities, reflecting the centrality of the city in the spatial network. The larger the degree centrality is, the closer the spatial connection between the core city and surrounding cities. In a directed network, degree centrality also has a direction, where the sum of links pointing towards a city node is represented as the in-degree, while the sum of links originating from the city node to other city nodes is represented as the out-degree. The calculation of relative degree centrality is shown by Eq (2.7), where N' represents the quantity of direct links between a city and other cities (the sum of in-degree and out-degree), N represents the network scale, and $2(N-1)$ is the maximum direct links a node can possess in a directed network. The ratio of N' to $2(N-1)$ is used to calculate the degree centrality:

$$De = \frac{N'}{2(N-1)}. \tag{2.7}$$

Betweenness centrality reflects the degree of "Betweenness" of a city in the spatial relevancy network, i.e., its ability to connect with other cities as a node in the network. If a node city is on the shortest path connecting multiple node cities, then that city acts as the "Middleman" connecting other cities, serving as a "Bridge" or "Hub" between them. The betweenness centrality indicates the extent to which the city controls other cities in terms of digital finance. It is expressed by Eq (2.8), where i is some node, y_{jk} sums the shortest paths connecting cities j and k, and $y_{jk}(i)$ represents the shortest path connecting cities j and k that passes through city i:

$$Be = \sum_j \sum_k \frac{y_{jk}(i)}{y_{jk}}. \tag{2.8}$$

Additionally, another important indicator to measure the centrality of a city in the city network is the closeness centrality. This indicator measures the shortest path distance between cities in the spatial relevancy network, with a larger value indicating that a city is more likely to be located in a central position in the network due to the shorter path distance to other cities. Denote by d_{ij} the shortest path distance between city i and city j, and then the formula for closeness centrality is calculated as

$$Ce = \frac{\sum_{j=1}^{N} d_{ij}}{N-1}. \tag{2.9}$$

2.2.3. Block model analysis

After working on the overall and individual characteristics of the network, the block model is adopted to cluster cities with similar functions in the spatial network. Through the block model analysis, the important roles played by PRD cities in the spatial relevancy network of digital finance can be characterized, thus revealing its structural characteristics. Generally, the CONCOR tool in UCINET 6.0 software is used to classify the cities in the spatial relevancy network into four blocks, and the specific classification criteria are shown in Table 2.

In Table 2, N_k denotes the quantity of cities in a block after classification, and $N_k \times (N_{k-1})$ denotes the maximum possible connections within this block. N denotes the overall quantity of cities in the entire network, and thus the maximum possible connections between the cities in this block is N_{k-1}. Therefore, the calculation method of the internal connection ratio within this block is shown as

$$\frac{N_k \times (N_k - 1)}{N_k \times (N-1)} = \frac{N_k - 1}{N-1}. \tag{2.10}$$

Table 2. Block model plate classification standard.

Block role	Ratio of inter-block relations	Ratio of relations received from other blocks
Bidirectional spillover	$\geq (N_k - 1)/(N - 1)$	≈ 0
Net beneficial	$\geq (N_k - 1)/(N - 1)$	> 0
Net spillover	$< (N_k - 1)/(N - 1)$	≈ 0
Broker	$< (N_k - 1)/(N - 1)$	> 0

Subsequently, according to (2.10), the spatial network is divided into the following four blocks:

1) The bidirectional spillover block is characterized by a large quantity of connections with its internal members, while also sending out significant connections to cities outside the block. However, it receives only limited connections from external members, displaying a bidirectional spillover effect.

2) The net beneficiary block exhibits both internal connections with cities within the block and received connections from external block cities, but it rarely sends out connections to external blocks.

3) The net outflow block is characterized by having more connections with external blocks than within the block but not receiving many connections from external blocks.

4) The broker block receives and sends out connections simultaneously. It connects more with other external blocks, while it connects less within the block, serving as a "Broker" with a bridging and linking role.

2.3. Data and descriptions

Most of the existing literature utilizes the digital inclusive finance index data, compiled by the Peking University Digital Finance Research Center, in collaboration with the Shanghai New Financial Research Institute and Ant Financial Research Institute. This index well measures the development of digital finance in China and has widely received great compliment, but one significant feature is its inclination toward inclusion. In this paper, we focus on the digital finance of PRD urban agglomeration, where we are more inclined to investigate digitization development. Accordingly, rather than the digital inclusive finance index from Peking University, we adopt the urban digital finance index issued by GIIF to evaluate the development of digital finance in the PRD urban agglomeration. The three first-level indicators of the urban digital finance index are digital financial services, digital financial technology and digital financial operating environment. Among them, digital financial service is the fundamental of urban digital finance, and it mainly reflects the extent to which cities can provide digital financial services in a comprehensive manner. Digital financial technology is the driving force for developing urban digital finance, and it mainly reflects the ability of the cities to continuously promote the development of digital finance in a comprehensive manner. Digital financial environment is the guarantee for the operation of urban digital finance, which mainly reflects the ability of the cities to effectively support the operation of digital finance. Liao et al. [45] used a combination of subjective and objective methods, first using a dynamic assessment method based on gray objectives to evaluate the level of each indicator, and then using hierarchical analysis, to measure the weight of each dimension to generate the city digital finance index. An elaborate explanation for the urban digital finance index can be referred to in [45].

The data for the permanent population (P) of each city in the gravity model and the year-end deposits and loans balance (M) were sourced from the Guangdong Statistical Yearbook. Since the annual data for the permanent population of each city have only been available since 2014, the data with time span of 2014–2020 were selected for subsequent empirical research. Regarding the measurement of distance in the model, we argue that directly using the spherical distance between cities is not appropriate because it cannot reflect the relevancy between two cities. Nowadays, communication between two cities does not necessarily depend solely on the proximity of their geographical location but also on their accessibility and convenience, so this study introduces the optimal highway distance and the time cost of passage to represent accessibility. The optimal road distance between cities is measured based on the shortest distance to each municipal government location in Baidu Maps. The data for driving time and traveling time by taking high-speed rail or train were obtained manually from Baidu Map and the Railway 12306 website, and the shortest travel time was taken as the data to measure time cost by comparing the length of driving and taking high-speed rail or train.

Table 3. Urban digital finance indexes in the PRD urban agglomeration.

City | Year	2014	2015	2016	2017	2018	2019	2020
Guangzhou	117.93	119.62	120.42	124.75	131.49	136.35	142.42
Shenzhen	128.75	128.67	135.47	141.25	155.15	161.43	167.07
Foshan	109.51	108.62	108.99	109.32	110.09	110.72	111.66
Dongguan	109.58	111.01	111.02	112.77	113.89	114.24	119.03
Huizhou	104.88	105.23	105.20	106.16	106.17	106.12	106.55
Zhongshan	106.38	106.97	106.63	107.86	107.81	107.06	107.96
Zhuhai	105.67	106.14	106.38	107.09	108.15	108.14	109.04
Jiangmen	104.62	104.87	105.31	105.01	105.30	104.82	105.00
Zhaoqing	103.98	103.79	103.72	104.52	104.60	104.02	104.42
Shanwei	103.20	102.98	103.06	104.69	103.47	104.10	104.01
Yangjiang	103.29	103.12	103.17	103.25	103.37	103.48	103.56
Qingyuan	103.24	103.61	103.54	103.63	103.81	103.70	103.51
Yunfu	103.51	103.55	104.13	103.52	103.47	103.61	103.87
Heyuan	103.13	103.33	103.32	103.35	103.70	103.85	103.42
Average	107.69	107.96	108.60	109.80	111.46	112.26	113.68

Table 3 gives the urban digital finance index values of the 14 cities in PRD, while Figure 1 shows their evolution tendencies. It can be seen that the development level of digital finance in cities such as Guangzhou, Shenzhen, and Dongguan displayed a significant increase during the period of 2014–2020. Although the digital finance indices of other cities in the PRD urban agglomeration did not show noticeable growth, there was no significant decline observed overall, indicating that the development of digital finance in the PRD urban agglomeration is both led by core cities with a competitive advantage and also maintains stability as a whole.

