Zhang et al. Heritage Science (2024) 12:287
https://doi.org/10.1186/s40494-024-01401-3

Heritage Science

RESEARCH

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The Changsha historic urban area: a study on the evolution characteristics and influencing factors of the connectivity of construction land

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Abstract
This study aims to understand the connectivity characteristics of construction land during the spatial evolution of historic urban areas. The complex network analysis method is employed to examine the evolution of the spatial structure of construction land in the four periods of the Changsha historic urban area. The results indicate that the spatial network morphology of construction land follows a repeated development pattern resembling a cluster–mother–child relationship. Additionally, the vulnerability in the evolution of land use spatial relationships is very low, while the overall stability of the land use network structure decreases. The spatial equilibrium of land use shows a downwards trend, the accessibility of land where existing cultural relics and historic sites are located is generally moderate to low, and some plots require improvement. In the evolution of connectivity in the construction land of historic urban areas, the main development challenges are the uneven growth caused by imbalanced land value influenced by capital and the need to balance the preservation of land use patterns with improved accessibility to cultural relics and historic sites. Therefore, it is highly important to dynamically detect and optimize the network structure of construction land to protect and develop historic urban areas.

Keywords Complex network, Construction land, Network structure, Connectivity, Changsha historic urban area

Introduction

The rapid development of urbanization has led to significant achievements in urban construction, particularly in terms of economic growth and social progress resulting from transforming suburban areas into urban areas. However, the conflict between economic development and preservation in historic urban areas has been a recurring issue throughout the process of urban function and structural evolution, particularly the use of urban construction land, which is necessary for economic activities. The spatial structure affects a region's development direction and spatial flow significantly impacts historical relics [1]. Urban land use is the foundation for urban development and functionality, serving as the bases for both material construction and intangible activities. The connectivity between land uses allows the exchange of material and intangible flows within the city. Therefore, studying the spatial connectivity of historic urban areas is important theoretically and practically. It protects historic urban areas and promotes social harmony throughout the city.

Research on the spatial protection of historic urban areas has focused on three main aspects: theoretical frameworks, planning strategies, and methods. Theoretical framework construction mainly involves strengthening the display and utilization of historical elements and proposing functional updates and spatial use

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optimizations for traffic based on the spatial morphology evolution of historic sites [2]. However, there is a scarcity of research analysing the evolution and impact factors of the flow of elements between historical spaces. The main theoretical achievements of scholars in the field include "integrated protection" [3], "organic renewal theory" [4], "dynamic protection" [5], and "adaptive regulation" [6]. Planning strategies mainly include zoning control, coordinating the contradictions between the preservation of historic sites and the development of urban transportation systems [7], preserving historical morphological characteristics, and meeting the diverse development needs of historical urban areas by carefully allocating construction land [8, 9]. Additionally, protection strategies based on land accessibility and spatial configuration have been implemented [10]. Research on enhancing the exchange of informational and material flows through land use connectivity is rare. In terms of methods and techniques, quantitative research on historical urban areas has become increasingly prevalent, including approaches such as the analytic hierarchy process [11], principal component analysis [12], space syntax analysis [13], social network analysis [14] and the gravitational model. In recent years, there has been a growing trend of integrating urban planning with spatial network analysis methods. This integration is particularly evident in the areas of tourism [15], ecology [16], urban transportation space [17], the spatial hierarchical structure of urban clusters [18, 19], and urban space [20]. In the application of network methods, the main focus is on visualizing urban agglomerations or urban functional zones using the gravity model to analyse large-scale nodal network relationships. However, there is a lack of calculations and quantifications of network structures and relationships. Furthermore, there is a significant lack of quantitative analyses of the evolution of land use at the mesoscale combined with the temporal dimension in urban land use. The above analysis indicates a lack of network thinking in the theoretical construction of historical urban area research. There is a deficiency in the analysis of the evolution of the circulation of elements between historical spaces and the influencing factors. Additionally, there is a lack of planning strategies to enhance spatial connectivity by exchanging land information and material flows. Specifically, there is a lack of focus on methodology and technology. Furthermore, there is a research gap on the evolution of connectivity in construction land in historical urban areas. This paper utilizes complex network analysis to examine the spatial characteristics of construction land in the four periods of Changsha's historic urban areas. The goal is to uncover the evolution patterns in the connectivity of construction land and the accessibility of cultural relics and historic sites. This analysis aims to support the integrated protection and development of Changsha's historic urban areas and optimise the utilization of its historical resources.

