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The Influence of Morphological Elements of Urban Gated Communities on Road Network Connectivity: A Study of 120 Samples of the Central Districts of Jinan, China

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Abstract: Currently, the dominant gated communities (GCs) in Chinese cities have fragmented the urban road network, causing traffic congestion, energy consumption, carbon emissions, and environmental pollution. The morphological elements of GCs are key factors affecting road network connectivity. This paper aimed to explore the influence of the morphological elements of GCs on road network connectivity, to provide a quantitative basis for the evaluation and renovation of the connectivity of GCs, and to provide insights for urban planning and policy. This paper quantitatively analyzed the connectivity of GCs using 120 samples from the central districts of Jinan, China. Morphological elements were the independent variables, while route directness (RD) and the network distance (D) to the nearest entrance were the dependent variables. RD measured the internal connectivity, and D measured the connectivity between the internal and external road networks of GCs. GIS was used to measure RD and D, and SPSS was used to conduct a correlation analysis to identify significant variables. Multiple linear regression and LASSO regression were used to test the influence of these factors on RD and D. LASSO regression was employed to construct prediction models for RD and D. We found that intersection density had the greatest impact on RD, while the number of entrances and exits, and the scale of GCs, had the greatest impact on D. Using thresholds of D = 250 and RD = 1.3, the four types of GCs were classified and corresponding renovation measures were proposed.

Keywords: gated community; connectivity; morphological element; route directness

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1. Introduction

The community is the basic unit of cities in China, and the choice of the form of these communities has a direct impact on the evolution of the entire urban form. In 1998, China fully promoted the commercialization of housing, and residential communities shifted from open to fully closed, with more than 80% of the communities in China becoming GCs [1,2]. At the same time, the dominant large-scale, fully enclosed superblock has formed, resulting in a dualistic division of China's urban roads and internal roads in GCs [3]. Many scholars have argued that China's political economy of development incentivized the creation of privatized superblocks and a spatial division between public and private responsibilities, which has worsened traffic problems [4]. The road network within GCs is independent from the urban road network, and GCs and superblocks are dismembering the urban road network. This fragmentation of internal and external road networks by GCs is one of the major reasons for the decrease in transportation accessibility, and increases in energy consumption, carbon emissions, and environmental pollution [5–8]. In order to address these issues, in 2016, the Chinese government proposed to gradually open up GCs, to improve the connectivity of the urban road network and alleviate urban congestion through the communalization of the internal roads within GCs [9]. The Chinese government proposed promoting a neighborhood system with small blocks and dense street networks, to alleviate the increasing urban traffic congestion [10]. Xin Ge proposed an improved representation of China's superblock street network based on Marshall's path structure analysis, pointing out that "small blocks and dense street networks" are the only sustainable model [11]; reducing automobile energy consumption and promoting sustainable urban development by optimizing transportation network structure [12]. Although there have been many articles on street connectivity as a key component of urban form and sustainable transportation modes [13–15], there have not been many studies on connectivity in GCs, where morphological elements are significantly related to urban transportation [2]. Connectivity is both internal (connection of roads within the area) and external (connection of main roads and adjacent neighborhoods) [10]. China's GCs have a small number of entrances and exits connected to urban roads, the roads inside GCs cannot be used by external residents, and the internal road network is fragmented from the external road network.

The key problem to be solved in this paper is how to reflect the influence of the morphological elements of GCs on the connectivity of internal road networks. This paper aimed to explore the influence of the morphological elements of GCs on road network connectivity, to provide a quantitative basis for the evaluation and renovation of the connectivity of GCs, to build regression prediction models of GC connectivity and to provide insights into urban planning and policy. A total of 120 GCs in the central districts of Jinan, China, were selected for this paper, and we quantitatively calculated indicators of the morphological elements and road network connectivity of the GCs, finally establishing regression models, so as to provide a quantitative basis for the sustainable urban street layout of small neighborhoods and dense street networks.

2. Literature Review

American urban theorist Jane Jacobs, in her book "*The Death and Life of Great American Cities*", made it clear that one of the prerequisites for vibrant and diverse cities and communities is small-scale, pedestrian-friendly neighborhoods and streets [16]. Alexander's "*The City is Not a Tree*" emphasized the connectivity of urban street networks, arguing that trees have only one type of connection, and that the recursive nature of their structural connections reduces their complexity, whereas cities should have a higher level of complexity, and therefore a living city is not a tree, but should be viewed as a complex network [17]. New Urbanism proposed TND (traditional neighborhood development) and TOD (transit-oriented development) [18], which advocated compact, highly connected walkable communities. Based on Alexander's theory, Salat S argued that the historical evolution of urban planning from leafy to tree-like networks has resulted in a loss of urban efficiency and resilience. Urban systems are most structurally efficient when designed according to a fractal structure. In this structure, the spatial distribution of elements follows a Pareto distribution [12].