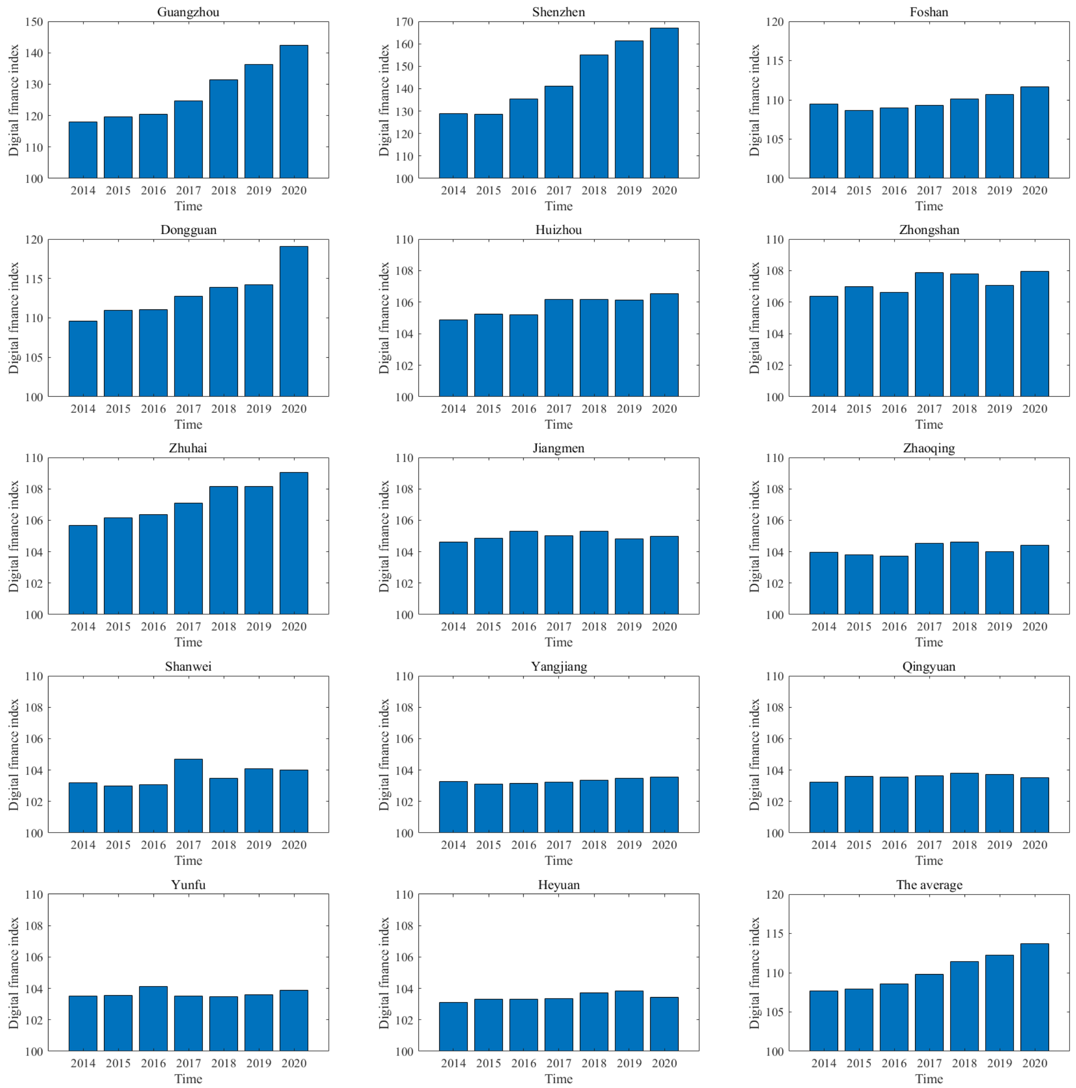

Figure 1. Tendencies of urban digital finance indexes in PRD urban agglomeration.

2.4. *Structural characteristics of the digital finance spatial network*

2.4.1. Overall characteristics of the digital finance spatial network

Using the modified gravity model equation (2.2) in Section 2.1.1, we calculated the relevancy indexes of digital finance in the PRD urban agglomeration and constructed a directed relevancy matrix R. Relevancy of some cities in the PRD urban agglomeration is shown in Table 4. It can be seen that the relevancy between Guangzhou, Shenzhen, Foshan and Dongguan is strong, while it is relatively weak between Jiangmen, Zhaoqing, Shanwei and other cities that do not belong to the core economy; the relevancy of digital finance in the PRD urban agglomeration shows an overall weakness, imbalance and significant differentiation between two levels.

Subsequently, the relevancy matrix R undergoes binary processing. Firstly, the average of each row in the relevancy matrix is taken as the threshold, and if the grid number is equal to or higher than the

Table 4. Relevancy of some cities in the PRD urban agglomeration.

	Guangzhou	Shenzhen	Foshan	Dongguan	Huizhou	Zhongshan	Zhuhai
Guangzhou		15,915.68	80,118.57	19,291.24	2031.023	6533.803	1641.544
Shenzhen	18,670.16		4019.423	36,121.53	9447.926	1424.392	620.2941
Foshan	66,509.28	2494.49		2339.839	252.8797	1165.427	356.485
Dongguan	16,123.12	24,221.64	2625.584		3056.138	771.7256	297.7844
Huizhou	1467.023	5523.156	272.4313	2984.246		128.8021	71.64999
Zhongshan	6603.963	1013.675	1126.833	679.6721	131.6305		3852.991
Zhuhai	1283.526	451.5524	352.4141	272.7857	69.73735	3891.408	

threshold, it is recorded as 1, indicating that there is a digital finance relevancy between two cities; if the grid number is lower than the threshold, it is recorded as 0, indicating that there is no digital finance relevancy between two cities. That is,

$$I = \begin{cases} 1, R_{ij} \geq average(R_{ij}), \\ \\ 0, R_{ij} < average(R_{ij}). \end{cases} \tag{2.11}$$

According to Eq (2.11), the directed relevancy matrix R is transformed into a binary matrix I, for instance.

Table 5. Binary matrix of some cities in the PRD urban agglomeration.

	Guangzhou	Shenzhen	Foshan	Dongguan	Huizhou	Zhongshan	Zhuhai
Guangzhou		1	1	1	0	0	0
Shenzhen	1		1	1	1	0	0
Foshan	1	0		0	0	0	0
Dongguan	1	1	0		0	0	0
Huizhou	1	1	0	1		0	0
Zhongshan	1	0	0	0	0		1
Zhuhai	1	1	0	0	0	1	

Subsequently, by utilizing the NetDraw function in UCINET 6.0 software, the binary 01 matrix of the digital finance in the PRD urban agglomeration was transformed into a spatial network structure graph as shown in Figure 2. It is found that during the development of digital finance, various cities have directly or indirectly established relevancies, and no city is in isolation. Among them, Guangzhou and Shenzhen serve as economic centers, while Dongguan, Foshan, Huizhou, and other cities act as bridges, forming a "Center-Bridge" network structure that effectively promotes their common development with surrounding cities, displaying distinct gradation characteristics. In general, the spatial network of digital finance in this urban agglomeration has obvious directionality, with most of the cities' digital finance connections directed to the core city or neighboring cities around it.

Table 6 presents the overall network characteristics of digital finance in the PRD urban agglomeration during the period of 2014–2020, calculated and compiled with the UCINET 6.0 software.