Research subject and methods

Research subject and brief introduction

Changsha city (111°53′–114°15′E, 27°51′–28°41′N), located in the middle reaches of the Yangtze River, has a subtropical monsoon climate. It is situated in a low-lying alluvial plain area on both sides of the Xiangjiang River. The city's favourable terrain and liveable climate have contributed to its long-lasting development. Since the Spring and Autumn Period and the Warring States Period, successive feudal dynasties have used Changsha as a county, country, state, government, road, and hall administrative centre. In 1664, Changsha city was designated the capital of Hunan Province, and has since consistently played a central role in central China's history and economic development. Over 3000 years of urban development, despite experiencing numerous wars and devastation, the urban district has gradually expanded from its original city site. The urban spatial pattern continues to grow along its historical features. It is adorned with numerous historical and cultural relics and possesses a rich historical and cultural heritage. As early as 1984, the State Council recognized it as a national historical and cultural city, one of the first cities to be so designated. The main factors that led to the selection of Changsha as the sample for this study are its economy and politics, its rich cultural heritage, and the consistently stable development of its geographical space. Different historical periods, influenced by factors such as politics, economy, and culture, have left unique traces in the urban space, resulting in dynamic changes in the city's spatial layout. Based on the significant changes in political, economic, and cultural aspects throughout its history, Changsha city can be divided into four periods: the feudal society period, the Republic of China Period, the planned economy period of the People's Republic of China, and the socioeconomic period of the People's Republic of China. The research subjects correspond to these four time periods.

The social background and economic situation are the main influencing factors of urban development patterns. The research scope is based on the designated historical and cultural preservation zones in the "Famous Historical and Cultural Cities of Changsha", the public's recognition of the old Changsha Historic City and its comprehensive knowledge of its construction history. The research scope uses the 2021 map as a reference, which is enclosed by the boundaries of Xiangya Road in the north, Furong Middle Road in the east, Baisha Road in the south, and Xiangjiang River in the west (shown in Fig. 1). In the

