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Spatial Morphology of Urban Residential Space: A Complex Network Analysis Integrating Social and Physical Space

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Abstract: Residential areas are primary functional spaces of urban built-up areas, representing urban social structure externally and influencing urban spatial fabric (SF). Chinese cities have increasingly experienced urban renewal following significant population growth and urban expansion in the last four decades. We selected built-up urban areas of Shanghai as the research scope, considering 6731 residential quarters as research objects, which were identified and classified into six types. Based on complex network theory and analysis methods, an urban residential spatial network (URSN) was constructed in central Shanghai implementing through code. The degree of distribution and network robustness of the URSN was examined, and network "communities" were identified. The findings indicate that URSN stability, like robustness, implies harmonious and smooth social interactions and information transfer, consistent with the SDG 11, where the large-degree node residential quarters play an important role and must be prioritized in urban renewal. Meanwhile, the identification results of the URSN "communities" help us understand territory identity in built-up urban areas. This research provides new concepts and methods for examining SF in urban residential areas that integrate "physical" and "social" spaces, compares this approach to the traditional point-axis structure, and pioneers the study of urban SF from the perspective of complex networks by providing a new way of visualizing the spatial relationship between residential quarters as a network-like structure.

Keywords: residential areas; urban residential spatial network; spatial fabric; complex network analysis; SDG 11; Shanghai metropolis

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Academic Editors: Qingsong He, Jiayu Wu, Chen Zeng and Linzi Zheng

Received: 6 February 2025
Revised: 4 March 2025
Accepted: 5 March 2025
Published: 6 March 2025

Citation: Yang, F.; Xu, L.; Wang, J. Spatial Morphology of Urban Residential Space: A Complex Network Analysis Integrating Social and Physical Space. *Sustainability* **2025**, *17*, 2327. https://doi.org/10.3390/su17052327

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1. Introduction

Living spaces are among the most important functional geographical areas of a city. With growing population density in urban areas triggering social contradictions and conflicts, the segmentation and inclusion of living spaces of residents from diverse classes and social backgrounds has become a concern in urban research. However, from a socioeconomic, cultural, and political perspective, groups choose different places to settle in a city, forming social spatial patterns or fortresses [1]. Recent studies have indicated that while appropriately mixed communities are conducive to a harmonious urban society [2], the isolation of urban living spaces prevents the realization of inclusion, especially in China's metropolises, where gated neighborhoods (GNs) form a "fence" between residential areas [3]. Moreover, the configuration of social public service and shared facilities around relatively separate residential areas often enhances rather than mitigates this pattern.

Chinese cities, particularly megacities, have undergone significant population growth and urban expansion over the past 40 years amid rapid urbanization [4]. Issues such as

the regeneration of old neighborhoods and subsidized housing have gradually gained attention in recent years as urban regeneration has become an important policy for national development. This research aims to examine the co-relationship between physical and social spaces of gated communities in metropolitan Shanghai. By constructing an urban residential spatial network (URSN), this study seeks to uncover whether cities that follow the principles and strategies of the urban planning spatial functional layout promote the formation of spatial correlation structures for citizens' living space, which can be characterized and analyzed by spatial model language.

2. Literature Review

2.1. Formation of Residential Space and Its Fabric

Urban spatial fabric (SF) is shaped by economic and social activities, reflecting the concentration and distribution of populations in their choice of residence, employment, interaction, travel, trade, and other activities, expressed in the spatial distribution of land-use functions [5]. Housing is one of the most fundamental functions of a city [6], contributing to the emergence of clear research directions focused on the residential behavior of individuals and families. This research encompasses the study of social space, including spatial and temporal processes of individuals, groups, social organizations, and social problems in urban society, as well as the study of physical space, including the location [7] and spatial structure of residential areas.

Urban social spaces reflect social relationships, with residents meeting for various types of "business" and forming social ties with strangers through contractual relationships, including the formation of families, unlike in rural areas where social relations are primarily organized through blood and ethnic ties [8]. Therefore, the diversity and heterogeneity of interactions and social relationship structures in a city determine the complexity and integration of social spaces. By contrast, rural areas are characterized by common living spaces with clear boundaries [9], leading to a growing interest in the study of urban spaces to understand how different social groups inhabit individual neighborhoods [10], how social relationships are maintained and nurtured [11], and how social relationships and activities are organized in space and time [12].

However, in the Chinese context, the construction and growth of urban living spaces are heavily influenced by the governance model, without the process of self-organization and formation. Between 1949 and 1998, urban residents were allocated housing by state-owned institutions, although individuals and families had no housing ownership and the living space was often close to production and work spaces [13]. Beginning in 1998, following the reform of housing commercialization, urban residents were granted "property use rights" on their housing for 70 years, and real estate development became the main method of generating housing supply. Under the influence of management associates, such as the acquisition of land use rights, development processes, property rights transfer, and property management, the structure of urban living space depended on the land development units formed at the time of land transfer, also known as GNs [14]. Residents and families from diverse social backgrounds, occupations, and income levels gradually relocated to the physically fragmented GNs built in different periods. Therefore, revealing the structure of living spaces under the interaction between physical space and social relations has both theoretical value and practical significance. Studies based on China's most recent settlements reveal that medium- and high-density apartment-style residential communities are in line with Chinese living habits and tend to be conducive to resident interaction and social harmony.

2.2. Studies on Residential Spatial Structure

Urban residential spatial structures stem from the inter-construction of physical and social spaces. Urban residents develop class [15] and territorial identities [16] through their daily behaviors and selection of different types, generations, and forms of residential quarters. Therefore, the heterogeneity of social space is reflected in the variability of physical space in terms of housing quality and quantity [17]. Spatial construction processes, such as urban expansion, housing marketization, and redevelopment, have disrupted social networks [18], further complicating and diversifying not only residential physical and social spaces, but also perceptions of "housing inequality" [19]. Urban spatial planning practices often emphasize the maintenance and repair of social networks [20] to facilitate the establishment of rich spatial and geo-relationships [21], ultimately contributing to the overall development and optimization of urban spatial structures [22].

The study of urban residential spaces provides insights into the behavior of urban residents from the perspective of physical spatial relations. The phenomenon of "housing inequality" has emerged in cities under the combined effect of institutional evolution and market-oriented reforms; it is reflected not only in the ownership of housing of different types, quality, and quantity by different economic and social classes, but also in the distribution of living spaces [19]. Residential areas of different types, ages, and forms create a diverse and complex structure of residential spaces with obvious spatial differences between housing types [23]. Meanwhile, residential "forms" and economic and social "connotations" interact to promote the overall development of the urban SF. It involves different functional spaces and services, such as employment spaces [24], commercial and shopping spaces [25], and green and recreational spaces [26]. By influencing the movement of people toward housing, employment, shopping, and leisure [27], the urban SF [28] is shaped, linking urban housing with local government finance [29]. Compared to the traditional point-axis structure, this method provides a new way of thinking for urban spatial research by visualizing and expressing the spatial relationship between residential quarters as a network-like structure based on the measurement of social relationships among residents.

2.3. Studies on the Urban Spatial Network

Urban spatial network research has focused on spatial elements that represent network types [30], such as urban roads, metros, and utility networks. Based on open street network data, some scholars have measured the distribution of "degrees" and network efficiency of urban street networks [31], using network modeling to calculate the street orientation entropy, street segment length, average circuity, and average node degree to reveal the order of urban street networks [32]. Methods to tackle congestion and improve urban resilience by quantitatively describing the morphological structure of cities have been explored.

Studies of urban spatial networks have gradually included spatial elements that lack a network form [33]. Some scholars have classified urban built-up areas into grids and divided cities into four attractive categories—employment, housing, landscape, and accessibility—according to the main functions within the grids. They measured the characteristics of network connections and distribution of amenities between spatial units using gravity models [34]. Urban fabric studies use network percolation analysis to identify and measure the proximity of buildings and spatial interactions [35], focusing on the interconnectedness of fabric units and the fractal characteristics of shapes and boundaries to support urban regeneration strategies.