The maximum directed connections of the urban agglomeration is 182 (14 × 13). As shown in Table 6, the network density from 2014 to 2020 is generally low and shows a slight fluctuation trend,

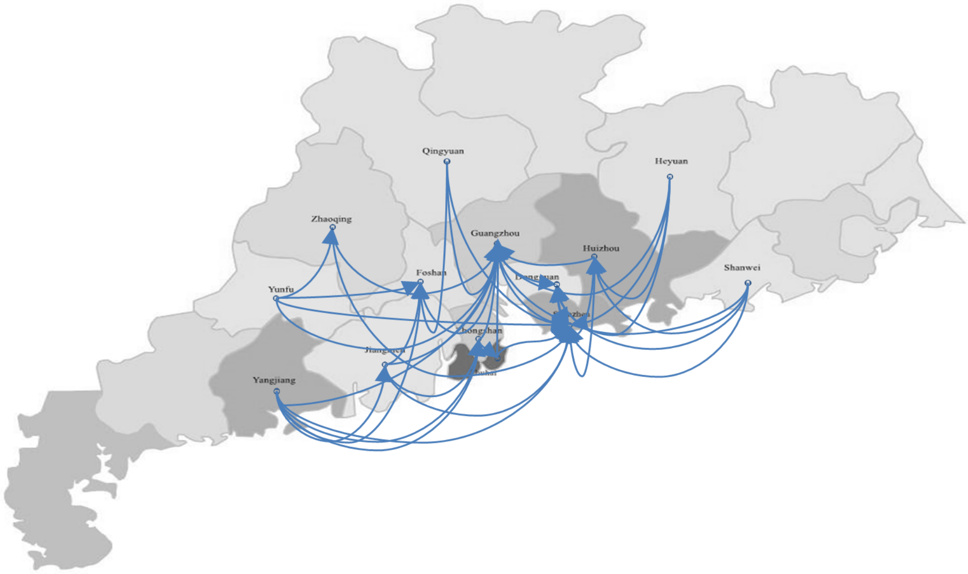

Figure 2. The spacial relevancy of digital finance in the PRD urban agglomeration.

Table 6. Overall network characteristics of digital finance in the PRD urban agglomeration.

Year	Density	Efficiency	Connectedness	Hierarchy
2020	0.247	0.6795	1.000	0.8065
2019	0.253	0.6667	1.000	0.8065
2018	0.247	0.6795	1.000	0.8065
2017	0.247	0.6795	1.000	0.8065
2016	0.247	0.6795	1.000	0.8065
2015	0.247	0.6795	1.000	0.8065
2014	0.247	0.6795	1.000	0.8065

indicating a low spatial relevancy of digital finance in the PRD urban agglomeration, and there is still a lot of efforts to promote the relevancy of digital finance in various cities. Indeed, cities are in the initial stage of digital finance, resulting in their weak connections with each other and leading to increasing differences in the development of digital finance among various cities. Although the network efficiency slightly decreased in 2019, there was no significant fluctuation, indicating that the connections in the network have decreased in 2019, but there was no significant change overall. The network connectedness is 1, indicating that there are no isolated cities in the digital finance spatial network, and the relevancy is strong. The network hierarchy remains at 0.8065, indicating that the network structure of digital finance in the PRD urban agglomeration is relatively stable, but polarization still exists, which needs to be improved gradually.

In conclusion, the overall spatial relevancy network of digital finance in the PRD urban agglomeration presents the characteristics of low density, close connection and strong stability.

2.4.2. Individual characteristics of the digital finance spatial network

In this sub-section, the individual characteristics of the spatial network in the PRD urban agglomeration will be analyzed through degree centrality, closeness centrality, and betweenness centrality. This exploration aims to identify the roles and functions of each city in the digital finance spatial relevancy network. Due to the timeliness and availability of data, this sub-section only discusses the individual network characteristics of the PRD urban digital finance in 2020. The calculation results are presented in Table 7.

Table 7. Individual network characteristics of digital finance in the PRD urban agglomeration.

City	Degree centrality				Closeness centrality		Betweenness centrality	
	Out degree	In degree	Centrality	Ranking	Centrality	Ranking	Centrality	Ranking
Guangzhou	3	13	61.54	1	100	1	29.833	1
Shenzhen	3	11	53.85	2	86.7	2	17.083	2
Foshan	1	6	26.92	3	65	3	2.667	3
Dongguan	2	5	26.92	3	61.9	4	0.25	7
Huizhou	3	3	23.08	5	61.9	4	0.25	7
Zhongshan	2	3	19.23	6	59.1	8	0.667	6
Zhuhai	3	1	15.38	11	56.5	13	0.25	7
Jiangmen	4	1	19.23	6	61.9	4	0.75	4
Zhaoqing	4	1	19.23	6	59.1	8	0.167	10
Shanwei	4	0	15.38	11	59.1	8	0	13
Yangjiang	5	0	19.23	6	61.9	4	0.75	4
Qingyuan	3	0	11.54	14	56.5	13	0.167	10
Yunfu	4	1	19.23	6	59.1	8	0.167	10
Heyuan	4	0	15.38	11	59.1	8	0	13
Mean	3.21	3.21	24.73		64.84		3.786	

With regard to the degree centrality, according to the results in Table 7, the maximum degree centrality among the 14 cities in the PRD urban agglomeration is 61.54, where the minimum is 11.54, and the average is 24.73. There are 4 cities that exceed the average degree centrality. From high to low, they are Guangzhou, Shenzhen, Foshan, and Dongguan, indicating that these cities are more concentrated and play the roles of leaders in the digital finance network.

In particular, Guangzhou and Shenzhen have degree centralities of 61.54 and 53.85, respectively, indicating that the spatial relevancy network of digital finance in the PRD urban agglomeration is highly dependent on these two central cities. Guangzhou is spatially connected with 13 out of 14 cities, indicating its core role in the development of digital finance in the PRD urban agglomeration. Zhuhai, on the other hand, should be among the cities with larger economic volume and better development in the PRD urban agglomeration, but its ranking of degree centrality is low, indicating that Zhuhai is not strongly connected to other cities in the spatial network and only strongly connected to individual cities. The reason for this may be that although it is adjacent to Hong Kong and Macau, it does not take full advantage of its location, and the transportation of Zhuhai is also lagging behind in development. At the same time, the average out-degree is found to be 3.21, with 6 cities exceeding the average, indicating that nearly half of the cities are receivers of the spatial spillover in the overall network, and they often spill over to neighboring cities or core cities with digital financial connections. The average in-degree is 3.21. Guangzhou, Shenzhen, Foshan and Dongguan are higher than the average in-degree, and the in-degrees of these cities are higher than their out-degrees. Since these cities are receivers in the spacial network, the direction of the spacial relevancy is towards these cities, thus forming the spillover effects. On the other hand, cities with lower in-degree generally have out-degree greater than in-degree, and they are the spillover of digital finance in the PRD urban agglomeration.

With regard to the closeness centrality, the maximum of the 14 cities in the PRD urban agglomeration is 100, the minimum is 56.5, and the average is 64.84. Guangzhou has the highest closeness centrality among the 14 cities, indicating that it is the most central city in the network of digital finance and enjoys a natural advantage in obtaining financial resources. The closeness centrality values of Guangzhou, Shenzhen and Foshan are above the regional average, which suggests that these three major cities can quickly establish connections with other cities in the network of digital finance. These cities play a core role mainly due to their central location in the region and the quick flow of financial resources. In contrast, cities such as Qingyuan and Zhuhai, which have lower closeness centrality, are influenced by factors such as the economy, geography and regional cooperation. They are considered as "Peripheral players" in the overall network.