Good connectivity is essential for transportation networks, as it reduces travel time and distance, offers more route choices, minimizes detours, and enhances accessibility [2]. Sreelekha considered connectivity as the directness of travel between destinations [19]. A well-connected network has many short connections, numerous intersections, and a minimum of dead ends, providing continuous, direct routes to destinations [19–22]. Pei Tong regarded road network connectivity as a key indicator of the structural characteristics of a road network, describing it as the strength of connectivity between nodes in a planning area through road transportation [23]. Cynthia Baby Daniel defined connectivity as the density of connections within a transportation network, noting that increased connectivity enhances the accessibility and mobility of the road network [24]. Roadway connectivity aims to improve accessibility and reduce barriers to traffic [25,26]. Stephen Marshell assessed the impact of street network characteristics on roadway safety. The results showed that intersection density, cul-de-sac density, and link to node ratios were significantly associated with roadway safety outcomes [27]. Kuo-Hao Chang argued that the connectivity of the roadway network after a disaster is critical because it greatly influences disaster response operations and long-term recovery operations. Connectivity is often the basis for measuring robustness, resilience, and vulnerability [14,28,29]. Aaron C. Poole's study stated that increased road network connectivity is associated with more positive health outcomes and a reduction in attack fatalities in urban areas [30,31]. Many studies have attempted to measure the relationship between urban form (particularly street network design) and transportation emissions, and modifications to urban road network design can potentially reduce transportation carbon emissions [14,32,33]. Street connectivity enhances urban permeability, reducing the vehicle kilometers traveled (VKT) and increasing walkability. Higher intersection density is strongly linked to reduced VKT [14]. Greater intersection density, street connectivity, land use diversity, and pedestrian-oriented design are associated with fewer automobile trips, potentially reducing traffic emissions [34].

The presence of GCs has a significant impact on the connectivity of the urban road network. Guibo Sun studied the association between walking patterns and street network structure in an urban morphology dominated by GCs in station areas, and found that GCs were the main cause of reduced network connectivity and pedestrian detours [35]. In a categorical analysis of street-network types, Christopher Barrington-Leigh cited GCs as a particularly illustrative instance of low-connectivity planning [36]. WANG QING found that GCs in Harbin resulted in lower connectivity and accessibility when compared with traditional districts [37].

Several studies have used different measures to quantify street network connectivity. Various network indices based on graph theory have been used to assess the connectivity of road networks. A graph consists of nodes and edges, where nodes correspond to intersections in a road network and edges correspond to different street segments between intersections [12,38–40]. Garrison and Marble computed the connectivity of a transportation network by introducing Alpha (α), Beta (β), and Gamma (γ) indices [19,41]. Mehmet Topcu argued that connectivity is the number of axes directly connected to intersect axial lines, and applied Hillier's spatial syntax [42] to investigate the connectivity of settlement patterns with different road network patterns in San Francisco [43]. Stephen Marshell combined graph analysis with hierarchical structure considerations by using the theory of spatial syntax [12,44]. Hess used pedestrian route directness (PRD) to calculate pedestrian connectivity, a measure of the directness of a chosen path to a specific destination [45]. A lower PRD value indicates a more direct and efficient pedestrian route, where the ideal metric of a straight or Euclidean distance is 1, while a higher PRD value indicates a more circuitous and less efficient route [46]. Metro Portland has developed design standards to improve pedestrian connectivity, requiring a PRD value of no more than 1.5 from any starting point to certain local destinations [47,48]. Measurable attributes of the roadway network (intersection density, block size, link node ratio, and route directness) [49,50] quantify network connectivity and walkability [34,51,52]. Martin Scoppa studied the connectivity of the street network in the superblocks of the city of Abu Dhabi in the UAE by measuring the distance, directness, and diversity of sidewalks [13]. Schön P used directness and steepness to measure network connectivity between home and school [53]. Randall used the ratio of route distances and pedestrian route directness to assess pedestrian connectivity [54]. Among these measures, route directness quantifies the additional distance traveled due to the road network's structure compared to the straight-line distance between origin and destination pairs. It reflects the network's connectivity and permeability [52].

The existing literature has focused on the study of urban road connectivity and lacks research on the connectivity of GCs. This paper argues that the connectivity of GCs has both internal and external dimensions. Taking the connectivity of GCs as the research object, this paper adopts route directness (RD) as a measure of internal road network connectivity, and the network distance (D) to the nearest entrance as an indicator of the connectivity between the road network within the GC and the external roads, to quantitatively reveal the influence of morphological elements of urban GCs on road network connectivity. Differently from the existing literature, which only calculated connectivity starting from a center point, this paper proposes a new method to calculate connectivity, with the center point and four corner points as the starting points. This method can achieve more accurate connectivity calculation. By calculating the two dependent variables of GC road network connectivity, regression models are established to provide a quantitative basis for the evaluation and renovation of the connectivity of GCs, and to provide insights for urban planning and policy.