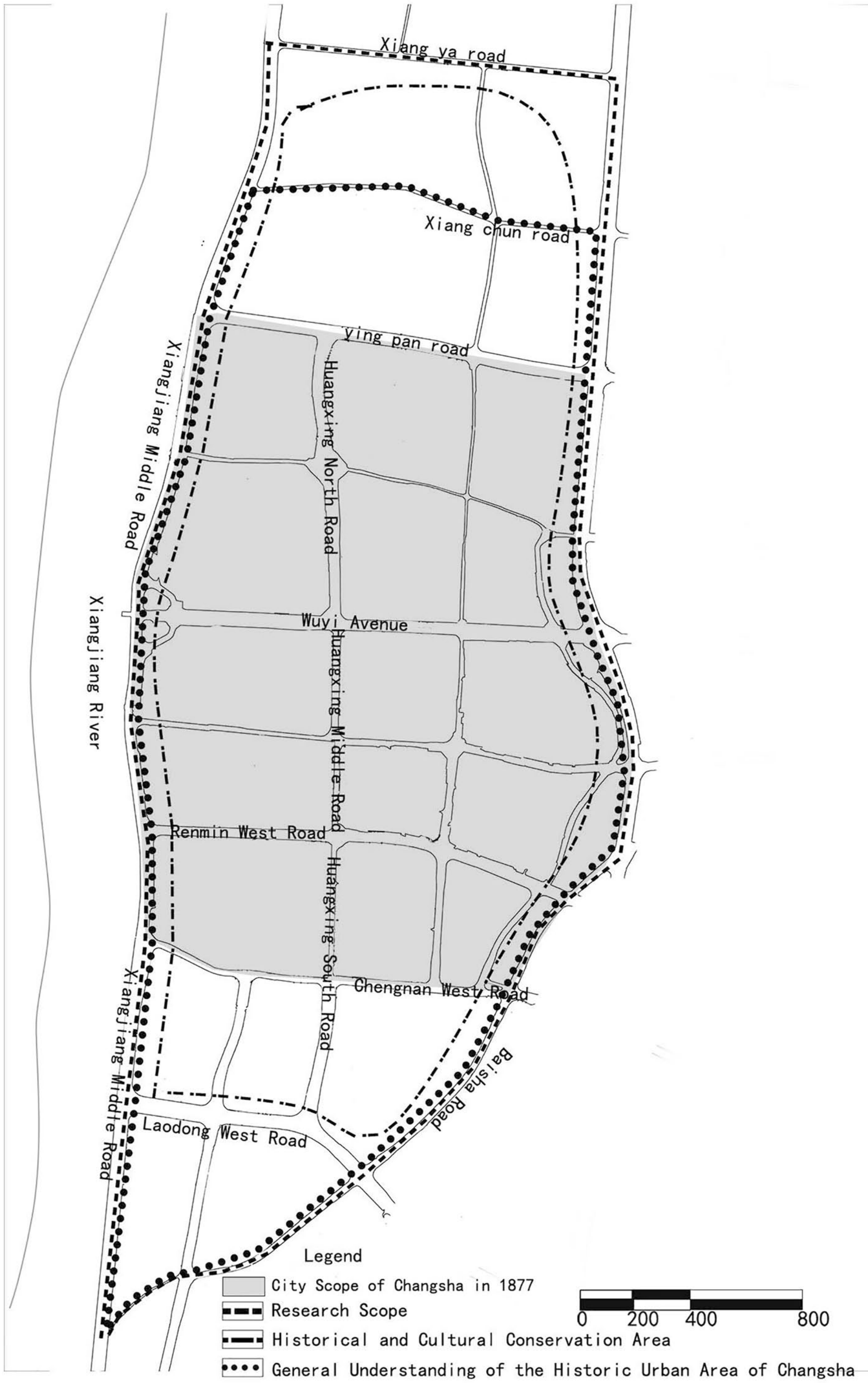


Fig. 1 Demonstration of research scope

early days, it depended on its evolution and expansion. The selection of the periods follows the principle of representation. From the Tang Dynasty onwards, the street and lane system began to align with the city's economic development and demonstrated the influence of land use structure on land value. Prior to the invasion of China by the Eight-Nation Alliance, the spatial and morphological structure of inland cities was relatively stable. Therefore, the map of Changsha during the late feudal period in 1877 [21] was chosen as a research subject. Considering the impact of social changes and the turmoil of war on urban construction, the map of Changsha in the early period of the Republic of China in 1914 [21] is chosen as another research object. After 1920, the urban roads were optimized, and the traffic around the city was built on the site of the demolished city wall, enhancing the city's accessibility and openness. After the establishment of the People's Republic of China, steady economic and social development transformed the country from a planned economy to a market economy, leading to a more open approach to urban development. Thus, maps of Changsha at the end of the planned economy period in 1987 [21] and of Changsha during the market economy development period in 2021 are also chosen as research objects (Fig. 2). This paper also paper studies the spatial topological relationship of land use, so differences in map clarity have little impact on the results of this study.

Research methods

Literature review and field investigation

The literature review method aims to understand the history, urban spatial morphological features, and changes of Changsha's social background. Therefore, representative periods of urban development are chosen as the research objects. This paper employs a field investigation method to examine the perceptions of Changsha citizens regarding historic urban areas, combining the preservation scope of the historic urban area outlined in the Protection Plan of Changsha Historical and Cultural City, and defines the specific scope of the research object.

Complex network analysis

The research involves obtaining basic data and then constructing a network relationship model for Changsha's historical urban area based on the semantic model. This is followed by conducting network structure calculations for the construction land network relationship models of Changsha's historical urban area during four different periods, ultimately obtaining quantitative results for the network characteristics. The network model is composed of "points" and "lines". "Points" refer to entities existing in real society, while "lines" refer to the mutual relationships or functions among social entities [22]. In this study, the urban internal construction land, road system, and connectivity are transformed into nodes and network edges, describing the spatial structure of urban land in the form of a network. The complex network analysis method can be used to systematically understand and translate the formation mechanism of "point" and "line" networks [22]. Additionally, the structural index system can quantitatively evaluate the spatial network of construction land in historic urban areas. In networks, vulnerability analysis can reveal which parts or nodes of the network's failure will have a significant impact on the entire network. Accessibility analysis measures the convenience and efficiency of connections between nodes in the network, which helps analyse whether the supply and demand match when important nodes exchange information and material flows. Balance analysis evaluates whether resources or loads are evenly distributed in the network to prevent the excessive concentration of resources in a few nodes, which can lead to lower overall network performance. Stability assesses the network's ability to maintain its functionality in changing and dynamic conditions. These analyses are crucial for understanding network dynamics and performance.The spatial network structure of construction land is used to analyse the spatial form, fragility, stability, balance and

Fig. 2 Maps of different periods

accessibility of cultural relics in historical urban areas. In addition, quantitative analysis is employed to examine the spatial evolution characteristics of construction land in historical urban areas and to address issues related to the preservation and utilization of historical relics.

1. Building the semantic model

   The complex network method is used to construct the "point" element, which determines the construction land (adjacent road enclosures) and the road (road segment between two intersections), as well as the "line" element, which directly connects adjacent intersections. This means that there is a connection (line) between the land (point) that is connected by the same intersection and the road (point). In constructing a complex network model, networks are divided into one-mode and multimode networks based on the number of network actor sets [22]. In line with the spatial relationship of construction land in historical urban areas, this paper obtains a 2-mode data matrix of construction land and roads. And generating matrix tables using Excel, this matrix is an undirected matrix. Subsequently, the network analysis software *Ucinet* is utilized to establish a 1-mode network model between construction lands.