Socio-spatial network research has extensively used complex network theory and methods to expeditiously identify the evolution of key individuals, groups, and relationships by analyzing patterns of distribution and competitive dynamics in networks. In particular, the phenomenon of multiplex communities in collaborative networks, "small

worlds" [36,37], and multi-layered networks (multi-attribute heterogeneity) [38] have been identified in studies of actors and scientists. In addition, multidimensional scaling analysis reveals the community structure, strengths and weaknesses, network development, network structure, value transfer, and social capital characteristics of social networks based on citation ratios of social media posts [39]. Furthermore, research on interactions among urban residents has determined more stable relationships among residents with short information paths [40].

Complex network theory (CNT) has been applied to urban studies, gradually forming a new field of research, Complex Urban Systems, based on the recognition of the interconnectedness between urban and social spaces. CNT is further combined with urban resilience theory to provide an effective analytical method for quantitatively describing the resilience of urban systems [41,42] by revealing the small-world properties of complex networks [43] and scale-free network properties [37], while exploring the possibility of network node failure and recovery performance after damage using network topology. For example, network robustness has been measured to identify critical stations in metro networks and evaluate the resilience of electrical networks [44], and the resilience of urban streets has been examined using percolation theory. These studies offer interesting prospects for applying complex network science to the study of urban spatial structures.

2.4. Complex Network Analysis Applied to the Study of Urban Spatial Fabric

Many urban developments are essentially network phenomena, such as hierarchical scale, resilience, and economies of scale [45]. Therefore, according to different research questions, the research scope and "node" and "tie" networks are clearly defined to reveal the mechanism underlying the generation and evolution of urban space through complex network analysis. Among them, the "node" can be defined as "individuals, organizations, cities", and other objects, whereas the "tie" represents associations between "nodes", including physical relationships, mutual influences, cooperation, and even the dissemination of information [46].

Three important aspects of urban intra-spatial networks deserve further exploration: first, the definition of the spatial network "node" is not rigorous enough to reflect the type of urban space addressed by the research problem. Second, the spatial network "ties" are mostly observable space objects with physical forms, which fail to reflect the interaction between urban society and spatial elements. Third, current network analysis mostly considers pressure, gravity, gravitational force, or "flow" as explanatory underlying mechanisms; studies attempting to combine physical space and socio-spatial networks by using information, ideas, and relationships as the explanatory dissemination mechanisms, have yet to be explored.

Residential space is an important component and driving force in the evolution of urban spatial structure [47]. Therefore, a complex network approach helps achieve the integration of physical and social spaces to reveal the characteristics of urban SF. This approach has theoretical and practical value for urban spatial planning, the allocation of public spaces and facilities, and the realization of a complete community.

3. Data and Methods

3.1. Study Area

This study focuses on the central urban area of Shanghai, encompassing the A20 outer ring road and spanning approximately 660 square kilometers. It comprises seven districts within the A20 ring road: Huangpu, Xuhui, Changning, Yangpu, Hongkou, Putuo, and Jing'an (the new Jing'an district after merging with Zhabei), as well as the part within the A20 outer ring road of Pudong New Area and other adjacent administrative divisions

(Figure 1). It is a concentrated built-up area with a dense population distribution. As of 2021, the population reached approximately 12 million, accounting for almost 50% of Shanghai's overall population. The study area represents the most economically and socially active part of Shanghai, with a long and complex spatial evolution, continuous urban renewal, changing spatial and functional structures, and diverse residential area types.

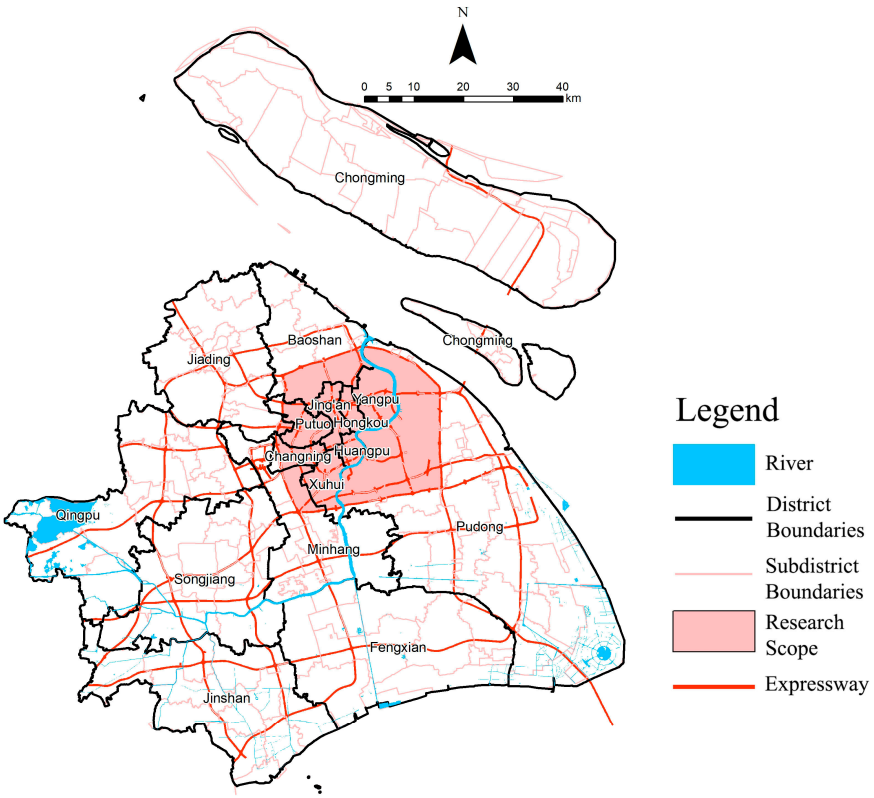


Figure 1. The study area.

3.2. Study Data Materials

The basic data included administrative boundaries and satellite image maps of the study area; satellite image maps of Shanghai from 2020 were obtained using an online open-data platform (https://earth.google.com/web/, accessed on 10 June 2021). Administrative boundaries were also acquired by consulting the official websites of each district government and civil affairs department.

3.2.1. Scope Identification and Type Classification of Different Types of Residential Quarters

The residential quarter data from Gaode Map were used to obtain area of interest (AOI) data, including information such as latitude, longitude, boundary, and name, through a web crawling method (https://www.amap.com/, accessed on 11 December 2021). We imported the satellite image maps into ENVI 5.0 for residential area identification and calibrated the identification results against the Gaode Map AOI data to obtain the 2020 data. The AOI data were integrated with satellite image map information and calibrated using semi-supervised classification and manual visual translation methods [48]. The semi-supervised learning method is able to achieve high classification accuracy using a small number of labeled samples and a large number of unlabeled samples. The extraction of residential area data is achieved by combining low-pass filtering and averaging features from the gray-scale co-occurrence matrix (Figure 2). The residential quarters were classified into six types: commercial houses, workers' new villages, garden lanes, lanes, apartments, and villas [49], resulting in 6731 residential quarters overall according to their architectural texture and

period of construction (Figure 3, Table 1). In addition, major differences were identified in the size of residential quarters, which only reflects the characteristics of the residential agglomeration scale to a certain extent, and cannot form the judgment of the residential spatial structure.