3. Methodology

We first conducted a qualitative study, interviewing and surveying the people concerned. For the people inside the GCs, they think that when the size of the GC is larger than 10 hectares or the number of entrances and exits is too small, it takes too long to reach the entrance and exit of the GC from their homes, which affects the convenience of travel. For residents with no access outside the GC, GCs that are too large or too narrow in form impede urban traffic and reduce the connectivity of urban roads, and they have to make long detours, which prolongs the travelling time. Therefore, both poor convenience inside GCs and low connectivity outside have a significant impact on the travel of urban residents.

The connectivity of the internal road network and the connectivity between the internal and external road networks of a GC are key factors affecting the connectivity of GCs and are strongly correlated with the connectivity of the urban street network. Existing studies focused on the urban road system, and there is a lack of systematic research on the internal road system of GCs, especially the connection between the internal roads of GCs and external urban roads. The purpose of this paper was to study the influence of the morphological elements of GCs on the connectivity of the road network inside the GCs and between the GCs and the outside through a more quantitative approach, so as to provide a quantitative basis for the opening of GCs and the planning of new communities. In this paper, 120 GCs in the central districts of Jinan, China, were selected as samples, and GIS was used to process the samples selected for the research and obtain data, and the relationship between the morphological elements of the GCs and the connectivity of the internal road network of the settlements, as well as that between the internal and external road networks, was analyzed based on the method of regression analysis.

3.1. Study Area and Data Acquisition Method

According to the "Jinan New Urbanization Plan (2021–2035)", this paper selected the central districts of Jinan, surrounded by the Jinan Bypass Highway, as the study area. This area includes the old urban area within the second ring road, and the new urban areas in the east and west surrounded by the second ring road and the Bypass Highway. Five administrative districts were included: Huaiyin District, Tianqiao District, Lixing District, Shizhong District, and Lixia District. In this research, the GCs studied were built from 1990 to 2019. There are 1351 communities in the central city of Jinan, 112 open communities and a total of 1239 GCs, with GCs occupying the absolute majority [55]. Jinan has serious traffic congestion problems, and its congestion index has repeatedly ranked at the top of the traffic analysis reports of major cities in China [56–59]. In the "2023 Annual Traffic Analysis Report of China's Major Cities", Jinan ranked fourth from the bottom in the Traffic Health Index among the 12 city classes with more than 3 million vehicles, ninth from the bottom in the traffic operation data of 25 major cities nationwide, and fifth in the Peak Journey Delay Index of major cities' road networks [60].

In the "urban residential planning and design standards" [61], the scale of a "residential neighborhood" is 150~250 m, surrounded by urban roads or land boundary lines, with a land scale of about 2–4 hm^2, which is the basic living unit of residence. Therefore, the research object of this paper was GCs with an area larger than 4 hm^2 in the central districts of Jinan (Figure 1).

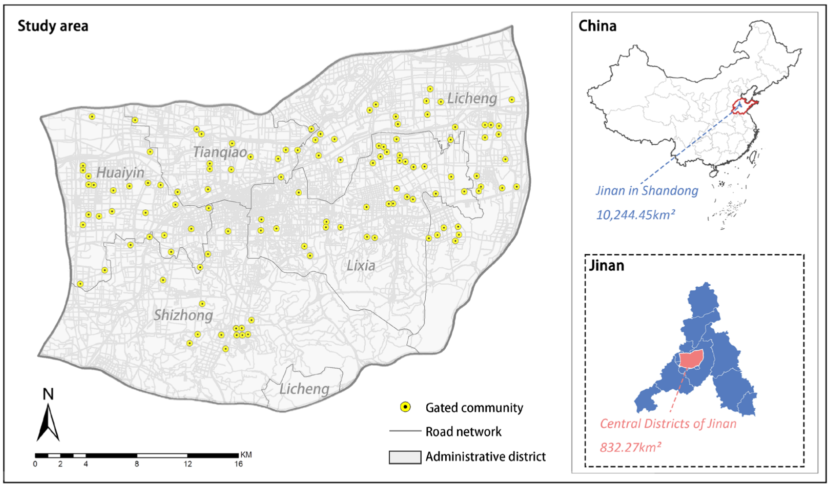


Figure 1. The 120 gated communities in central districts of Jinan.

Data collection was carried out through field research and using online satellite maps, in which the field research was divided into two steps: preliminary research and measurement, and later supplementary measurement, which mainly included the details of the shape of the plot, the organization of the internal road network, and the relationship with the city streets and roads; then, the structure of the internal road network of the district was depicted, with the number and type of intersections being statistically recorded, and the number and location of entrances and exits being marked, etc. The data were obtained online through the API (application program interface) of public map websites and national geographic databases, imported into ArcGIS software (version 10.8) and mapped onto the road network; then, combined with the results of the offline field research, the road network was corrected and supplemented accordingly in GIS, and the dataset was created. This study used IBM SPSS Statistics 27.0 and PyCharm Community Edition 2023.1.3 for data analysis.