   Computer-aided design (CAD), geographic information systems (GIS), and other software are used to digitize the selected maps to construct a semantic model (Fig. 3). This process involves the creation of a 2-mode relationship matrix between construction land and roads. *Ucinet* software is used for matrix processing to obtain the 1-mode network model between construction lands. Additionally, visualization processing is carried out.
2. Indicator system
   The connectivity of the construction land network in Changsha Historic City is characterized by the vulnerability, stability, equilibrium and accessibility of the network, and the relevant indicators in the 1-model network model of construction land and construction land are calculated. Node density and tangent point reflect the vulnerability of construction land, network density, Lambda set and k-core reflect the stability of construction land, the degree centre potential and intermediate centre potential reflect the equilibrium, and the centrality of land protection land degree reflects the accessibility of land protection and construction land. All the indicators can be calculated using Ucinet software.

   1. Node density

      Node density refers to the level of connectivity between individual network nodes and other

Fig. 3 Numbering of construction land in the Changsha historic urban area in different periods

nodes in the overall network, which is calculated as the ratio of the actual number of relationships in the individual network to the total number of relationships among all network members. The lower the density value, the more vulnerable the network is. It is calculated as follows:

$$D = m/[n(n-1)] \tag{1}$$

where D denotes the network density, m denotes the actual number of relationships in the individual network, and n denotes the size of the individual network.

2. The point of contact
The point of contact is when certain nodes are removed from a network, the entire network will be separated into multiple independent parts. Therefore, the vulnerability of a network is typically measured by the proportion of these nodes to the total number of network nodes.
3. Network density
Network density reflects the level of interconnectedness between nodes in a network relationship, which is defined as the ratio of the actual number of connections in the graph to the maximum number of possible lines. The network density formula measures the overall completeness of the network. It is calculated as follows:

$$P = L/[n(n-1)/2] \tag{2}$$

where P denotes the network density, L denotes the number of connections that actually exist in the network, and n denotes the number of nodes that actually exist in the network.

4. Lambda collection
By analysing the degree of edge correlation at the network level, the overall stability of the network structure is measured.
5. K-core
core (k = 1, 2, 3, etc.) calculations measure the local stability of a network. The higher the K value, the greater the proportion of local network components with a stable structure, resulting in a more stable network overall. This indicates a positive correlation between network stability and both the K value and the proportion of K cores.
6. Degree centre potential
The degree centre potential analyses the overall degree centrality of a network by testing the general equilibrium of relationships in the network structure. The greater the proportion of the centre potential, the greater the concentration of relationships between urban construction lands, and the lower the network equilibrium. It is calculated as follows:

$$C = \frac{\sum_{i=1}^{n}(C_{max} - C_i)}{max\left[\sum_{i=1}^{n} C_{max} - C_i\right]} \tag{3}$$

where C_{max} is the maximum value of the degree centrality of each node in the network, and C_i is the centrality of node *i*.

7. Degree centrality
Point centrality refers to the centrality of the research object in a social network, indicating the number of points connected by other points in the network. The greater the degree of centrality, the more related connection points, resulting in greater network centrality.

Results

Analysis of the evolution of the overall spatial form of construction land in different periods

Figure 4 illustrates that the spatial arrangement of urban land in 1877 was the most compact and evenly distributed. This suggests that the urban form and land use patterns were influenced by political and military factors. Furthermore, the exchange of information about urban land was highly centralized and balanced due to feudal centralization. In 1914, the development of the subgroup was highly dispersed. The main reason for the emergence of the subgroup was the rapid development of the area that broke through the city wall after 1914. This indicates that the construction of the new area was not closely

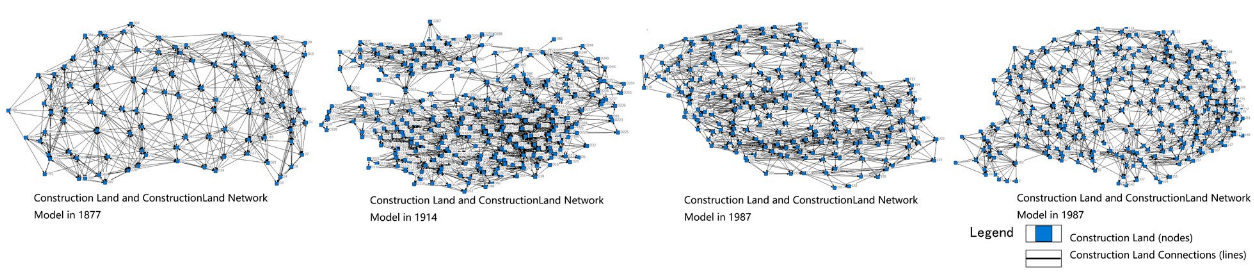


Fig. 4 Construction land and construction land network model in the Changsha historic urban area in different periods

Table 1 Node density of Changsha historical city in different periods

	1877 urban land	1914 urban land	1987 urban land	2021 urban land
Minimum node density	27.51	0	0	19.14
Percentage of the lowest value of node density	0.9%	0.9%	0.4%	0.4%