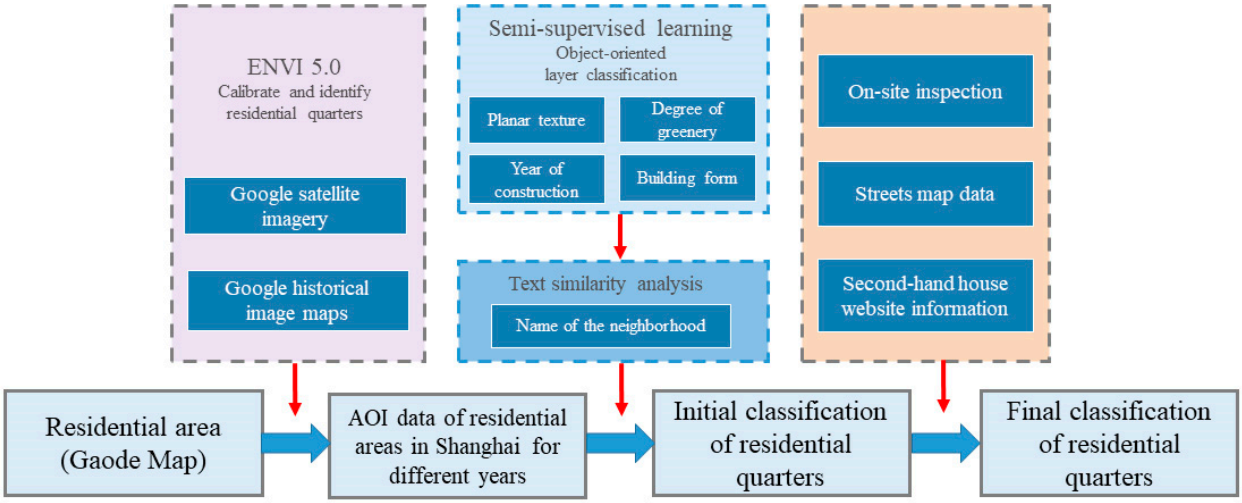


Figure 2. The process of residential area identification.

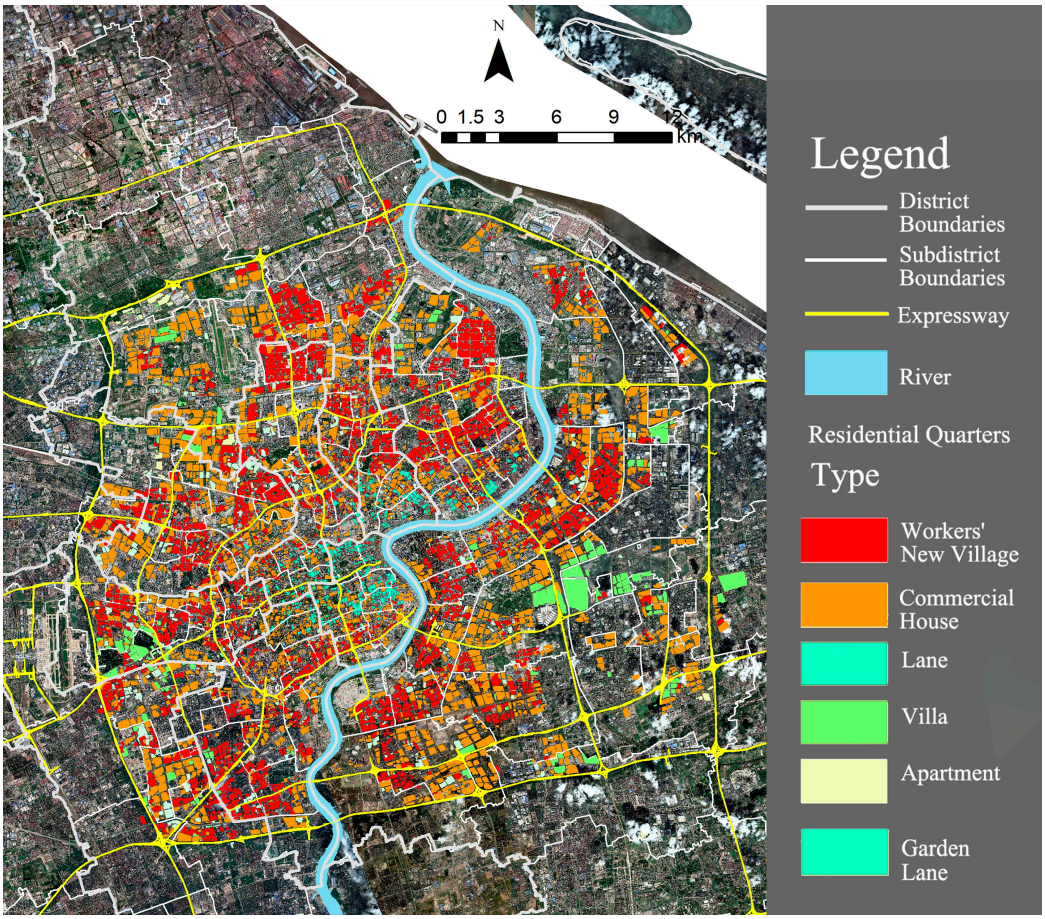
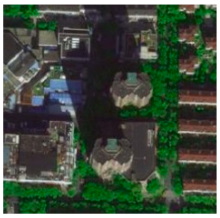
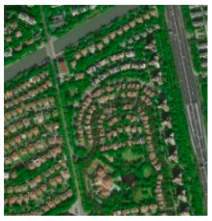


Figure 3. Type and distribution of residential quarters.

Table 1. Classification and types of GNs in the study area.

GN Types	Satellite Image	GN Types	Satellite Image
1. Commercial house		4. Garden lanes	
2. Workers' new villages		5. Lilongs	
3. Apartments		6. Villas	

3.2.2. Spatial Distribution of Park Green Spaces

The AOI data for park green spaces were obtained from the Gaode Map, while urban green spaces were extracted from satellite images using a semi-supervised classification method. The boundaries were refined, and open green spaces available for human activities were screened to obtain the vector data of all park green spaces in the study area (Figure 4).

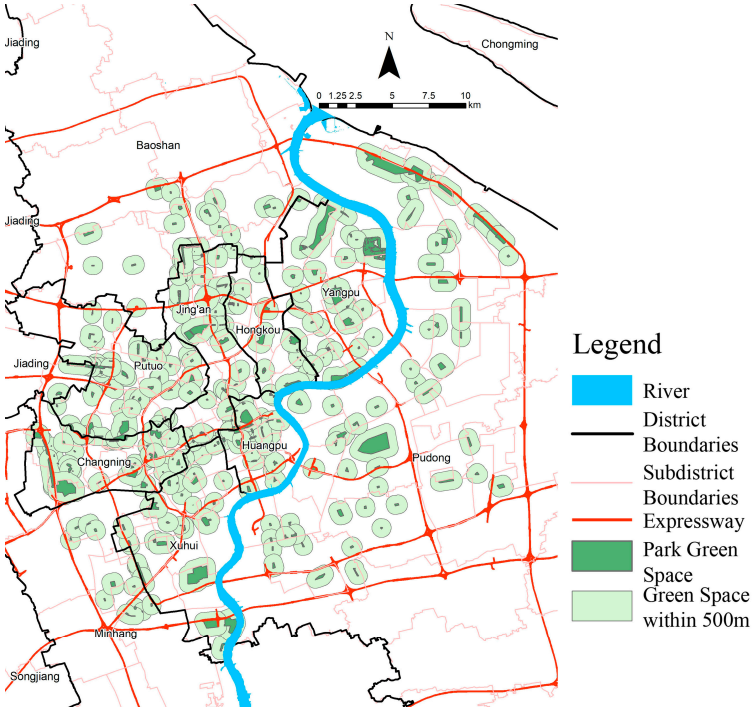


Figure 4. Spatial distribution of park green spaces.