3.2. Indicator Data

3.2.1. Morphological Elements of a Gated Community

According to the measurement method of street networks [34,62], based on the relevant theory and the calculation method of road network connectivity, as well as the morphology characteristics of GCs, this paper proposed four categories of 21 urban morphology indicators of GCs as independent variables (Table 1). The number of X-intersections, Y-intersections, and cul-de-sacs resulting from the intersection of roads to form the network are shown in Figure 2.

Table 1. Indicators that were used in the analysis.

Morphological Elements	Indicators	Calculation Method or Data Source	Formulas	Unit
Basic Information (I)	Number of buildings (I_1)	https://jinan.anjuke.com/ (accessed on 9 March 2024)		RCS
	Building density (I_2)			—
Basic Form (S)	Length (S_1)	Caculated by GIS	—	m
	Width (S_2)			
	Length-width ratio (S_3)	Ratio of the long side of GC to its short side	$S_3 = \frac{S_1}{S_2}$	—
	Perimeter (S_4)	Caculated by GIS	—	m
	Area (S_5)			hm^2
	Perimeter-area ratio (S_6)	Ratio of perimeter to area of GC	$S_6 = \frac{S_4}{S_5}$	—

Table 1. *Cont.*

Morphological Elements	Indicators	Calculation Method or Data Source	Formulas	Unit
Entrance and Exit (E)	Quantity (E_1)	Caculated by GIS	—	RCS
	Width (E_2)	Sum of the widths of all entrances to the GC	$E = \sum_{i=1}^{n} W_i$	m
	Urban road width (E_3)	Sum of the widths of urban roads connected to all entrances and exits of GC		
	Degree of articulation (E_4)	Ratio of the width of all entrances to the width of its connecting urban roads	$E_4 = \frac{E_2}{E_3}$	—
Internal Road Network (R/N)	Total road length (R_1)	Caculated by GIS	$R_1 = \sum_{i=1}^{n} l_i$	km
	Road network density (R_2)	Ratio of total length of road network to area of GC	$R_2 = \frac{R_1}{S_5}$	km/km^2
	Road area (R_3)	Sum of the products of road width and road length within GC	$R_3* = \sum_{i=1}^{n} w_i l_i$	hm^2
	Road area ratio (R_4)	Ratio of road area to area of GC	$R_4 = \frac{R_3}{S_5}$	—
	X-intersection (N_1)	Number of X-intersections	—	PCS
	T-intersection (N_2)	Number of T-intersections		
	cul-de-sacs (N_3)	Number of cul-de-sacs		
	Intersection density (N_4)	Ratio of number of intersections to area of GC	$N_4 = \frac{N_1+N_2}{S_4}$	—
	Number of nodes (N_5)	Number of all nodes	$N_4 = N_1 + N_2 + N_3$	PCS

* $l_1 + \ldots + l_n = R_1$.

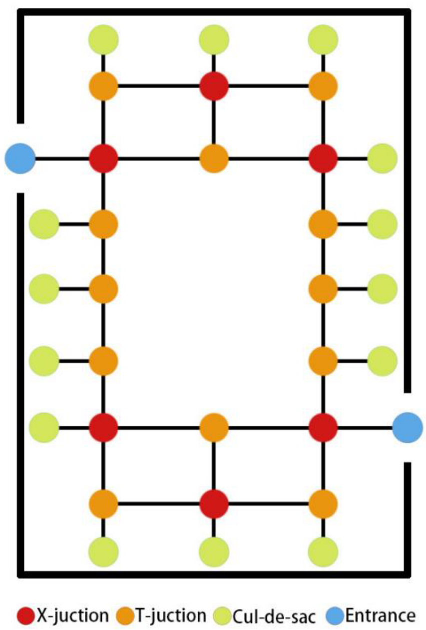


Figure 2. Intersection form of the road network in a gated community.

3.2.2. Indicators of Connectivity in a Gated Community

The connectivity of GCs includes internal connectivity and connectivity between the inside and the outside. In this paper, RD was used to represent the internal connectivity and D was used to represent the connectivity between the inside and the outside. Since the object of other connectivity studies was urban roads, and the object of this paper is GCs, it is obviously not precise enough to calculate the RD and D from the center point of the community to the entrance and exit to express the connectivity of the GC. Therefore, this paper adopted five points (center and four vertices) of the GC as the starting point to calculate RD and D, which is more accurate for the calculation of road network connectivity in GCs. The connectivity of urban GCs was quantitatively analyzed using RD and D together, and the relationship between the connectivity and the morphological elements of GCs was found.

- Dependent Variable 1: RD

RD is defined as the ratio of the shortest network distance between the starting point and the destination to the straight line distance between the two points [52,62]. In this paper, RD is used to represent the road connectivity within the settlement, calculated as the ratio of the shortest network distance to the straight line distance from the five points of the GC (the center point and the four corner points) to all destinations (all the entrances and exits), so that RD is able to reflect the connectivity of the internal road network (Figure 3a). Where the shortest network distance was calculated by the OD cost matrix in Network Analyst of GIS, calculations were based on Dijkstra's shortest path algorithm [63,64]. A formal definition is introduced in Equation (1):

$$Route\ Directness[i] = \frac{1}{5n}\sum_{j \neq i}^{5n} d_{ij}/d_{ij}^{Eucl} \quad (1)$$

where *Route Directness* [*i*] is the directness value of the 5 starting points i; d_{ij} is the shortest network distance from the 5 starting points i to all destinations j, d_{ij}^{Eucl} is the Euclidean distance from the 5 starting points i to all destinations j, and n is the total number of destinations reached.