With regard to the betweenness centrality, the maximum is 29.833, while the minimum is 0. The average is 3.786. Guangzhou significantly exceeds the regional average, indicating that Guangzhou plays a dominant role in the development of digital finance in the PRD urban agglomeration. It serves as the "Bridge" and "Hub" in the spacial network of digital finance. Furthermore, Guangzhou, Shenzhen, Foshan all surpass the average, implying that they are capable of dominating other cities in the development of digital finance. This control capability will further increase as these cities continue to develop economically, in terms of transportation, technology, financial resources, and information exchange. On the other hand, cities such as Shanwei and Heyuan have centrality of 0, indicating that they will be more easily dominated by other cities in the spatial network of digital finance. Overall, the betweenness centrality shows a severe polarization. Each city presents a clear manifestation in terms of dominating and being dominated.

Through the above results, we find that cities in the spatial network of digital finance exhibit their individual characteristics of unevenness and imbalance in development, where Guangzhou occupies the top ranking in terms of all three centrality indicators, indicating that the city is not only the core role in the overall network but also addresses a "Broker" function. While cities such as Zhuhai have relatively large economic volume, they are less likely to integrate into the core range of the entire network. At present, the spatial relevancy of digital finance is mainly realized through major economically developed cities such as Guangzhou and Shenzhen. Therefore, through the above analysis, to continue developing digital finance in the PRD urban agglomeration and even the Guangdong-Hong Kong-Macao Greater Bay Area (the Greater Bay Area (GBA)), it should not only maintain the leadership and radiation roles of cities like Guangzhou and Shenzhen, but also give full play to the geographical advantages of cities like Zhuhai, developing their transportation, and enhancing their connections with neighboring cities.

2.4.3. Spatial clustering analysis of the digital finance spatial network

In this sub-section, we further take the clustering analysis for the 14 cities. The block model can group together cities with similar functions, where the PRD urban agglomeration is divided into 4 blocks according to the principle of maximum cutoff 2 and concentration standard 0.2. The results obtained through the CONCOR tool of UCINET 6.0 software are shown in Figure 3.

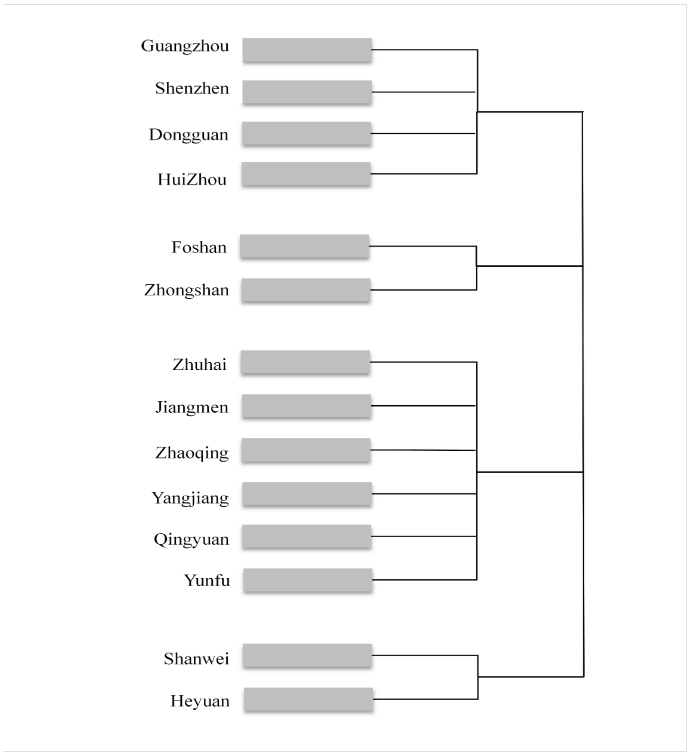

Figure 3. Clustering result of digital finance in the PRD urban agglomeration.

In the following we analyze the status and functions of the four blocks in the network. As revealed by the previous analysis, there are a total of 45 connections in the spatial relevancy network of digital finance in the PRD urban agglomeration. The calculation results reflecting the block characteristics are presented in Table 8, where the internal connections of blocks are 13, while the external connections between blocks are 32. Indeed, there are strong connections and spillover effects between blocks. The external connections between blocks are closer than the internal ones of each block. Subsequently, some parameters are calculated with Table 8, and then we identify the roles of each block in accordance with the classification criteria specified in Table 2. The results are presented in Table 9.

In Table 9, the expected internal connection ratio of Block 1 is 23%, while the actual situation is 91%, and the actual reception connection ratio is 74% (greater than 0), indicating that Block 1 is a Net Beneficiary Block. The block has connections not only with cities within its own block but also receives connections from cities in external blocks. Although Block 1 receives more connections than it spills over, its external spillover effect cannot be ignored. Indeed, it is not an extreme Net Beneficiary Block. The expected ratio of the internal connections in Block 2 is 8%, while the actual ratio is 0, with an actual reception connection ratio of 75% (greater than 0), indicating that the block not only receives connections from other blocks, but also spills over through digital financial activities. As it

Table 8. Block characteristics of digital finance spatial network in PRD urban agglomeration.

Spillover Relationship Board	Receiving relationship board				Total spillover connections	Number of internal connections	Number of external connections	
	1	2	3	4			Received	Sent
1	10	1	0	0	11	10	22	1
2	2	0	1	0	3	0	9	3
3	12	8	3	0	23	3	1	20
4	8	0	0	0	8	0	0	8
Total reception	32	9	4	0				

Table 9. Roles of blocks in the digital finance spatial network.

Block	Reception connection ratio		Internal connection ratio			Block role
	Actual	Actual VS 0	Actual	Expected	Actual VS Expected	
1	0.74	>	0.91	0.23	>	Net Beneficiary Block
2	0.75	>	0	0.08	<	Broker Block
3	0.15	>	0.13	0.38	<	Broker Block
4	0	=	0	0.08	<	Net Outflow Block

Note: The reception connection ratio=Total reception connections/(Total spillover connections+Total reception connections); Expected internal connection ratio=(Cities within the block−1)/(Cities in the network−1); Actual internal connection ratio=Internal connections within the block/Spillover connections of the block.

receives more connections than spilling over, it is indeed a Broker Block that benefits more. Similarly, the expected ratio of internal connections in Block 3 is 38%, while the actual ratio is 13%, and the actual reception connections ratio is 15% (greater than 0), also belonging to the Broker Block. Block 3 has more outgoing connections than reception connections, and its outflow effects are stronger than its inflow effects, making it a broker block with more outflow effects. The expected ratio of internal connections within Block 4 is 8%, while the actual ratio is 0, resulting in an actual inflow ratio of 0 (equal to 0). Thus, Block 4 belongs to the category of Net Outflow Block. The internal connections in Block 4 are less than its external connections with other blocks. In addition, it receives no connections from other blocks.

Accordingly, it can be inferred that the spatial network of digital finance in the PRD urban agglomeration does not have a bidirectional spillover block. The reason for this is that the distribution of financial resources in the region varies greatly, with some cities benefiting from their geographical and political advantages, but rarely spilling over digital finance to the outside. Most of the other cities have a preference for spillover digital finance to cities in the external block but rarely have digital finance connections within their own blocks. Thus, there is a lack of a bidirectional spillover block that both connects with internal cities and spills over to external blocks.

Finally, to explore the spillover effect between the blocks in digital finance, we calculate the density matrices of four blocks, with large density having spillover effects on other blocks. As shown in Table 6, the overall density of the digital finance spatial network is 0.247. Among these four blocks, if the density of a block is greater than 0.247, it is recorded as 1, indicating a correlation between the two blocks; otherwise, it is recorded as 0, meaning that there is no correlation between the two blocks. Thus, the density matrix is transformed into an image matrix, showing more clearly significant spillover effects, either between blocks or within blocks. The results are shown in Table 10.

Table 10. Block density matrix and the image matrix.