3.2.3. Primary School District Boundaries

The spatial boundaries of all primary school districts within the study area in 2020 were obtained by entering their addresses into the corresponding areas of the Gaode Map (Figure 5). This was achieved using the 2020 Primary School District Boundary Notification published on the websites of the seven districts in the central city and the Pudong New Area District Government, combined with the school district boundary information published on the Internet (https://www.sohu.com/a/386317057_120621829, accessed on 19 December 2022).

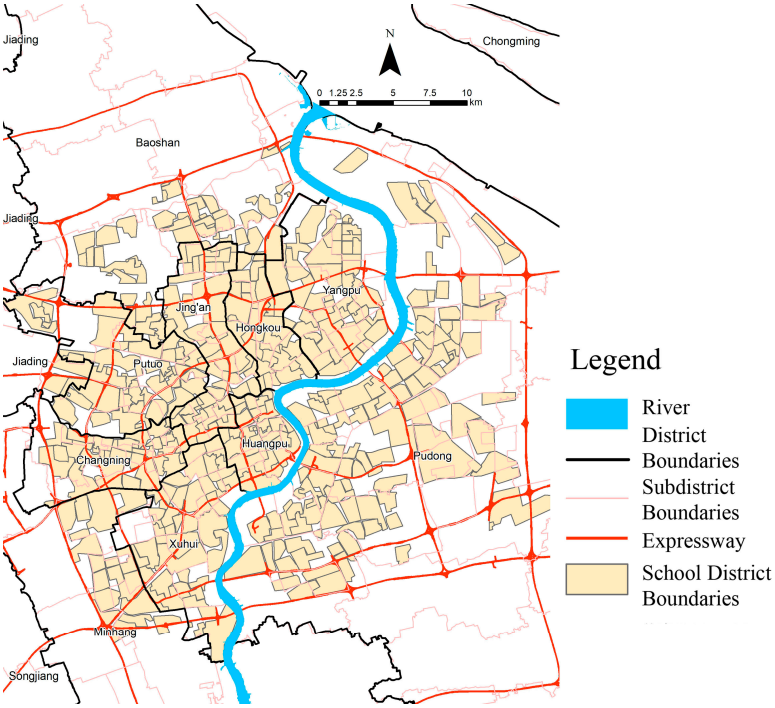


Figure 5. Primary school district division.

3.3. Methodology

3.3.1. Semi-Supervised Learning Based on Spatial Recognition of Satellite Images

Semi-supervised learning (SSL) of Google Earth satellite imagery was used to identify and delineate the spatial boundaries of residential quarters using Environment for Visualizing Imagery. SSL uses limited labeled samples and substantial unlabeled samples to achieve high classification accuracy. The classification and extraction of residential quarters were achieved by combining low-pass filtering and averaging the features of a gray-scale co-occurrence matrix [50].

3.3.2. Analysis of Complex Networks

- Network construction

The meaning of "nodes" and "ties" is defined as follows: the network "nodes" constructed with individuals as the study object reveal interpersonal relationships and interaction mechanisms (individual networks). The network "nodes" constructed with groups as the study object are "clusters" or "colonies", which aim to reveal the structural characteristics of the whole (the whole network) [51]. Meanwhile, the network "ties" reflect the relationships or connections between the "nodes", both in terms of their subordination and the strength of their relationship. They can be tangible or intangible. Therefore, the data on which network analysis is based contain both the attribute data of "nodes" and relational data of "ties".

According to the basic rules of network analysis, the spatial extent of each complete residential quarter is identified as a "node", and the connections between residential quarters resulting from residents' daily interactions are identified as "ties". Specifically, the identified shape and center of the residential quarters are used as network "nodes". The spatial network is both "physical space" and "social space"; the former is an external form, whereas the latter is an internal substance [33]. Therefore, the basic rule for creating ties between residential areas is to strike a balance between physical proximity and opportunities for social interaction.

Based on on-site observations and interviews conducted in typical gated settlements, this study proposes that spatial proximity is a prerequisite for facilitating daily social interactions among residents of different gated settlements. The likelihood of such interactions occurring is increased if they have similar levels of residence. In addition, it has been suggested that 15 min is the ideal walking time for residents to reach various services, which corresponds to the time it takes an average person to walk 500 m [52].

First, residential quarters should be located within 500 m of each other. According to the first law of geography (i.e., geographical objects or features are related to each other in their spatial distribution) and the fact that human travel distances adhere to the law of scalarization (i.e., the number of visitors to a place decreases as the inverse square of the product of the frequency of visits and distance traveled increases) [53], residential quarters with close spatial distribution are closely related to each other. Established research indicates a nonlinear relationship between residential proximity and residents' social interaction that decays rapidly with increasing distance [54]. Residents are more likely to meet or develop social relationships through daily activities and interactions in public spaces such as streets, shops, and street corners. In addition, 500 m is a common and reasonable walking distance for multi-aged populations [55].

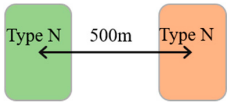
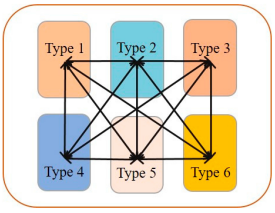
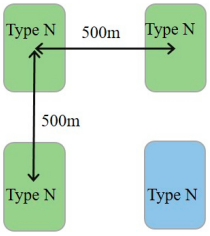
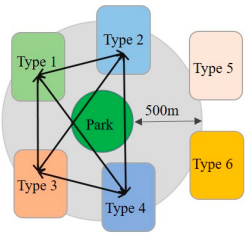
Second, residential quarters of the same type should be located within 500 m. Influenced by factors such as income and occupation, residents choose different spatial areas for their activities and interactions. Segregation occurs among income groups [56]. Differences in residential types reflect, to some extent, differences in residents' lifestyles, life trajectories, and the manner in which residents' activity spaces overlap, as well as differences in residential populations owing to variations in house prices [57].

Third, residential quarters should be located within the same primary school district. Recent research has determined that primary school districts in metropolitan China have a positive effect on resident interactions, with broader social interactions indicating closer ties between residents of the same school district and more frequent social interactions across residential quarters. The longstanding emphasis in residential planning on allocating primary schools according to population size, combined with buildings in residential quarters of a certain size, has objectively contributed to this social phenomenon. Opportunities for interaction among residents within the same primary school district across age, occupation, income, and family size have increased by linking family members through commuting and primary education [58]. In Shanghai, an elementary school district covers about 20–50 quarters.

Fourth, residential quarters should be located within 500 m of the same green space. Green spaces and squares promote social interactions between strangers [59]. Most residents use green spaces for physical activity. Activities within green spaces increase the chances of becoming more familiar with others, which is an important trigger for the creation of cross-residential associations [60].

Based on these four rules, an URSN with both physical spatial proximity and a socio-spatial association was constructed in the study area (Table 2).

Table 2. The establishment rules of "tie" connecting the "nodes" [1].

Rules	Illustrations	Scenarios	Rules	Illustrations	Scenarios
Rule 1			Rule 3		
Rule 2			Rule 4		

[1] a. Most living quarters, also known as GNs, are equipped with primary schools and green parks according to the planning regulation documents. It is a widely adopted spatial method to form social organizations and ties, shaping public service facilities and open space as the core place, which has the characteristics of walking accessibility and convenience shared by surrounding GNs. The construction of complex spatial networks reflects the organizational rules of the development of living space, while also testing whether such planning actually promotes the stability and resilience of the URSN. b. N represents any type of GN.

The mechanisms that generate linkages between residential quarters due to residents' social relations are not limited to the above. However, considering the data limitations and difficulty of analysis, this paper only discusses the networks constructed by these four linkage mechanisms as a preliminary exploration of using this method for residential system analysis.

Among the edges of residential areas, some are found to overlap, and are accounted for in the weights of the edges when imported into the analysis software. Specifically, a maximum of one edge can exist between two residential neighborhoods, but this edge has a minimum weight of 2 and a maximum weight of 8–10.