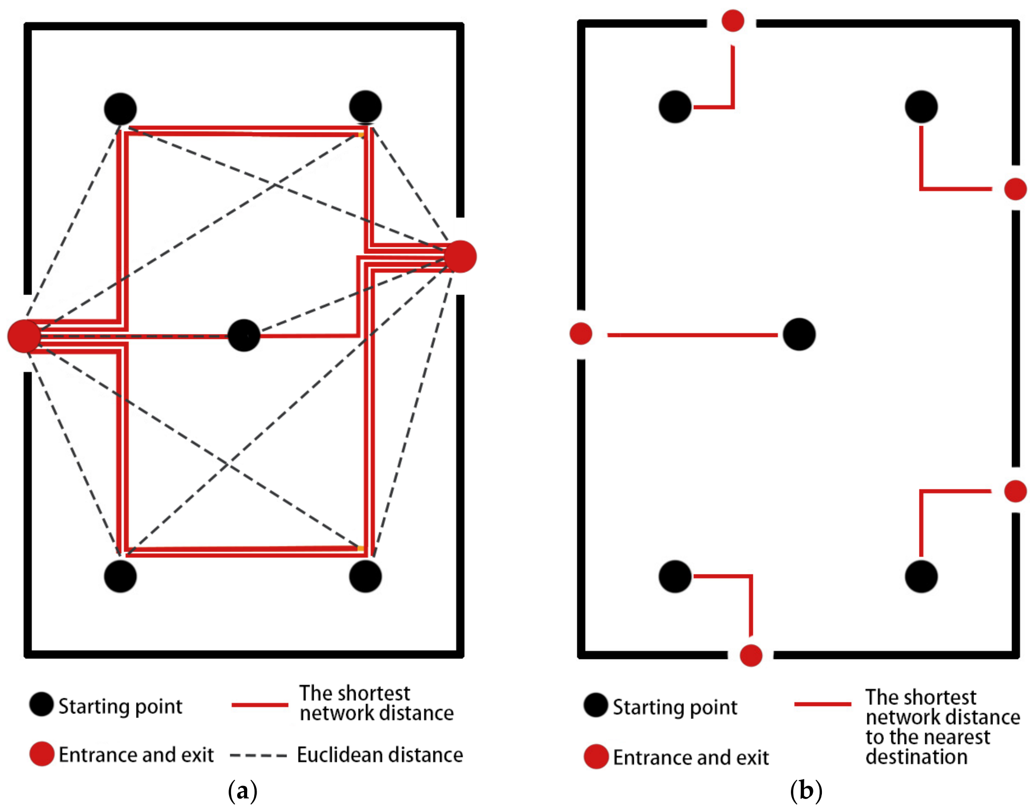


Figure 3. (**a**) Route directness; (**b**) shortest network distance to the nearest entrance.

- Dependent variable 2: D

D is used to indicate the road connectivity between the inside of GCs and the outside, and is calculated as the shortest network distance from five points (center and four vertices) inside the GC as the starting points to the nearest entrance and exit (destination). D is calculated using the closest facility analysis in the network analysis of the GIS [65,66], and then averaged to be used for the later analysis. A graphic representation of D is presented in Figure 3b. Equation (2) below shows a formal definition of D:

$$Distance[i] = \frac{1}{5}\sum_{j_n \neq i}^{5} d(ij_n) \tag{2}$$

where *Distance* [*i*] is the shortest network distance *d* from the 5 starting points *i* to the nearest destination j_n.

3.3. Flowchart of This Work and Analysis Method Adopted

In this paper, multiple linear regression and LASSO regression were used and compared to study the effect of the morphological elements of GCs on road network connectivity. Due to the large number of independent variables and multicollinearity among independent variables, factor dimensionality reduction analysis was performed before conducting multiple linear regression, and the obtained principal components were fed into the multiple linear regression to obtain the regression equations. LASSO regression could effectively deal with the multicollinearity of the independent variables, so there was no need to carry out factor dimensionality reduction analysis, and the independent variables that were correlated with the dependent variable were input into the LASSO regression directly to obtain the regression equation. The flowchart of this work is illustrated in Figure 4.