Block	Density matrix				Image matrix			
	1	2	3	4	1	2	3	4
1	0.833	0.125	0	0	1	0	0	0
2	0.25	0	0.083	0	1	0	0	0
3	0.5	0.667	0.1	0	1	1	0	0
4	1	0	0	0	1	0	0	0

It can be observed that Block 1 benefits from spillover effects within the block, without showing significant spillover effects towards other blocks. Both Block 2 and Block 4 spill over towards Block 1, while Block 3 spills over towards both Block 2 and Block 4. Overall, there are few connections between blocks. Thus, it should strengthen the cooperation between segments of the PRD urban agglomeration. Cities such as Guangzhou and Shenzhen need to receive more digital financial spillover linkages from others while spilling out more digital financial linkages. The segment cities with few linkages need to take advantage of geographical, economic and policy advantages to develop digital finance, thus promoting the coordinated development of digital finance in the PRD region.

3. Empirical test for influencing factors of digital finance in the PRD

According to the spatial relevancy of digital finance in the PRD urban agglomeration analyzed in Section 2, there are differences in the development of digital finance among cities. To explore the causes of these differences, it is necessary to further analyze the influencing factors. Influencing factors of digital financial inclusion can be referred to in Allen et al. [46], Appleyard [47], Chakravarty and Pal [48], Kabakova and Plaksenkov [49].

3.1. Indicators of influencing factors

According to the theories of financial development and urban economics, the level of regional financial development is closely associated with factors such as economic development, openness to the outside world, industrial structure, and geographical location.

Digital finance and its spatial relevancy are an important aspect of regional financial development, which has significant implications for modern strategy of the financial industry. Therefore, in this study, we selected seven factors, including economic level, investment behavior, degree of opening-up, urbanization level, industrial structure, Internet level, and geographical location, to conduct an in-depth examination of the impact on the spatial relevancy of digital finance in the PRD urban agglomeration. The explanations, calculation methods, and data sources of indicators are shown in Table 11.

First, it is from a direct theoretical inference that there is co-development between the economy and the digital finance. Hence, this paper includes the economic level as a variable and measures it by GDP.

Second, digital finance can effectively alleviate the crowding-out effect of financial investment behaviors on corporate innovations. For small and medium-sized enterprises, non-state-owned enterprises and enterprises with high dependence on financing, the moderating mechanism of digital finance

Table 11. Variables and indicators.

Variable		Indicator	Variable description
Dependent variable	Network relations	Spatial relevancy network of digital financial development (R)	Spatial relevancy matrix of digital financial development
Independent variable	Economic level	Difference in GDP (GDP)	GDP difference matrix
	Investment behavior	Difference in the proportion of investment in fixed assets to GDP (IA)	Investment in fixed assets to GDP ratio difference matrix
	Degree of opening-up	Difference in the proportion of imports and exports to GDP (IE)	Import-export volume to GDP ratio difference matrix
	Urbanization level	Difference in the urban population ratio (UR)	Urban population to total population ratio difference matrix
	Industrial structure	Difference in the tertiary industry output value per to GDP (TI)	Output value of tertiary industry to GDP ratio difference matrix
	Network level	Difference in the number of Internet users (NIU)	Number of Internet users difference matrix
	Geographical location	Spatial adjacency relation (BOR)	Spatial adjacency matrix

remains significant. The inclusive effects of digital finance allow weak groups to benefit more. Hence, the investment behavior on digital finance should be considered, which is measured by "Proportion of investment in fixed assets (IA)" as an indicator.

Third, the differences in opening-up degree between cities cause direct impacts on their digital finance. In this paper, we use the "The ratio of exports and imports to GDP" to measure the opening-up degree of a city.

Fourth, [39] argued that there is a positive relationship between the development of digital finance and urbanization level. The economic level and urbanization process can simultaneously promote the development of digital finance in the cities. Hence, in this paper, we incorporate this indicator and measure it by "Urban population ratio."

Fifth, a well-structured industry is one of the important factors driving the healthy development of an economy. Indeed, it also affects the distribution and allocation of resources in digital finance. The tertiary industry is mainly service-oriented, including industries such as finance and information transmission. Regions with similar industrial structures may have easier communications due to technological spillovers. Hence, we consider industrial structure as an influencing factor, taking the proportion of tertiary industry value added to GDP as the measurement.

Sixth, the Internet plays a crucial role in the development of digital finance. Digital financial inclusion is a new financial model that uses digital technology to provide low-cost and sustainable financial services to economically backward cities. Cities with high Internet levels are conducive to the development of digital information technology, thereby creating favorable conditions for digital finance. In this paper, we use the number of Internet users in each city to characterize their Internet levels.

Seventh, influencing factors may show heterogeneous effects on different cities, which may also radiate to their surrounding regions. Thus, we set a dummy variable, which equals to 1 imply the adjacency between two cities and otherwise, equals to 0. That is, we establish an adjacency matrix to illustrate the geographical characteristics of each city.

3.2. Empirical results based on the QAP analysis

3.2.1. Model construction

In social network analysis, the QAP method (quadratic assignment procedure) is used to study the correlation and regression of two square matrices. It compares the similarity of each entry of the two square matrixes and gives the correlation coefficients between the two matrices, while performing nonparametric tests on the coefficients. Its calculation is based on random replacement of the matrix data. In our paper, the objective is constructing a digital financial spatial network of urban agglomeration, which is a multidimensional matrix. Accordingly, it is appropriate to adopt the QAP analysis. The difference between QAP and other standard statistical procedures is that the individual values of the matrix are not independent of each other. Hence, many standard statistical procedures cannot be used for parameter estimation and statistical tests; otherwise, incorrect standard deviations will be calculated. In addition, as QAP analysis is a nonparametric estimation method, it allows independent variables correlated with each other. In other words, the results of regression analysis through QAP are not affected despite the correlation between different independent variables, and thus the problem of multicollinearity can be effectively avoided. Firstly, we obtain a correlation coefficient by comparing the size and similarity of each entry in the two matrices. Then, the matrices are randomly replaced several times. After each replacement, the correlation coefficients between the matrices are re-calculated and compared. The QAP analysis first requires estimating the multivariate regression coefficients and determination coefficients between the dependent variable and independent variable. Then, before regression, randomly replace the rows and columns of the dependent variable matrix multiple times. This process is repeated to obtain standardized regression coefficients to evaluate significance. The standardized regression coefficient represents the impact intensities of different matrices on the dependent variable matrix, while their signs represent the impact directions.

In this paper, given that the dependent variable is the spatial relevancy matrix of digital finance, the independent variables should be transformed into a relation matrix. The geographical matrix is already a relation matrix, and no further transformation is necessary. The remaining variables are transformed into absolute difference matrices. Finally, to eliminate the impact of different scales across matrices, all variable matrices are standardized and then used to explore the impact of these factors on the spatial network of digital finance. The model is as follows:

$$R = F(GDP, IA, IE, UR, , TI, NIU, BOR). \tag{3.1}$$

Table 12 presents the correlation analysis of the seven factors that influence the special relevancy of digital finance in the PRD urban agglomeration. It can be seen that a significant correlation exists between most of the factors, with some of them having a correlation coefficient of 0.637, indicating a high likelihood of multi-collinearity among the variables. In this case, using traditional regression analysis methods may result in a discrepancy between the theoretical meaning of the parameters and the actual situations, leading to biased results. However, as the QAP analysis method is a non-parametric estimation approach, it allows for the interdependence of variables without the requirement for independence. This means that, although there is a correlation between the variables, the regression analysis results with QAP are impervious, effectively avoiding the issue of multi-collinearity.

Table 12. Correlations between influencing factors.