- Network analysis

Complex networks can be used to analyze the topological properties of networks; the distribution patterns of "degrees"; the identification of the structure of "communities"; and the measurement of the robustness, percolation, and propagation mechanisms of networks. This helps reveal the convergence and agglomeration characteristics of research objects defined as "nodes" in the given research area to interpret the homogeneity and heterogeneity of society and space. Meanwhile, it is imperative to further analyze how individual behavior is transmitted and influenced through networks, and how individual preferences and choices create links between "nodes". The deeper economic and social mechanisms behind urban space are thus revealed, as well as the interplay between "node" associations and "node" attributes.

Firstly, network robustness, also referred to as network stability, measures the resilience of a network and reveals its ability to recover from disturbances and identify critical nodes [61,62].This reflects the network's ability to maintain its overall functionality and determine alternative paths for network connectivity when it is disrupted or its structure changes. In the face of random attacks, networks with a power-law distribution of "node degrees", small-world characteristics, and complex and multiple relationships tend to be more robust. In general, the network robustness can be tested by "attack" detection, "percolation" detection, and slime mold algorithm tests [63]. There are two types of attacks: random and deliberate. A random attack randomly removes "nodes" or "ties" from

the network, while a deliberate attack eliminates "nodes" from the network in order of "degree" to measure network connectivity and stability, and obtain a threshold for network "collapse"; a higher threshold indicates a more robust network.

The "attack" on "nodes" corresponds to situations where certain residential quarters are demolished, redeveloped, closed, or under-occupied. The "attack" on "ties" corresponds to the inadequate provision of social interaction and community facilities such as green and activity spaces and basic education. The robustness of the URSN reflects the ability of the physical and social spatial network to repair itself and form a connected circuit [64]. Simultaneously, different measures were applied to different rules of network construction. The network propagation mechanisms differ between networks based on social relationships of "nodes" and networks based on material carriers; therefore, these networks reflect a very different economic and social interpretation of robustness.

Network robustness can be measured by the relative size of the maximum connected subgraph and network efficiency [65].

Maximum connected subgraph: This subgraph connects all of the "nodes" in the network with the least number of "ties". Its relative size is equal to the ratio of the number of "nodes" in the maximum connected subgraph to the number of "nodes" in the network.

$$S = \frac{|V'_d|}{|V_d|} \tag{1}$$

where $|V'd|$ is the number of "nodes" in the maximum connected subgraph.

Network efficiency: This is the average of the efficiency of all "node pairs" and is an important indicator of network capacity, given by

$$E = \frac{1}{N(N-1)} \sum_{i,j} \frac{1}{d_{ij}} \tag{2}$$

where N is the total number of "nodes" in the network, and dij is the shortest distance from "node i" to "node j".

Identification of "community" in the network: A "community" in a complex network is defined as a collection of nodes that are densely connected internally and sparsely connected externally. The community algorithm divides the nodes into groups. Relationships within groups are dense, whereas relationships between groups are sparse [66]. Community structures can help explore the clustering of elements, such as the occupational and age composition of people in social networks and the distinction between different domains in citation networks [67].

The URSN is a key urban functional network linking physical and socio-spatial networks, reflecting both the spatial fabric and socioeconomic processes of the city. These two factors interact and shape each other to some extent. The application of the complex network approach known as "community identification" for place identification in urban areas reflects spatial organization in terms of proximity, shared facilities, and school districts, as well as relatively consistent social backgrounds, lifestyles, characteristics, and social trust [68]. The modular definition of "community" is expressed as follows:

$$Q = \frac{1}{2m} \sum_{i,j} \left[A_{ij} - \frac{K_i K_j}{2m} \right] \delta(c_i, c_j) \tag{3}$$

where Q is the module degree; Aij represents the weight of the ties between node i and node j (in this study, the weights of all the ties are 1); Ki represents the degree of node i; and ci represents the "community" to which i belongs. If node i and node j belong to the same "community", δ (ci, cj) is 1; otherwise, it is 0. m represents the sum of the edge

weights in the network. Each node is assigned to a different "community" during the computation; each computation takes a node from the community to which it belongs, adds it to a neighboring community, and calculates the change in that community's modularity. If the gain is less than 0, it is returned to the original community; otherwise, it is added to the community with the greater gain. This process is repeated until all of the nodes are in the same community (Figure 6).

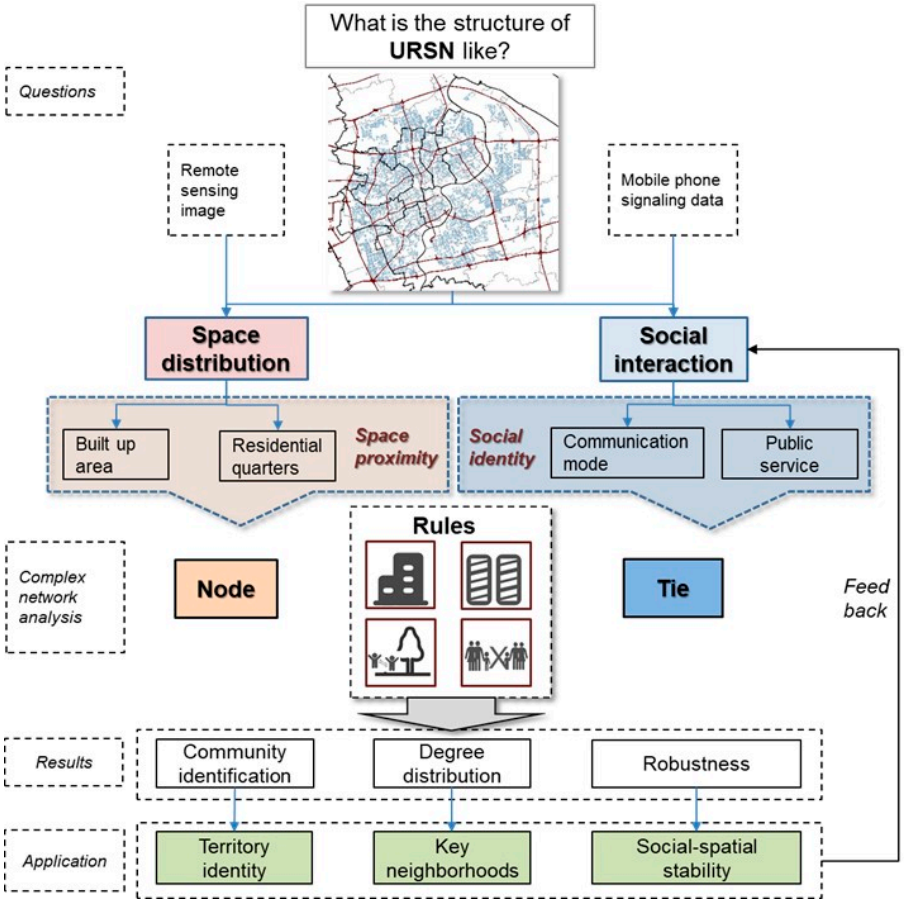


Figure 6. The concepts and working flow of the research.

4. Results

4.1. Significant Differences in the "Degrees" of Residential Quarters in the Study Area

The "degree" in complex network analysis refers to the number of links to that specific "node". The "degree" in this study represents the estimated daily interactions between the residents of a specific residential quarter and those from other quarters. It indicates the likelihood of socioeconomic connections through utilizing the same public facilities and spaces. A greater "degree" indicates that residents in the quarter are more likely to have overlapping life trajectories with residents from other parts of the city, promoting social interaction across residential quarters. Conversely, residential quarters are likely to be relatively independent and closed and less connected to other residential quarters [69].