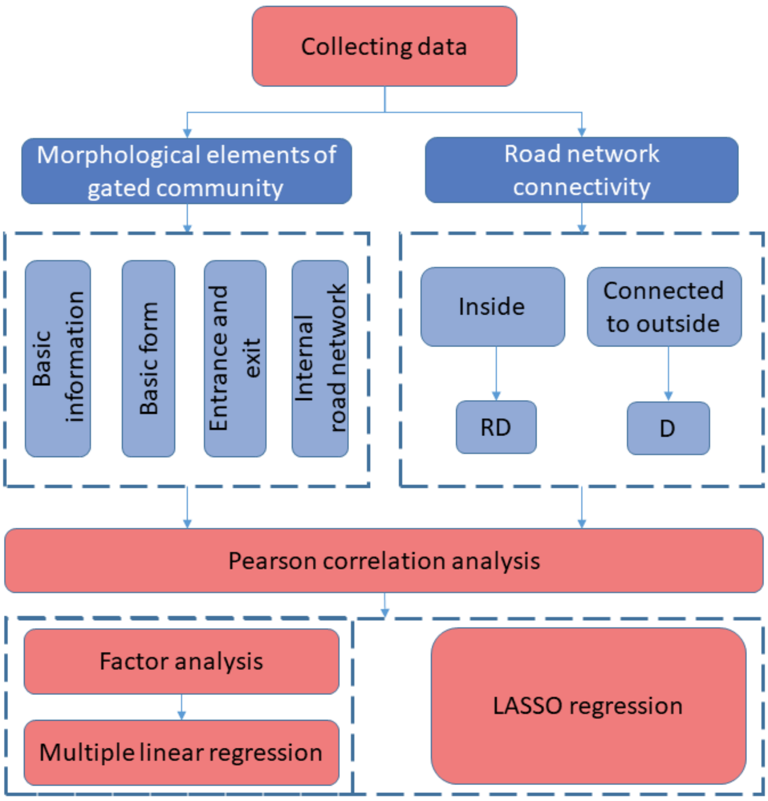


Figure 4. Flowchart of this work.

- Correlation analysis:

The 21 independent variables were correlated with RD and D, respectively, and the correlation coefficients and significance levels (P) were calculated and analyzed to explore the correlations between the independent variables and dependent variables (RD and D). The *p*-values less than 0.05 were considered to be statistically significant [67].

- Factor analysis:

After passing the Kaiser–Meyer–Olkin (KMO) and Bartlett's tests (KMO > 0.5, $p < 0.001$), principal component analysis was used to reduce the dimensionality of the independent variables that were correlated with the dependent variable, and to identify, respectively, the principal components that significantly affected RD and D. The use of principal component analysis before fitting the equations can reduce the correlation of the independent variables, improve the stability of the equations, and solve the problem of collinearity in constructing multiple linear regression equations.

- Multiple linear regression:

After dimensionality reduction, the dependent variables RD and D were analyzed by multiple linear regression to obtain their respective regression equations. The model can be expressed as

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots + b_ix_i \quad (3)$$

where y is the dependent variable (D and RD), b_0 is the intercept, x_i is the independent variable, and b_i is the regression coefficient.

- LASSO regression:

LASSO regression can effectively deal with the multicollinearity of independent variables. It enables variable selection by imposing L1 Regularization on the regression coefficients, which can compress some coefficients to zero. This property makes LASSO regression particularly suitable for cases where there is multicollinearity among the independent variables, as it reduces the complexity of the model and improves its interpretability. RD and D were used as dependent variables in the LASSO regression analyses to explore the effects of the morphological elements of GCs on the connectivity of GCs. The final LASSO regression model obtained expressed the significant influencing factors for RD and D. The model can be expressed as Equation (3).