Table 2 Cut points of Changsha Historic district in different periods

	1877 urban land	1914 urban land	1987 urban land	2021 urban land
Number of tangent points	0	1	0	0
Tangent scale	0	0.3%	0	0

Table 3 The network density of Changsha historical urban area in different periods

	1877 urban land	1914 urban land	1987 urban land	2021 urban land
Network Density	0.43	0.11	0.18	0.14

connected to that of the old area. However, in 1987, it evolved into a mass form, whereas in 2021, a mother–child form emerged. Compared to the significant changes in urban construction areas, the spatial network structure of land use in historical areas has undergone a regular pattern of development known as group–mother–child. This pattern reflects the adaptability of old urban spaces to new functions and demonstrates that the spatial morphological structure has undergone a dynamic upwards spiral change.

Vulnerability analysis over time

Node density analysis in different periods

Table 1 shows that over time, there was a decreasing trend in the lowest node density of construction land in the Changsha Historic Urban Area. This indicates that the minimum connection between construction land in the area continues to decrease, suggesting that the rate of land utilization in the marginal area is most controllable under centralization. In 1914 and 1987, although the node density value was 0, the proportion was relatively low. This indicates that it was easy to have isolated land with no connection to the surrounding land during the process of social change and land use expansion. However, the overall connectivity of land use was good, and vulnerability was low.

Point of contact analysis in different periods

Table 2 shows that, except for one tangent point in 1914, there are no other tangent points in the other periods. This indicates that the vulnerability of the land use structure in the spatial evolution of the Changsha historic urban area has consistently remained low over time. The flow of people and vehicles has been steady, with no hidden risk of congestion. In 1914, the cut-off point for the suburbs was the D80 plot. This was because there was only one road connecting the area, and if the D80 plot had been cancelled, it would have isolated the D81 plot, which was farther away from the urban area. However, this would have little impact on the overall structural connectivity of the land. Considering the characteristics of Changsha's historic urban area, which has never been relocated or extensively developed, it is evident that the preservation of the ease of construction of the ancient Changsha site plain and the rational layout of the urban land pattern have been maintained.

Comparative analysis of stability in different periods

Network density analysis in different periods

Table 3 shows that the network density was the highest in 1877 and lower in the other three periods. Network density exhibited a downwards trend throughout historical development, indicating that the land use structure was most stable under centralized rule. Of the other three periods, the network density in 1914 was the lowest. The historical pattern was studied extensively, revealing that in 1914, the city expanded externally as a result of the railway breaking through the city wall. The connection between construction lands was also found to be too rough, indicating that the initial improvement in transportation modes weakened the stability of the land use structure due to changes in the mode of disseminating land use information.

Lambda collection in different periods

Table 4 shows that the urban construction land network structure was the most stable in 1877 and was lower in 1914, 1987, and 2021, indicating a downwards trend

Table 4 Lambda gathering in Changsha historic district in different periods

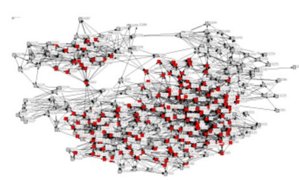
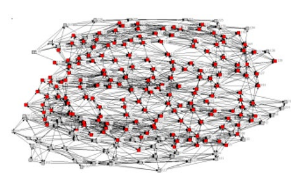
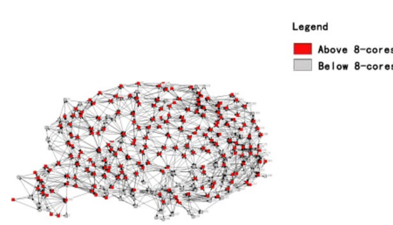
Research samples	Relevance level	Minimum edge affinity	The value corresponding to the edge correlation degree of the network hierarchy	Network structure stability %
1877 urban land	45	10	1, 1, 1, 1, 2, 1, 1, 2, 3, 1, 4, 2, 1, 4, 2, 2, 4, 1, 9, 4, 1, 5, 4, 1, 3, 2, 2, 4, 1, 4, 1, 5, 3, 2, 3, 1, 2, 1, 1, 1, 2, 1, 1, 1, 2	7.92
1914 urban land	63	0	1, 1, 2, 3, 1, 7, 9, 6, 4, 6, 11, 10 10 12, 4, 7, 6, 8, 8, 10, 5, 4, 7, 8, 4, 7, 8, 6, 7, 3, 2, 7, 7, 5, 4, 5, 7, 6, 6, 3, 5, 5, 5, 3, 4, 1, 3, 5, 1, 1, 5, 1, 1, 1, 1, 1, 2, 3,	3.89
1987 urban land	51	12	1, 1, 2, 1, 1, 1, 4, 1, 3, 1, 2, 4, 2, 1, 1, 4, 3, 10, 4 10, 1, 3, 10, 5, 7, 7, 7, 6, 5, 3, 8, 5, 7, 6, 4, 5, 3, 1, 2, 1, 4, 6, 2, 1, 12, 2, 1, 3, 2, 1	4.59
2021 urban land	63	4	1, 1, 2, 4, 1, 1, 3, 3, 2, 3, 4, 5, 6, 4, 6, 11, 6, 6, 4, 8, 5, 8, 9, 12, 9, 7, 9, 7, 6, 7, 5, 5, 4, 12, 8, 8, 7, 5, 5, 2, 3, 7, 3, 5, 3, 2, 6, 4, 5, 3, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 3	3.97