Variable	*GDP*	*IA*	*IE*	*UR*	*TI*	*NIU*	*BOR*
GDP	1.000*** (0.000)						
IA	0.179* (0.068)	1.000*** (0.000)					
IE	0.463*** (0.003)	0.375*** (0.006)	1.000*** (0.000)				
UR	0.485*** (0.000)	0.351** (0.010)	0.637*** (0.000)	1.000*** (0.000)			
TI	0.290** (0.027)	-0.004 (0.536)	0.080 (0.218)	0.087 (0.171)	1.000*** (0.000)		
NIU	0.448*** (0.003)	0.393*** (0.005)	0.457*** (0.008)	0.522*** (0.001)	0.391** (0.024)	1.000*** (0.000)	
BOR	−0.152** (0.048)	−0.177* (0.060)	−0.292*** (0.007)	−0.101 (0.173)	0.057 (0.284)	−0.132* (0.089)	1.000*** (0.000)

Note: *, ** and *** represent significance at 10%, 5% and 1% levels respectively.

3.2.2. Correlation analysis with QAP

Using the QAP method, with 5000 times of random permutations, the correlation analysis between the influencing factors and the spatial network of digital finance in the PRD urban agglomeration is presented in Table 13.

Table 13. Correlation analysis between digital finance network and influencing factors.

Variable	Correlation coefficient	P-value	Mean correlation coefficient	Std. Dev.	Min	Max	Prop ≥ 0	Prob ≤ 0
GDP	0.173***	0.005	0.0002	0.0676	−0.2512	0.2614	0.0050	0.9952
IA	0.037	0.323	−0.0004	0.0766	−0.3560	0.2667	0.3233	0.6769
IE	−0.115*	0.066	−0.0001	0.0738	−0.3070	0.2163	0.9338	0.0664
UR	0.073	0.180	−0.0001	0.0793	−0.3535	0.2141	0.1796	0.8206
TI	0.060	0.194	0.0006	0.0693	−0.2939	0.2549	0.1936	0.8066
NIU	0.132**	0.015	−0.0002	0.0667	−0.2691	0.2223	0.0154	0.9848
BOR	0.381***	0.000	−0.0010	0.0851	−0.2328	0.3430	0.0002	1.0000

Note: *, ** and *** represent significance at 10%, 5% and 1% levels respectively.

Table 13 illustrates the driving effect of different influencing factors on the spatial relevancy of digital finance in the PRD urban agglomeration with the QAP correlation analysis. Through the correlation coefficients generated in the permutation process, it is found that investment behavior, urbanization level and industrial structure do not pass the significance test, while the other four factors all pass, indicating that the factors of urban investment behavior, urbanization level, and industrial structure do not significantly drive the spatial relevancy of digital finance in the PRD region. The economic level, degree of opening-up, Internet level, and geographical location show significant impacts on the formation for the spatial network of digital finance. The correlation coefficient between the difference matrix of the opening-up degree and the spatial network of digital finance is −0.115, indicating that the smaller the difference in opening-up degree between two cities, the more easily digital finance can be exchanged and form the relevancy.

3.2.3. Regression analysis with QAP

Through the correlation analysis with QAP, it is found that the absolute difference matrices of investment behavior, urbanization level, and industrial structure are not significantly correlated with the correlation matrix of digital finance. These three variables were excluded when taking regression. The remaining four significantly correlative variables were regressed with the spatial correlation matrix R. After 5000 random permutations, the regression results are shown in Table 14. If the correlation coefficient is positive, it indicates that the larger the difference in the influencing factors, the greater the promotion to the relevancy of urban digital finance. If the correlation coefficient is negative, it indicates that the smaller the difference in the influencing factors, the stronger the spatial relevancy of digital finance.

Table 14. Regression results with QAP.

Variable	Regression results					
	Un-Stdized	Stdized Coef	P-value	As Large	As Small	Std. Err.
GDP	0.10210***	0.24789	0.00500	0.00500	0.99520	0.03829
IE	−0.07491***	−0.18958	0.00800	0.99220	0.00800	0.03559
NIU	0.07563**	0.15804	0.01380	0.01380	0.98640	0.03460
BOR	0.34851***	0.38455	0.00020	0.00020	1.00000	0.07657
R^2	0.232					

Note: *, ** and *** represent significance at 10%, 5% and 1% levels respectively.

The results show that the economic level, degree of opening-up, Internet level, and geographical location are all significant at the 5% level, with standardized coefficients of 0.24789, −0.18958, 0.15804, 0.38455, respectively, indicating that the four factors have significant impacts on the spatial network of digital finance in the PRD urban agglomeration. The regression coefficients of the GDP difference matrix, the Internet level difference matrix, and the geographical location difference matrix are all positive. First, the financial resources are more likely to be transferred from cities with higher GDP and higher Internet level to cities with relatively lower economic level, thereby driving the development and relevancy of digital finance. Second, the higher the Internet level is, the more effective the technology exchange and the more convenient the financial services. Third, the closer the two cities are geographically, the more likely they are to have relevancy in digital finance. Thus, the three factors show positive impacts on the formation of spatial network of the digital finance. On the other hand, the regression coefficient between the difference matrix of opening-up degree and the spatial relevancy matrix of urban digital finance is negative, indicating that the more similar the opening-up degree between two cities is, the stronger their relevancy in digital finance. This is because the more similar the opening-up degree between two cities is, the more information they can share, and the smaller difference in their financial development.

3.2.4. Robustness test

To further take the robustness test for the empirical results, we continue with the QAP regression by adding variables to see if there is any significant difference between the two estimation results.

According to the definition of digital finance in the World Bank's Digital Financial Services Report released in April 2020, digital finance is a financial model in which traditional financial sectors and fintech companies use digital technology to deliver financial services. Therefore, the nature of digital finance cannot be separated from financial attributes, and it still follows the laws of the financial market and is regulated by market policies. Haddad and Hornuf [50] and Schindler [51] analyzed the effects of demand factors, such as market size, demographics, and cell phone penetration, and supply factors, such as technological advances, traditional financial markets and regulatory policies, on the global impact of digital finance development. Among these factors, the influence from traditional finance cannot be ignored. Digital finance is an emerging form of financial supply outside the traditional credit and capital markets, and its development is inextricably linked to traditional financial supply. Accordingly, in this paper, we include the influence of the traditional finance on the spatial relevancy of digital finance to test whether it will have an impact on the results in Section 3.2.3.

In this paper, we use the ratio of loan balance of financial institutions to GDP as a measure of traditional finance level (FIN) and first use the QAP method to correlate the influencing factors and spatial network of digital finance in the PRD urban agglomeration after 5000 random permutations, as shown in Table 15.

Table 15. Correlation analysis between digital finance network and influencing factors.

Variable	Correlation coefficient	p-value	Mean correlation coefficient	Std. Dev.	Min	Max	Prop ≥0	Prob ≤0
GDP	0.173***	0.004	0.001	0.069	-0.279	0.230	0.004	0.996
IA	0.037	0.324	0.001	0.074	-0.316	0.259	0.324	0.676
IE	-0.115*	0.069	0.001	0.074	-0.336	0.202	0.932	0.068
UR	0.073	0.174	0.000	0.079	-0.34	0.304	0.174	0.826
TI	0.060	0.181	-0.001	0.069	-0.299	0.273	0.181	0.819
NIU	0.132**	0.021	0.000	0.068	-0.249	0.261	0.021	0.979
BOR	0.381***	0.000	-0.001	0.083	-0.271	0.343	0.000	1.000
FIN	0.132***	0.008	0.001	0.057	-0.170	0.175	0.008	0.992

Note: *, ** and *** represent significance at 10%, 5% and 1% levels respectively.

From Table 15, it can be found that the influence of traditional finance level is significant; also, it does not change the influence of other factors on the spatial relevancy of digital finance. The correlation coefficients of other factors did not change significantly, not only in value but also in sign.

Next, we performed the QAP regressions of the significantly correlated variables with the spatial relevancy matrix R with 5000 random permutations, and the correlation regression results are shown in Table 16.

From Table 16, we can see that coefficients of other influencing factors changed slightly, after adding the indicator of traditional financial level for QAP regression. In particular, both the significance and the directions of their influence on the spatial relevancy of digital finance did not change. Thus, the results are robust for the influencing factors of the spatial relevancy of digital finance in the PRD urban agglomeration.