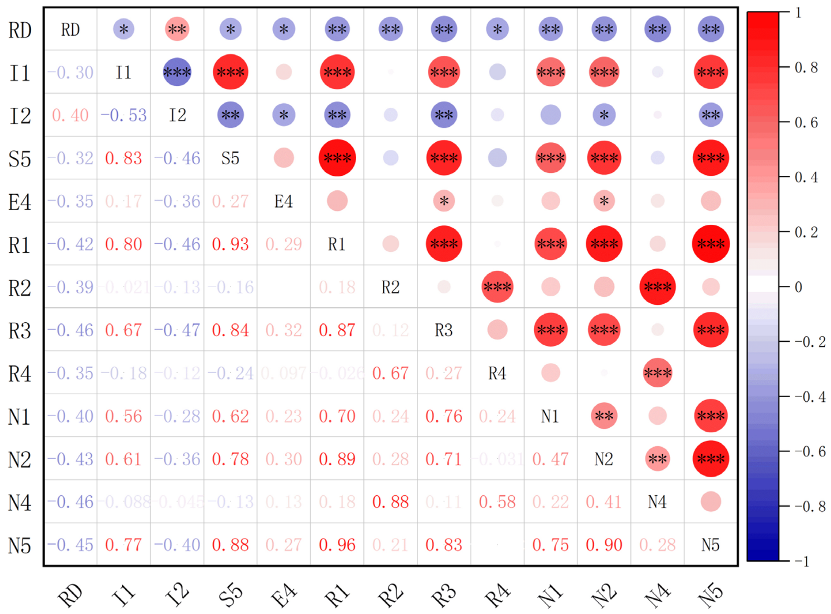
4. Results and Analysis

4.1. Correlation Analysis Results

As shown in Figure 5, RD is correlated with the number of buildings (I_1) and building density (I_2) in the basic information of the GCs. RD is only correlated with area (S_5) among the six indicators of basic form. RD is only correlated with the degree of articulation of entrances and exits (E_4) among the four indicators for entrances and exits. RD is only uncorrelated with cul-de-sacs (N_3) among the nine indicators of the internal road network. In addition, of all the indicators with correlations, only building density (I_2) is positively correlated with RD, and the rest are all negatively correlated. The correlation with the number of buildings (I_1), area (S_5), road area ratio (R_4), and degree of articulation of entrance and exit (E_4) is low ($p < 0.05$).

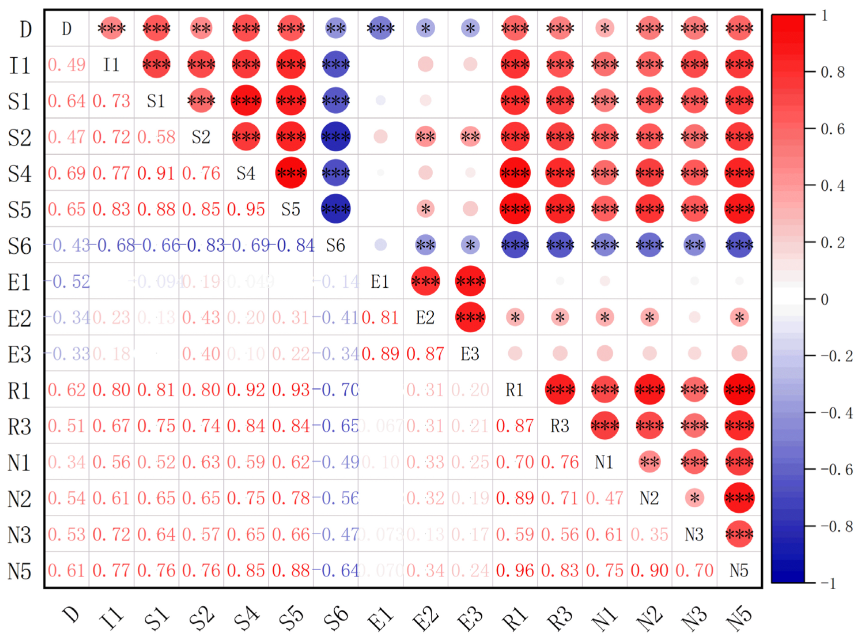
Among the strongly correlated independent variables ($p < 0.001$), the strongest correlation is the intersection density (N_4). The order of the correlation coefficients is N4 > R3 > N5 > N2 > R1 > I2 > N1 > R2. It can be seen that RD has the highest correlation with the indicators of the internal road network, and a lower correlation with the indicators of basic form and entrances and exits. Among the indicators of the basic information of GCs, RD is only more significantly correlated with building density (I_2).

As shown in Figure 6, D is only related to the number of buildings (I_1) among the four indicators of basic information of GCs. D is only unrelated to length–width ratio (S_3) among the six indicators of the basic form of GCs. Among the four indicators of entrances and exits, D is only unrelated to the degree of articulation of entrances and exits (E_4). Among the nine indicators of the internal road network, D is unrelated to the road network density (R_2), the road area ratio (R_4), and the intersection density (N_4). Except for the negative correlation with perimeter–area ratio (S_6), the number of entrances and exits (E_1), the width of entrances and exits (E_2), and the width of articulated urban roads (E_3), the correlation with the remaining relevant independent variables is positive. The correlation with the number of X-intersections (N_1), the width of exits and entrances (E_2), and the width of articulated urban roads (E_3) is low ($p < 0.05$).



∗ p<=0.05 ∗∗ p<=0.01 ∗∗∗ p<=0.001

Figure 5. Analysis of correlations between morphological elements and RD based on Pearson's correlation coefficient.



∗ p<=0.05 ∗∗ p<=0.01 ∗∗∗ p<=0.001

Figure 6. Analysis of correlations between morphological elements and D based on Pearson's correlation coefficient.

Among the strongly correlated independent variables ($p < 0.001$), the most significant correlation is with the perimeter (S_4). The correlation coefficients in descending order are S4 > S5 > S1 > R1 > N5 > N2 > N3 > E1 > R3 > I1 > S2 > S6, which shows that D has the highest correlation with the indicators of the basic form of GCs, followed by the indicators of the internal road network. D is only significantly correlated with the number of entrances and exits (E_1) among the four indicators of entrances and exits.

4.2. Factor Analysis Results

The independent variables with correlation were factor analyzed to reduce the dimensionality, in order to reproduce the relationship between the original variables and the factors, and the variables were categorized through different factors to eliminate the correlation and to simplify the data structure, with minimum loss of information.