The "degrees" of the "nodes" in the 2020 URSN vary significantly. The overall distribution of the "degrees" is a Poisson distribution, contrary to the more commonly assumed power law distribution [70]. The maximum "degree" in a residential quarter is 126, whereas the minimum is 0. The majority degrees of residential quarters are between 10 and 50, with very few exceeding 100 (33.2%). This implies that most residents in a residential quarter overlap and interact with residents in approximately 30 nearby residential quarters;

very few residents in residential quarters are highly active and connected to more than 100 residential quarters.

Residential quarters with higher "degrees" may play a more critical role in promoting social integration and urban vitality. In addition to the high number of households and populations in residential quarters, which may increase external interactions, higher economic and social status and broader interpersonal skills contribute to the apparently large distribution of "degrees" in residential quarters in the city center and smaller ones in the periphery. Residential quarters with the highest "degree" are concentrated in the northwestern part of Huangpu District bordering Huangpu and Jing'an Districts, and the North Bund area of Hongkou District. Additionally, residential quarters with higher "degrees" are located in the southern and western parts of Changning District, northern part of Xuhui District, and southwestern part of Yangpu District. Generally, the residential quarters in Puxi have a higher "degree" than those in Pudong, while the central area demonstrates a higher "degree" than those in the periphery (Figure 7).

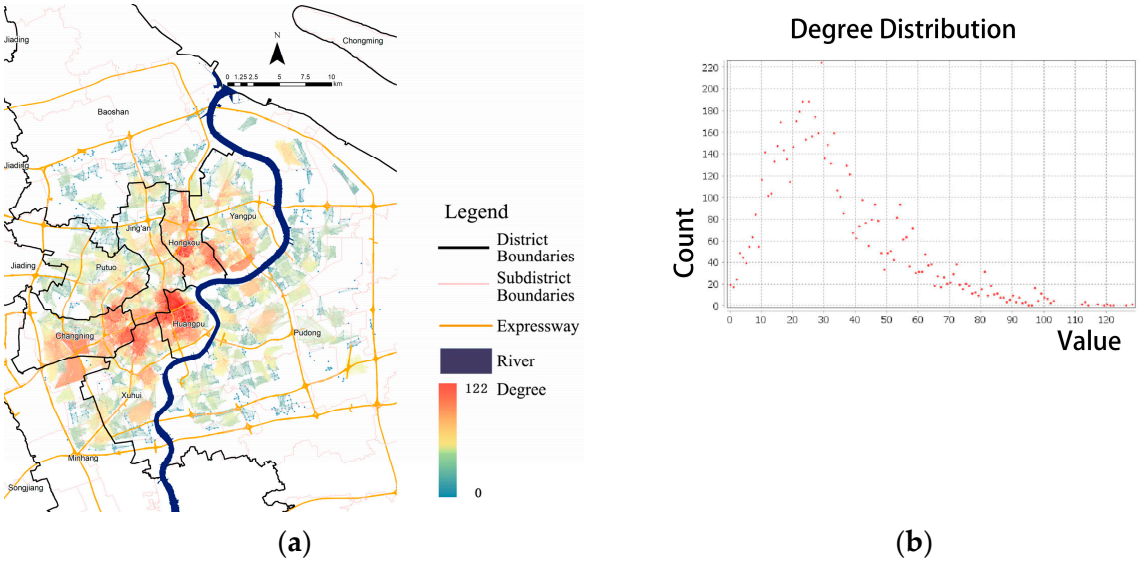


Figure 7. Distribution of URSN "degrees" in the study area in 2020: (**a**) geographical distribution of node "degrees" of residential quarters; (**b**) number distribution of node "degrees" of residential quarters.

The contribution of four "tie" establishment rules to the URSN network characteristics is different. Considering the node with higher "degrees", the contributions are defined as follows: Rule 1 leads to apparent connections with 40–50 residential areas; Rule 2 leads to connections with about 20 residential areas; Rule 3 leads to 15–25 residential areas; and Rule 4 leads to 70–100 residential areas. Therefore, residential areas with the four rules have a higher weighted "degree"; essentially, they have a higher possibility of generating social connections.

4.2. High-"Degree" Nodes and Robustness Measures for URSNs

URSN robustness refers to its stability, which is reflected in the frequency of social interactions and the closeness of relationships between residents in different residential quarters. If the network "collapses", it means that the daily interactions between residents of different residential quarters are disrupted, and common activities disappear, effectively turning residential areas into spatial "islands". For example, the demolition or closure of residential areas impacts interactions among residents in built-up areas. Given that the Huangpu River has a strong spatial barrier effect, a maximum connectivity submap was selected as the initial network. The measurement results revealed the following.

First, a residential network is more robust to random attacks but vulnerable to deliberate attacks. The size of the maximum connected subgraph decreased more rapidly in the deliberate attack mode when 30% of the nodes were removed. In addition, network efficiency decreased rapidly in the deliberate attack mode, collapsing almost completely when 60% of the nodes were removed. In the random attack mode, network efficiency began to decrease significantly, but not until 60% of the "nodes" were removed (Figure 8).

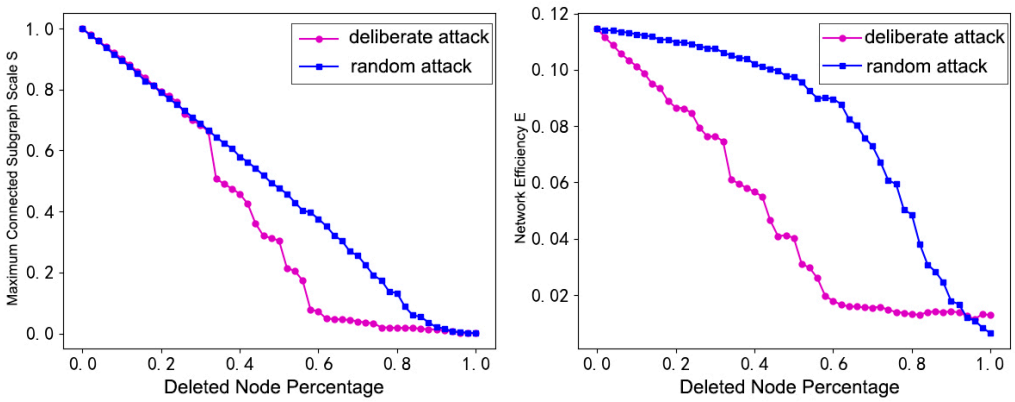


Figure 8. Robustness measures of URSN based on four rules.

Second, a relationship exists between residential network robustness and residential quarter type. Residential quarters with large "degree" nodes are mostly lane-type residential quarters. The robustness of the residential space network was measured separately using Rule 2 to construct the residential space network for two types of residential quarters: lane residential quarters and workers' new villages. The results show that Lilong quarters (lane-type residential quarters) not only exhibit higher initial network efficiency and greater resistance to attacks (the network efficiency decreases gradually when nodes are removed)—implying that Lilong clusters are more closely connected to each other—but also are a more stable residential space model compared to workers' new villages (Figure 9a,b).

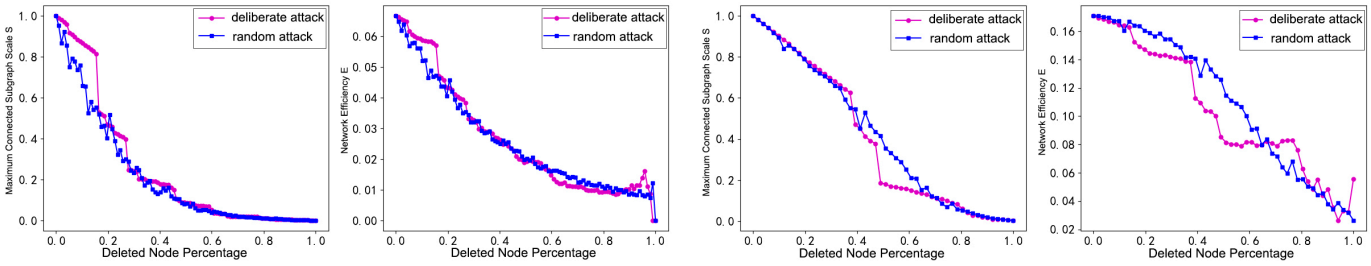


Figure 9. (**a**) Robustness measures of URSN of workers' new villages based on Rules 1 and 2; (**b**) robustness measure of URSN in lanes based on Rules 1 and 2.