Table 16. Regression results with QAP.

Variable	Regression results					
	Un-Stdized	Stdized Coef.	P-value	As Large	As Small	Std. Err.
GDP	0.10526***	0.25557	0.00460	0.00460	0.99560	0.04196
IE	-0.07795***	-0.19727	0.00780	0.99240	0.00780	0.03756
NIU	0.10363**	0.21655	0.05019	0.05019	0.95001	0.06485
BOR	0.34911***	0.38521	0.00020	0.00020	1.00000	0.07871
FIN	-0.03652	-0.06806	0.27455	0.72565	0.27455	0.06610
R^2			0.233			

Note: *, ** and *** represent significance at 10%, 5% and 1% levels respectively.

4. Conclusions and policy recommendations

4.1. Conclusions

In this study, using the urban digital finance index developed by the Guangzhou Institute of International Finance and data in the statistical yearbooks of Guangdong Province and various cities, we measured the spatial relevancy of digital finance in the PRD urban agglomeration through the modified gravity model. A spatial relevancy network was built, with the overall characteristics, individual characteristics and spatial clustering characteristics analyzed in detail. Finally, the QAP method was used to study the correlation between the spatial relevancy network of digital finance in the PRD urban agglomeration and its influencing factors, as well as their regression relationship. The main conclusions are summarized as follows.

First, the spatial network of digital finance in the PRD urban agglomeration is highly connected but with a low network density, and the overall structure is relatively robust. Although all cities play roles in the overall network, there is a polarization phenomenon. Second, top cities like Guangdong, Shenzhen, Foshan are leading the development of digital finance in the PRD region, playing the roles of “Broker” in the network and serving as the “Hub” and “Bridge” for other cities. Cities on the edges of the PRD urban agglomeration, such as Shanwei, Qingyuan and Heyuan, are less involved in the development of digital finance. Third, by taking block analysis, Block 1 with top cities in economic development receives more spillover of digital finance from other blocks and is referred to as the Net Beneficiary Block. Blocks 2 and 3 with obvious regional advantages play the roles of “Broker” in the network, driving the factor mobility of digital finance in the PRD urban agglomeration. Block 4 with cities in the edges of PRD spills more effects of digital finance and is referred to as the Net Overflow Block. Finally, the QAP analysis reveals that economy, Internet levels and geographical location show significantly positive effects driving the formation of the spatial network of digital finance in the PRD urban agglomeration, while the degree of opening-up shows a negative effect.

4.2. Policy recommendations

The PRD urban agglomeration is an important part of the Greater Bay Area (GBA). However, the overall digital finance of the PRD urban agglomeration fails to develop in a synergistic manner. Based on the above findings, we propose the following recommendations.

First, the strategic position of digital finance should be raised. The plenary session of the Pearl Bay

Finance Summit (2023), jointly organized by the China Finance Forty Forum and the China Finance Forty Research Institute, released the "Opportunities, Challenges and Prospects for the Development of Digital Finance in the Guangdong-Hong Kong-Macao Greater Bay Area," which pointed out that digital finance has a good prospect for development. On the one hand, digital finance can serve the high-quality development of the real economy by the way of inclusive services. On the other hand, it can promote the integration of data elements. Therefore, the PRD urban agglomeration and even the Greater Bay Area (GBA) should raise the importance of digital finance to a higher level and strengthen special policies. Second, the overall pattern of optimizing the development of digital finance in the PRD urban agglomeration should be promoted from a holistic perspective to jointly promote the prosperity of the GBA. The government should focus on the spatial relevancy mechanism of digital finance by enhancing the relationship and spillover channels among cities in the entire GBA. For cities with a low level of digital finance, it should lower the threshold of various financial services. The effects of digital finance of Guangzhou should be extended in all directions, forming a radial pattern with it as the core and Foshan, Huizhou, etc., as important nodes. Shenzhen should also strengthen its own capability of digital finance and promote the mutual integration and interoperability between the Guangzhou radial area and the Shenzhen network area. Finally, we should improve the development system of digital finance. On the one hand, it should focus on the roles of openness to the outside, Internet level and geographic location in the development of digital finance. On the other hand, it should accelerate the construction of transportation and communication infrastructure in the GBA. The time cost of inter-city communication can be reduced by building high-speed railways, major highways, maritime shipping centers, etc.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare there is no conflicts of interest.

References

1. Y. Liu, J. Liu, L. Zhang, Enterprise financialization and R&D innovation: A case study of listed companies in China, *Electron. Res. Arch.*, **31** (2023), 2447–2471. https://doi.org/10.3934/era.2023124
2. S. Inna, B. Yana, H. Ruslan, The compliance of the regional development strategies and funding with the sustainable development concept: The case of Ukraine, *Green Finance*, **4** (2022), 159–178. https://doi.org/10.3934/gf.2022008

3. Q. Song, J. Li, Y. Wu, Z. Yin, Accessibility of financial services and household consumption in China: evidence from micro data, *North Am. J. Econ. Finance*, **53** (2020), 101213. https://doi.org/10.1016/j.najef.2020.101213
4. Z. Li, J. Zhu, J. He, The effects of digital financial inclusion on innovation and entrepreneurship: A network perspective, *Electron. Res. Arch.*, **30** (2022), 4697–4715. https://doi.org/10.3934/era.2022238
5. Y. Liu, P. Failler, Y. Ding, Enterprise financialization and technological innovation: Mechanism and heterogeneity, *PLoS ONE*, **17** (2022), e0275461. https://doi.org/10.1371/journal.pone.0275461
6. Z. Li, B. Mo, H. Nie, Time and frequency dynamic connectedness between cryptocurrencies and financial assets in China, *Int. Rev. Econ. Finance*, **86** (2023), 46–57. https://doi.org/10.1016/j.iref.2023.01.015
7. Z. Li, L. Chen, H. Dong, What are bitcoin market reactions to its-related events, *Int. Rev. Econ. Finance*, **73** (2021), 1–10. https://doi.org/10.1016/j.iref.2020.12.020
8. S. Gammage, A. Kes, L. Winograd, N. Sultana, S. Hiller, S. Bourgault, *Gender and Digital Financial Inclusion: What Do We Know and What Do We Need to Know*, International Center for Research on Women, Washington, DC, USA, 2017.
9. J. He, Q. Li, Can online social interaction improve the digital finance participation of rural households, *China Agric. Econ. Rev.*, **12** (2020), 295–313. https://doi.org/10.1108/CAER-11-2019-0213
10. Z. Huang, H. Dong, S. Jia, Equilibrium pricing for carbon emission in response to the target of carbon emission peaking, *Energy Econ.*, **112** (2022), 106160. https://doi.org/10.1016/j.eneco.2022.106160
11. Z. Li, Z. Huang, Y. Su, New media environment, environmental regulation and corporate green technology innovation: Evidence from China, *Energy Econ.*, **119** (2023), 106545. https://doi.org/10.1016/j.eneco.2023.106545
12. T. Li, J. Wen, D. Zeng, K. Liu, Has enterprise digital transformation improved the efficiency of enterprise technological innovation? A case study on Chinese listed companies, *Math. Biosci. Eng.*, **19** (2022), 12632–12654. https://doi.org/10.3934/mbe.2022590
13. Y. Liu, C. Ma, Z. Huang, Can the digital economy improve green total factor productivity? An empirical study based on Chinese urban data, *Math. Biosci. Eng.*, **20** (2023), 6866–6893. https://doi.org/10.3934/mbe.2023296
14. D. Radcliffe, R. Voorhies, A digital pathway to financial inclusion, *SSRN Electronic Journal*, 2012.
15. J. Zhu, Z. Li, Can digital financial inclusion effectively stimulate technological Innovation of agricultural enterprises?—A case study on China, *Natl. Account. Rev.*, **3** (2021), 398–421. https://doi.org/10.3934/NAR.2021021
16. A. Demirguc-Kunt, L. Klapper, D. Singer, Financial inclusion and inclusive growth: A review of recent empirical evidence, *Policy Research Working Paper Series*, (2017), 1–27.