in the stability of the construction land network in the Changsha Historic Urban Area over time. Interestingly, the stability in 1987 was slightly greater than in 1914 and 2021. This is due to a mother–child network of construction land during this period. The most significant decrease in stability was observed in 1914. The main reason is that in 1914, the economy and society were undergoing a period of transition, and the development of productive forces was progressing positively. Therefore, a certain amount of construction land in the form of mother–child networks became the driving force for economic and social development.

K-cores

Table 5 shows that network stability in Changsha's historic urban area exhibited an overall downwards historical trend. The K value was evenly distributed, with a large proportion of high K values occurring in 1877, indicating that the land use was the most stable. Of the

Table 5 K-nucleus of the Changsha historical city in different periods

Research samples	K-number of kernel partitions	K-kernel partition results and quantity	8-nuclear ratio (%)	K-nucleus distribution
1877 urban land	5	4 K:2, 5 K:2, 6 K:9, 7 K:4, 8 K:84	83	
1914 urban land	10	1 K:1 2 K:2, 3 K:3, 4 K:15, 5 K:37, 6 K:45, 7 K:30, 8 K:109, 9 K:44, 10 K:11	55	
1987 urban land	5	5 K:5, 6 K:8, 7 K:41, 8 K:161, 9 K:10	76	
2021 urban land	7	2 K:2, 3 K:3, 4 K:4, 5 K:9, 6 K:16, 7 K:43, 8 K:193	71	

remaining three periods, the K value in 1914 was the lowest, and there was a clear distinction between the two levels, which corresponded to the plot number, with the subgroup mainly consisting of land used for new construction between the city wall and the railway. The parent group still had a higher K value with a larger proportion, indicating that the connectivity of construction land within the original city wall area remained relatively unchanged in 1914. However, the overall stability decreased mainly due to the expansion of new construction land beyond the city wall. The increase in the K value in 1987 indicates that the upgrading of road traffic facilities in postdisaster reconstruction improved traffic in the original urban area. However, there was damage to the street surface and a lack of new branch roads, diminishing overall land stability relative to that in 1877. The K value in 2021 was slightly lower than that in 1987, which led to converting some land into marginal areas and constructing new roads. The in-depth reason for this was the extensive development of the market economy, which resulted in consolidating land plots. As a result, the original, diverse street layout of the historic urban area was gradually being replaced by an orthogonal grid pattern. This change made the central network more compact but caused the development of some nonkey areas to lag behind. This led to the reemergence of a hierarchical network structure, indicating that slower traffic was more beneficial for strengthening land connectivity and stability. It also showed that the profit-seeking model of the market economy was not conducive to the stable development of the overall network of construction land and the preservation of spatial patterns.

Comparative analysis of equilibrium in different periods

Table 6 shows that the degree of central potential was the highest in 1877 and lower in the remaining three years. This indicates that the balance of the construction land network in the Changsha Historic City exhibited a downwards historical trend. The most prominent concentration of construction land was observed in 1877, when equilibrium was the weakest. However, the degree of central potential gradually increased in 1914, 1987, and 2021. Some scholars have noted that in 1877, there was a single-centre polarized urban space under centralized control. By the end of feudalism in 1914, a north–south dual centre had gradually formed, replacing the single-core centre. In 1987, construction of the historic urban area was reduced, and a dominant single-centre urban space focused on administrative functions was restored. In 2021, the centrality of the historic urban area continued to increase, and the benefits of commercial agglomeration in a single centre continued to develop [9]. The main factors influencing equilibrium were the changes in land use function and centrality caused by political and economic changes. The imbalance of land use in historic urban areas was primarily due to the concentrated development of functional zoning around a single centre.