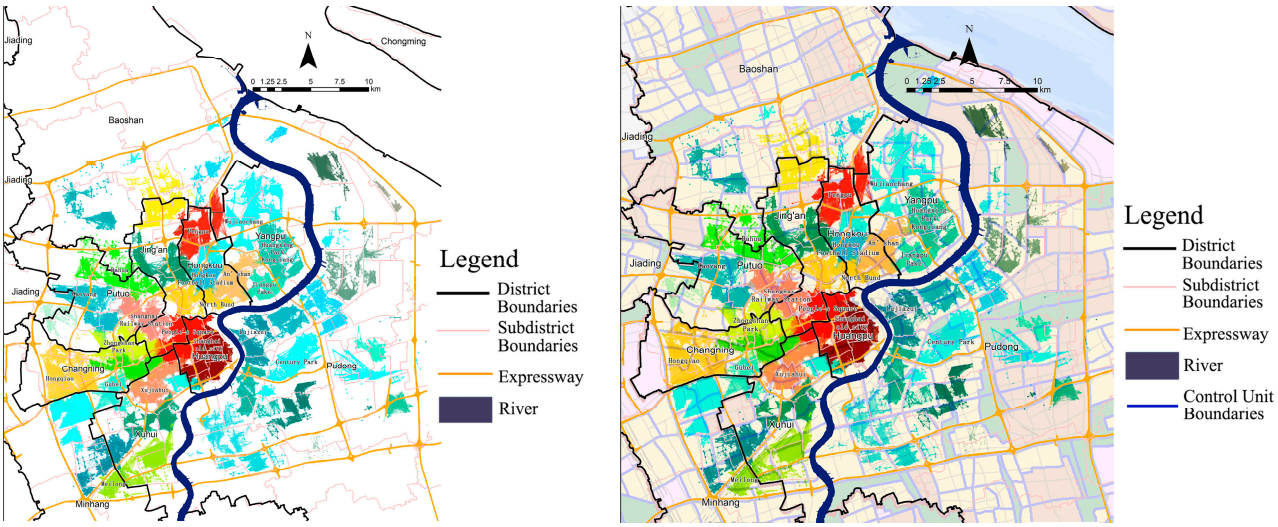
Third, the demolition or artificial closure of higher-"degree" residential quarters could lead to a reduction in the rate of interaction, information exchange, and communication between residents of the entire city. This can generate negative effects such as social isolation and reduced vitality.

4.3. Identification and Distribution of "Communities" in Residential Spaces

A residential "community" in a city implies a spatial collection of closely related residential quarters. In contrast to classifying residential quarters based on the period of construction, population, and type, complex network analysis offers a new method for analyzing the SF of residential quarters. This method involves the clustering and

differentiation of residential quarters according to the social associations of their unknown "nodes" in the network.

According to data from 2020, a total of 73 "communities", generally large, have been identified in the URSN. The largest "community" is located in the central part of Huangpu District, with 445 "nodes" (i.e., residential quarters). While 14 communities have more than 200 "nodes", 13 have between 100 and 200 "nodes", and the remaining communities are relatively small. Additionally, the boundaries of these "communities" coincide significantly with the boundaries of administrative districts and major transport routes. This alignment is a result of the combined effects of school district boundaries and geographical proximity. In contrast to the control detailed planning unit, a single community may cover more than one unit, and there is an overlap between the boundaries of the community and the boundaries of the unit. Furthermore, there are 15 larger "communities" within the inner ring, while the smaller "communities" are located at the edge of the study area. This suggests that school district boundaries play an important role in the identification of "communities" (Figure 10).



(**a**) (**b**)

Figure 10. "Community" identification and distribution of URSNs in the study area in 2020: (**a**) "community" identification results; (**b**) overlay of "community" identification and control planning unit.

5. Conclusions and Discussion

5.1. Main Conclusions

Complex network analysis offers a new method to characterize urban functional–spatial structure. Urban planning traditionally adopts a "multi-center" or "core-edge" structure to express policy objectives, although it is obvious that the economic and social connotation of spatial structure could be better revealed. Spatial network analysis provides an improved way to balance physical space and social space.

The network metrics obtained from the complex spatial network analysis provide a new perspective and inspiration for understanding reality. Furthermore, increasing the accuracy and dimensions of the measurement and comparing the measurement results has scientific reference value for optimizing spatial planning, such as the "degree" of network nodes, community identification, resilience, and robustness.

The division and integration of residential areas has advantages and disadvantages. Based on the relatively divided living space, creating opportunities for residents to share the space and facilities is conducive to creating more choices. Spatial network analysis suggests that spatial governance that integrates top-down and bottom-up approaches

is more conducive to establishing the social resilience of the URSN, which represents network resilience.

The identification results of the "network community" overlap with the boundaries of the administrative division of street-level governance units. This suggests that the division of urban school districts depends on the scope of government management and is a social organization rule below the administrative divisions in China. Top-down management rules reduce residents' mobility and social self-organization, and the positive and negative effects need to be further investigated.

This study attempts to construct URSN based on the quantitative measurement of residents' social interactions between gated neighborhoods, thus providing a new method and idea for urban spatial structure research.

5.2. URSN Analysis Helps Reveal the Spatial Patterns of Urban Residential Space

This research proposes complex network construction rules that combine both "physical" and "social" space, and reveals the characteristics of URSNs under the combined effect of geographical distribution and social ties. Social connections among residents are generated through the sharing of basic educational facilities and green spaces, reflecting the social organization of the city around family members and the validity of classical planning theories and methods in the social and spatial organization of the city. The distribution of the "degree" of "nodes" and the robustness of the network, obtained by measuring the network of residential spaces, reflect the degree of social connection between residential quarters and the stability of the neighborhoods built up by shared facilities.

First, the "degree" and centrality of the "node" reflect the extent and opportunities for residents to come into contact with residents of other residential quarters in their daily lives. Areas with a high level of service provision create the basis for residents to build social relationships, and the provision of basic educational facilities and green spaces for various activities is particularly important.

Second, the type of residential area is another important factor influencing URSNs. Lanes provide rich and appropriate spaces for neighborhood interactions and promote diversity in social relationships. Accordingly, lanes have the highest "degree" and centrality in the spatial network and the most significant impact on the integrity and stability of the network. Apartment-type housing is generally conducive to network stability because of its dispersed distribution and the large number of these units [71]. However, newly built commercial living quarters are often larger but more enclosed and less connected to neighboring settlements, resulting in a lower "degree" in the spatial network. Their large scale and number lead to inattentive, fragile, and less stable networks.

Urban residential networks provide the basis for studying urban social relationships and disease transmission. The transmission of social relationships, opinions, and even epidemics through contact between urban residents has driven research on group decision games, the expression of social will [72], and the prediction of epidemic transmission pathways [73]. It provides new ideas for revealing the spatial structure of such invisible networks of relationships and for intervening through spatial means. Moreover, the rules for establishing "ties" between the "nodes" of residential quarters are an expression of a complex network language for the planning of facilities and the behavior of urban residents in their daily social interactions, and are closer to reality than "random networks" based on spatial proximity and individual cooperation.