17. D. Gabor, S. Brooks, The digital revolution in financial inclusion: international development in the fintech era, *New Political Econ.*, **22** (2016), 423–436. https://doi.org/10.1080/13563467.2017.1259298
18. Z. Li, C. Yang, Z. Huang, How does the fintech sector react to signals from central bank digital currencies, *Finance Res. Lett.*, **50** (2022), 103308 https://doi.org/10.1016/j.frl.2022.103308
19. P. Ozili, Impact of digital finance on financial inclusion and stability, *Borsa Istanbul Rev.*, **18** (2018), 329–340. https://doi.org/10.1016/j.bir.2017.12.003
20. S. Gottschalk, Digital currency price formation: A production cost perspective, *Quant. Finance Econ.*, **6** (2022), 669–695. https://doi.org/10.3934/QFE.2022030
21. K. Lauer, T. Lyman, *Digital Financial Inclusion: Implications for Customers, Regulators, Supervisors, and Standard-Setting Bodies*, Consultative Group to Assist the Poor, Washington, DC, USA, 2015.
22. Z. Li, H. Chen, B. Mo, Can digital finance promote urban innovation? Evidence from China, *Borsa Istanbul Rev.*, **23** (2022), 285–296. https://doi.org/10.1016/j.bir.2022.10.006
23. C. Fang, Important progress and future direction of studies on China's urban agglomerations, *J. Geogr. Sci.*, **25** (2015), 1003–1024. https://doi.org/10.1007/s11442-015-1216-5
24. C. Fang, D. Yu, Urban agglomeration: An evolving concept of an emerging phenomenon, *Landscape Urban Plann.*, **162** (2017), 126–136. https://doi.org/10.1016/j.landurbplan.2017.02.014
25. Y. Liu, P. Failler, Z. Liu, Impact of environmental regulations on energy efficiency: A case study of China's air pollution prevention and control action plan, *Sustainability*, **14** (2022), 3168. https://doi.org/10.3390/su14063168
26. Y. Liu, L. Chen, L. Lv, F. Pierre, The impact of population aging on economic growth: a case study on China, *AIMS Math.*, **8** (2023), 10468–10485. https://doi.org/10.3934/math.2023531
27. J. Manyika, S. Lund, M. Singer, O. White, C. Berry, *Digital Finance for All: Powering Inclusive Growth in Emerging Economies*, McKinsey Global Institute, San Francisco, CA, USA, 2016.
28. Y. Ji, L. Shi, S. Zhang, Digital finance and corporate bankruptcy risk: Evidence from China, *Pac. Basin Finance J.*, **72** (2022), 101731. https://doi.org/10.1016/j.pacfin.2022.101731
29. J. Deng, Y. Liu, Does digital finance reduce the employment in the finance industry? Evidence from China, *Finance Res, Lett.*, **48** (2022), 102994. https://doi.org/10.1016/j.frl.2022.102994
30. J. Li, Y. Wu, J. Xiao, The impact of digital finance on household consumption: Evidence from China, *Econ. Modell.*, **86** (2020), 317–326. https://doi.org/10.1016/j.econmod.2019.09.027
31. Y. Sun, X. Tang, The impact of digital inclusive finance on sustainable economic growth in China, *Finance Res. Lett.*, **50** (2022), 103234. https://doi.org/10.1016/j.frl.2022.103234
32. T. Li, J. Ma, Does digital finance benefit the income of rural residents? A case study on China, *Quant. Finance Econ.*, **5** (2021), 664–688. https://doi.org/10.3934/qfe.2021030
33. X. Wang, J. Guan, Financial inclusion: Measurement, spatial effects and influencing factors, *Appl. Econ.*, **49** (2017), 1751–1762. https://doi.org/10.1080/00036846.2016.1226488
34. Y. Shen, C. Hueng, W. Hu, Measurement and spillover effect of digital financial inclusion: A cross-country analysis, *Appl. Econ. Lett.*, **28** (2021), 1738–1743. https://doi.org/10.1080/13504851.2020.1853663

35. X. Liu, J. Zhu, J. Guo, C. Cui, Spatial association and explanation of China's digital financial inclusion development based on the network analysis method, *Complexity*, **2021** (2021), 6649894. https://doi.org/10.1155/2021/6649894
36. H. Dong, M. Du, X. Zhou, Spatial temporal differentiation and dynamic evolution of digital finance inclusive development in the Yangtze River Delta economic cluster of China, *Mobile Inf. Syst.*, **2022** (2022). https://doi.org/10.1155/2022/5470373
37. Y. Li, H. Long, J. Ouyang, Digital financial inclusion, spatial spillover, and household consumption: Evidence from China, *Complexity*, **2022** (2022). https://doi.org/10.1155/2022/8240806
38. J. Ma, Z. Li, Measuring China's urban digital economy, *Natl. Account. Rev.*, **4** (2022), 329–361. https://doi.org/10.3934/nar.2022019
39. M. Sarma, *Index of Financial Inclusion*, Indian Council for Research on International Economic Relations New Delhi Working Papers, 2008.
40. D. Ambarkhane, A. S. Singh, B. Venkataramani, Developing a comprehensive financial inclusion index, *SSRN Electronic Journal*, 2014.
41. M. André, A. Goran, M. Alexander, Assessing countries' financial inclusion standing—A new composite index, *J. Banking Financ. Econ.*, **2** (2017), 105–126. https://doi.org/10.7172/2353-6845.jbfe.2017.2.5
42. I. Inyang, E. Omini, F. Bekun, A composite measure of financial inclusion in Nigeria (1992–2019): A principal component analysis approach, *SSRN Electronic Journal*, 2020.
43. P. Khera, S. Ng, S. Ogawa, R. Sahay, Measuring digital financial inclusion in emerging market and developing economies: a new index, *Asian Econ. Policy Rev.*, **17** (2022), 213–230. https://doi.org/10.1111/aepr.12377
44. Y. Xu, T. Li, Measuring digital economy in China, *Natl. Account. Rev.*, **4** (2022), 251–272. https://doi.org/10.3934/NAR.2022015
45. G. Liao, Z. Li, M. Wang, K. Albitar, Measuring China's urban digital finance, *Quant. Finance Econ.*, **6** (2022), 385–404. https://doi.org/10.3934/qfe.2022017
46. F. Allen, A. Demirguc-Kunt, L. Klapper, M. S. Martinez Peria, The foundations of financial inclusion: Understanding ownership and use of formal accounts, *J. Financ. Intermediation*, **27** (2016), 1–30. https://doi.org/10.1016/j.jfi.2015.12.003
47. L. Appleyard, Community development finance institution (CDFIs): Geographies of financial inclusion in the US and UK, *Geoforum*, **42** (2011), 250–258. https://doi.org/10.1016/j.geoforum.2010.09.004
48. S. R. Chakravarty, R. Pal, Financial inclusion in India: An axiomatic approach, *J. Policy Model.*, **35** (2013), 813–837. https://doi.org/10.1016/j.jpolmod.2012.12.007
49. O. Kabakova, E. Plaksenkov, Analysis of factors affecting financial inclusion: Ecosystem view, *J. Bus. Res.*, **89** (2018), 198–205. https://doi.org/10.1016/j.jbusres.2018.01.066
50. C. Haddad, L. Hornuf, The emergence of the global fintech market: Economic and technological determinants, *Small Bus. Econ.*, **53** (2019), 81–105. https://doi.org/10.1007/s11187-018-9991-x

51. J. W. Schindler, FinTech and financial innovation: Drivers and depth, FEDS Working Paper, 2017. https://doi.org/10.17016/feds.2017.081

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