Accessibility of land for cultural relics and monuments

Cultural relics and historic land refer to structures on land with conservation value. For cultural relics and historic sites to fully utilize their value, it is essential to first ensure that their construction land is easily accessible. The greater the accessibility, the greater the historic relics' meaning and ability to maintain their value [23]. Therefore, in the construction of a land network structure, the greater the centrality of construction land, the greater the land's connectivity and accessibility and the more conducive it is to possessing cultural heritage. Table 7 shows that, overall, the centrality of the network relationship in the land for the construction of cultural relics and historic sites is relatively

Table 6 Statistics of Centrality of Changsha Historic District in Different Periods

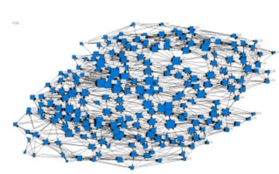
	1877 urban land	1914 urban land	1987 urban land	2021 urban land
Degree of central potential proportion	4.52%	1.61%	1.97%	2.22%
Point degree centre potential distribution				 

Table 7 Centrality of construction land in the current state of cultural relics and historic sites in 2021

	Relics plot number	Preservation level	Centrality
Statistical results	268	Provincial	57
	93	Provincial	44
	97	Provincial	24
	66	Provincial	46
	62	Provincial	44
	64	Provincial	27
	57	Provincial	41
	285	Provincial	38
	16	Provincial	54
	294	Provincial	60
	303	National	61
	41	National	75
	240	National	15
	242	National	51
	73	Provincial	32
	277	Provincial	52
	178	Provincial	77
	234	Provincial	28
	245	Provincial	43
	239	Provincial	45
	220	Provincial	26
Location	Specific location is shown in Fig. 3 (Numbering of Construction Land in the Changsha Historic Area in 2021)		

balanced. The grade is medium, and the spatial accessibility of the construction land is average. Considering the preservation of historical sites and the influence of the market economy, the spatial connectivity of construction land in most areas has not changed significantly. However, the centrality of the five cultural relic construction sites is less than 30, indicating a lower utilization rate. In particular, one of these sites is still a key national cultural relic unit that requires improvement.

Discussion

Connectivity features of construction land in the Changsha historic area

This study has demonstrated that the vulnerability of the construction land network in Changsha's historic urban area has remained consistently low and has not undergone significant changes over time. However, network stability showed a downwards trend, while equilibrium exhibited an upwards trend. Shi Yaling utilized the network analysis method to compare three historic districts in Chongqing. The study revealed that the network stability of the historic district building complex varies with changes in topography and building layout. The network structure of densely distributed historic districts is more compact and exhibits a more stable network relationship compared to strip historic districts. The long-distance distribution of strip districts and the presence of natural barriers were identified as the primary factors contributing to their vulnerability [14]. This study shares similarities and some features with the research conducted by Shi Yaling. The commonality is reflected in the evolution of the land use structure in Changsha's historical urban area. The trend of stability is observed as down–up–down pattern, which echoes the network structure trend of cluster–group–cluster–group. This also indicates that the morphological relationship of the network is the main factor influencing the stability of the land use network. However, the vulnerability of the network has been low, primarily due to Changsha's plain topography, which hinders linear development in the urbanization process. Shi Yaling's analysis of the internal land use of the three parks also revealed that the mountainous topography and land use function affected the network structure of the park. The presence of topographic barriers and diverse land use has led to the formation of clusters in the network structure, weakening stability and enhancing the balance of the park's land use network. On the other hand, the dynamic mixed land use function has improved the stability of the network structure [14]. This study also adheres to this law, although there are differences in the barriers and the dynamic mixed land in the mother–child network. The primary barriers include the social instability caused by the changes to city walls over time, while dynamic mixed land mainly refers to public service facilities and administrative and recreational land. The change in land use in Changsha's historic urban area is primarily attributed to the shift in the proportion of public services and administrative land. The trend of network structure equilibrium follows an upwards–downwards process, which is consistent with the law that the construction land function in Changsha's old urban area has evolved from a single centre to a multicentre and then back to a single centre, as found in previous studies [9]. This suggests that the dispersed layout of dynamic mixed land improves network equilibrium. Lu Zheng noted that the spatial evolution of historic urban areas is influenced by various social, economic, and political factors, emphasizing that space and its organizational relationships are shaped by changes in society, the economy, and institutions in a specific period and also play an active role in confirming and influencing the development of urban society and the economy [9]. The findings of this study support the perspective that the appropriate mother–child form promotes social development and the efficient use of land, as evidenced by the increased stability observed after 1914. In addition, this study conducted an analysis of the cultural relic land that showcases the characteristics of the historical urban area and found an overall balanced centrality of the construction land network relationship of cultural relics and historical sites, with a moderate level of centrality. The spatial accessibility of construction land for cultural relics is average, indicating that the utilization of cultural relic protection areas within existing urban land is not high.