5.3. Identification of Online "Associations" Contribute to the Investigation of Place Identity in Built-Up Areas

The spatial scope of "communities" identified in the complex network analysis is an area where residents have closer interactions with each other, reflecting their place

identity. This includes their proximity to each other, overlapping spheres of daily activity, and recognition of the same landmarks. Among them, the old residential quarters and the new workers' village quarters have formed distinct residential "communities" that align with residents' perceptions and sense of community belonging.

Based on the identification of "community", the actual spatial scope of residential quarters was further integrated. The analysis revealed that several residential quarters are spatially clustered together, forming urban spatial "cells" with place identity [74]. Integrating this spatial boundary with the administrative boundaries of built-up areas presents new possibilities for understanding urban SF. It facilitates the delineation of spatial units for planning, management, and social governance as well as the rational allocation of common services, such as primary and secondary schools, kindergartens, community parks, culture, and sports. Furthermore, it enables the establishment of community governance mechanisms and platforms. However, further research is needed to verify whether residents within the "cell" spatial unit identify with the "cell" border, have closer contact with residents within the unit, possess a stronger sense of community belonging, and engage in interrelated and interdependent activities (Figure 11).

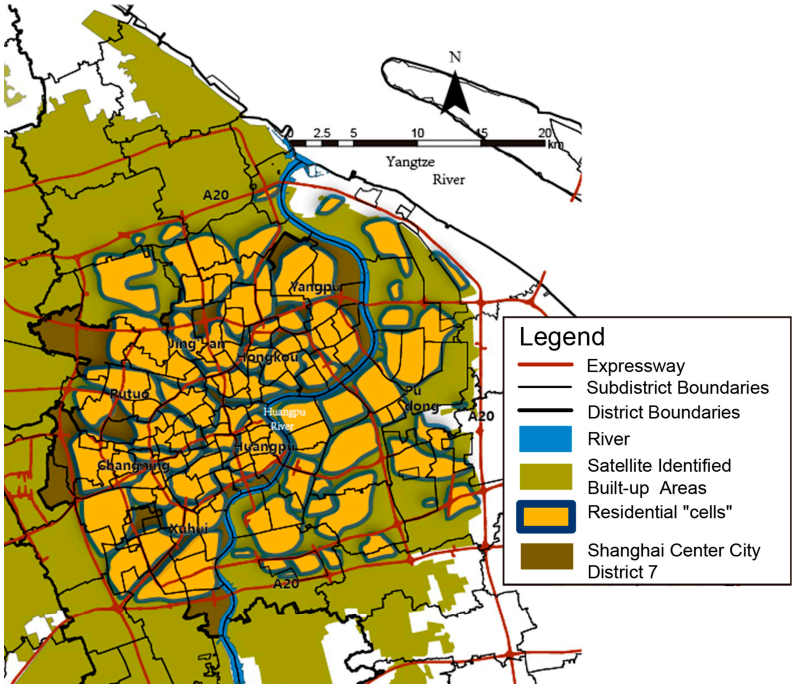


Figure 11. Diagram of the residential spatial "cells" in the study area of Shanghai in 2020.

5.4. Limitations and Prospects

Aligned with the underlying explanatory mechanism of complex network analysis, this study conceptualizes residential quarters as "nodes" in a complex network and uses the social interactions of individual residents as the basis for establishing "ties" between residential quarters. A coarse-grain strategy was used to study groups of individuals of a specific size. This is only appropriate for a particular question at a specific spatial and temporal scale and does not allow for the emergence of patterns across scales (Figure 12) (https://swarma.org/?p=34352, accessed on 26 June 2024). Therefore, an appropriate spatial "coarse-graining" scheme should be developed according to the characteristics of the urban problem under study, considering the correlation and consistency between individual behavior and macroscopic phenomena. For example, cell phone signaling data can be used to solve the coarse-graining problem. Location information obtained through cell phone signaling can be used to identify more specific homogeneous residential

groups in a larger gated residential area and to resolve the daily interactions between residential groups. At the same time, based on residents' daily movement trajectories, the social connections between different residential spaces due to residents' visits can be more accurately revealed.

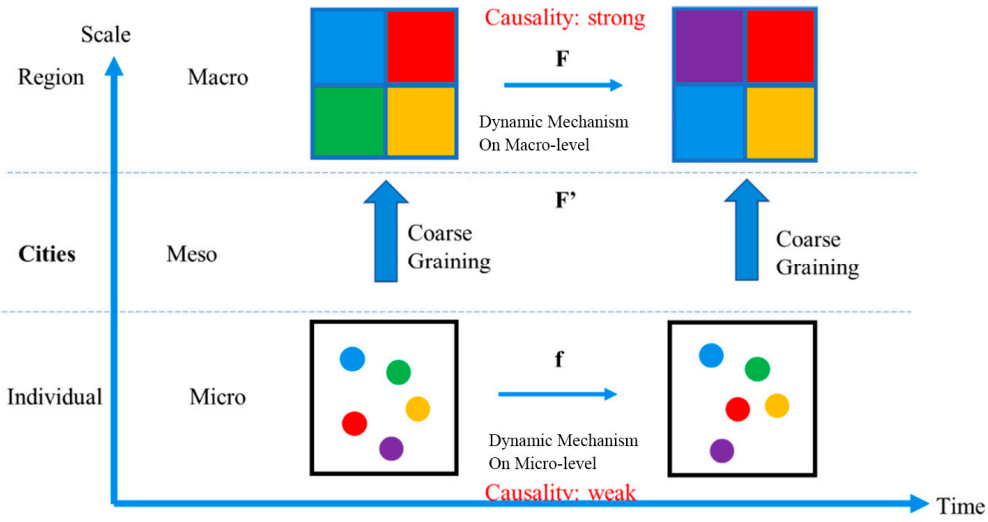


Figure 12. Problems caused by the graining of data and abstraction of research objects in urban research.

Meanwhile, the rules for identifying residential quarters and constructing URSNs require further optimization. The spatial units identified by AOI acquisition and SSL from satellite imagery may exhibit inaccuracies compared to the actual situation. These errors may result in the omission of very small areas, individual houses, or changes in the use of houses in historical districts, which could affect the "degree" analysis and "community" identification. Meanwhile, the four tie establishment rules employed in the study are consistent with planning principles and generalities but may not consider special circumstances, such as social connections and interactions across school districts and administrative areas, potentially leading to invalid conclusions. In addition, urban residents engage in a wider range of social interactions beyond their daily activities, such as work relationships, transactions, and recreation. It is necessary to use multi-source and multi-frequency big data (e.g., social media data and mobile phone signal data) and time-span data. The optimization of the data sources mentioned above represents the most effective approach to address the limitations of this study. This optimization will create new opportunities for us to uncover the diverse network characteristics, evolution patterns, game dynamics, and communication mechanisms of URSNs. The methodology adopted in this study has the potential to provide quantitative support for urban regulation planning unit delineation in the future, and could also become a powerful tool for urban planning management through integration with multi-source data. Further, carrying out comparative analysis of URSN among different cities based on mature analytical techniques may be able to find out the differences and common patterns among each other. It will have greater theoretical value and practical significance for spatial networks to express urban spatial structure.

Author Contributions: Conceptualization, F.Y.; methodology, F.Y.; software, L.X. and J.W.; validation, J.W. and L.X.; formal analysis, J.W. and F.Y.; investigation, J.W.; resources, F.Y.; data curation, J.W.; writing—original draft preparation, J.W. and F.Y.; writing—review and editing, F.Y.; visualization, J.W. and L.X.; supervision, F.Y.; project administration, L.X. and F.Y.; funding acquisition, F.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 51778436.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Although Jiayin Wang is affiliated with Power China Huadong Engineering Corporation Limited, this paper did not receive financial support from this company. Therefore, all authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SF	spatial fabric
URSN	urban residential spatial network
GNs	gated neighborhoods
CNT	complex network theory
AOI	area of interest
SSL	semi-supervised learning

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