The main obstacles in the development of construction land connectivity in Changsha's historic city

This study demonstrated that the vulnerability of Changsha's historic urban area has consistently been very low, and there is no threat to its network structure. The flow of people and materials between different plots is steady. The evolution of construction land connectivity is primarily characterized by stability and equilibrium. Huang Yong proposed that the rational layout of construction land clusters and rational functional partitioning can enhance network stability and balance [14]. In developing construction land connectivity in Changsha's historic urban area, the stability and balance of the construction land network are also influenced by functional zoning. Early barriers, such as city walls and railways, no longer exist, eliminating any natural environmental obstacles in the area. Therefore, the loss of artery roads and the decrease in road density due to rapid urbanization are among the main factors affecting the connectivity of construction land in Changsha Historic City. Against the backdrop of a market economy, the altered land functional zoning in Changsha's historic urban area has resulted in imbalanced values, reinforcing uneven development driven by capital. Therefore, the unreasonable zoning of land functions is the main obstacle to the stability and balance of the land use structure in the Changsha Historic City. Changsha Historic City is still an important central area of Changsha. However, in developing the city's historic urban area, the construction of large-scale commercial complexes in the old city has resulted in a significant loss of immovable cultural relics and the disappearance of historical streets and alleys. Additionally, the market economy has strengthened the role of the historic city as a business centre; however, there remains the serious issue of spatial and functional relations, which hinders the preservation of historical and cultural heritage. Therefore, another key point in the development of construction land connectivity in Changsha Historic City is how to protect land use function patterns and improve transportation connections for cultural and historic relic land at the same time.

Conclusions and recommendations

Conclusion

The vulnerability of the construction land network in Changsha has consistently been very low. The evolution of construction land connectivity is primarily reflected in the stability and equilibrium of the network structure, in which network stability shows a downwards trend while the equilibrium shows an upwards trend. The stability of the construction land network is primarily influenced by the relationships among network structures, which are primarily determined by the level of difficulty in connecting the land areas. Unlike mountainous cities, Changsha is situated in a plain with few natural barriers. The primary factors influencing the connection between land use in the city are the changes that took place in particular eras. This includes the construction changes brought about by historical developments, such as city walls and railways in the early stages, and road network density resulting from urban renewal during the period of rapid urbanization. The equilibrium of the construction land network is influenced primarily by the functional zoning of construction land in historic urban areas. The unbalanced development of land value and unreasonable functional zoning are caused by the control of capital under the market economy. Furthermore, it poses a significant obstacle to preserving historical and cultural heritage.

Therefore, it is crucial to actively conduct dynamic monitoring of the network structure of construction land in the Changsha Historic City and similar historical sites. It is important to identify and improve important connecting channels, optimize the stability of the network structure, enhance the central potential of key nodes, achieve a balanced network structure through reasonable functional zoning, and improve the accessibility of land where cultural relics and historic sites are located to promote their utilization. This method can also be extended to other urban areas, old areas, rural settlements, and other construction areas. It can be used to monitor the compatibility of existing land use functions and land connectivity, providing a reference for urban and rural construction management. Furthermore, this method can be applied to village cluster management to monitor the compatibility of network relationships and development positioning between village clusters, providing insights for regional rural planning strategies.

Suggestions for optimizing the connectivity of construction land in Changsha historic city

In developing construction land connectivity in Changsha's historic urban area, it is necessary to prioritize stability and balance. In terms of the structural stability of the construction land network, the dynamic stability of the network can be tested to identify crucial internal connecting channels and roads with low connectivity. Optimizing the stability of the construction land network structure through planning and management aims to enhance the overall structural stability of the network. At the same time, the network structure characteristics and functional properties of construction land can be overlaid and analysed. The finding that dynamic mixed land can improve the stability of construction land can then be used to guide the layout of construction land with different demand properties in urban planning. Regarding the balance of the construction land network structure, it is necessary to increase the number of nodes with a lower degree of central potential in the social network [18]. Additionally, the commercial agglomeration effect in the core area can be weakened by implementing commercial zoning, which would facilitate polycentric development and result in more balanced urban land connectivity. The preservation of historical resources is crucial for urban development [3]. Currently, the amount of land available for cultural relics and historic sites in Changsha's historic urban area is not high. Therefore, it is worth considering enhancing the centrality of land use for historical relics to improve their accessibility. In the face of the contradiction between the need to preserve the historical pattern, an intermediate-level grid can be introduced between the outer road network of the historical reserve and the internal tree grid, which aims to reconcile the contradiction between microeconomic movement and increased historical and cultural use. The factors influencing vulnerability, stability, balance, and accessibility in urban construction are similar, and the adjustment measures of urban land relationships in this study can also provide a reference for other urban–rural construction lands.

Author contributions

Boyang Zhang and Jinyu Fan wrote the main manuscript text, Piao Zhang, Sha Shen, and Yangming Ren processed the data together, and PiaoZhang translated all manuscript text into English. All authors reviewed the manuscript.

Funding

This paper was funded by the National Natural Science Foundation of China, Project No. 52308057. This paper was funded by the Guizhou Province 2022 Higher Education Teaching Content and Curriculum System Reform Project, Project No. 2022240.

Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Ethical approval was not required for this paper.

Competing Interests

The authors declare no competing interests.

Received: 26 February 2024 Accepted: 28 July 2024
Published online: 07 August 2024

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