4.2.1. Factor Analysis of Independent Variables Related to RD

Bartlett's test of sphericity (Significant at 0.001) was conducted to test whether the correlation between the variables was sufficiently large for factor analysis. In this study, there are 21 independent variables from 120 samples. Bartlett's test index was calculated for the data using factor analysis (Table 2).

Table 2. Bartlett index of data related to RD.

The Index Name		Value
Kaiser–Meyer–Olkin measure		0.621
Spheroid test of Bartlett	Approximate chi square	816.722
	df	66
	Sig.	<0.001

The Kaiser–Meyer–Olkin metric for all independent variable data is 0.621, which exceeds the threshold of 0.5, this indicates that the content validity of the independent variable data is high. The approximate chi-square values of all independent variable data are large, indicating that the data have high significance. In addition, the significance level of all data is less than 0.001, indicating that the reliability of the survey data is high.

The three new factors accounted for 81.143% of the total variance in the dataset and were assigned as the common factors influencing RD in GCs (Table 3).

Table 3. Explanation of the total variance related to RD.

	Initial Eigenvalue			Extraction of the Sum of Squares of Loads			Sum of Squared Rotating Loads		
Ingredients	**Total**	**Percentage of Variance**	**Cumulative**	**Total**	**Percentage of Variance**	**Cumulative**	**Total**	**Percentage of Variance**	**Cumulative**
1	6.088	50.73	50.73	6.088	50.73	50.73	5.621	46.839	46.839
2	2.593	21.606	72.336	2.593	21.606	72.336	2.641	22.008	68.847
3	1.057	8.807	81.143	1.057	8.807	81.143	1.496	12.296	81.143
4	0.822	6.846	87.990						
5	0.703	5.859	93.849						
6	0.366	3.046	96.895						
7	0.213	1.777	98.673						
8	0.101	0.838	99.511						
9	0.024	0.197	99.708						
10	0.017	0.144	99.852						
11	0.016	0.134	99.985						
12	0.002	0.015	1000						

As shown in Table 4, the factor analysis produced three sets of elements:

Table 4. Factor loading matrix after rotation related to RD.

Index	Component		
	F1	**F2**	**F3**
R1	0.971	0.059	0.162
N5	0.969	0.125	0.096
S5	0.931	−0.263	0.204
N2	0.864	0.201	0.075
R3	0.844	0.119	0.314
I1	0.827	−0.199	0.198
N1	0.733	0.229	0.147
R2	0.11	0.939	−0.025
N4	0.143	0.922	−0.06
R4	−0.098	0.818	0.232
E4	0.133	0.069	0.818
I2	−0.364	−0.025	−0.712

F1: basic form and the road network within the GC, including the number of buildings (I_1), total road length (R_1), number of nodes (N_5), rea (S_5), number of X-intersections (N_1), number of T-intersections (N_2), and road area (R_3).

F2: Density of the GC road network elements, including road network density (R_2), road intersection density (N_4), and road area ratio (R_4).

F3: Basic information and entrances, including the degree of articulation of entrances and exits (E_4) and building density (I_2).

4.2.2. Factor Analysis of Independent Variables Related to D

Bartlett's test index was calculated for the data using factor analysis (Table 5). The Kaiser–Meyer–Olkin metric for all independent variable data is 0.823, which exceeds the threshold of 0.5, this indicates that the content validity of the independent variable data is high. The approximate chi-square values of all independent variable data are large, indicating that the data have high significance. In addition, the significance level of all data is less than 0.001, indicating that the reliability of the survey data is high.

Table 5. Bartlett index of data related to D.

The Index Name		**Value**
Kaiser–Meyer–Olkin measure		0.823
Spheroid test of Bartlett	Approximate chi square	945.427
	df	91
	Sig.	<0.001

The two new factors accounted for 81.221% of the total variance in the dataset and were assigned as the common factors influencing D in GCs (Table 6).

F1: the basic form and the road network within the GCs, including area (S_5), total road length (R_1), perimeter (S_4), number of nodes (N_5), length (S_1), road area (R_3), number of buildings (I_1), width (S_2), number of T-intersections (N_2), perimeter–area ratio (S_6), and number of cul-de-sacs (N_3).

F2: Entrances and exits, including number of entrances and exits (E_1), width of entrances of GCs (E_2), and urban road width connected to the entrance of GCs (E_3).

Table 6. Explanation of the total variance related to D.

	Initial Eigenvalue			Extraction of the Sum of Squares of Loads			Sum of Squared Rotating Loads		
Ingredients	**Total**	**Percentage of Variance**	**Cumulative**	**Total**	**Percentage of Variance**	**Cumulative**	**Total**	**Percentage of Variance**	**Cumulative**
1	8.715	62.247	62.247	8.715	62.247	62.247	8.460	60.429	60.429
2	2.656	18.974	81.221	2.656	18.974	81.221	2.911	20.793	81.221
3	0.774	5.53	86.751						
4	0.569	4.067	90.819						
5	0.365	2.606	93.425						
6	0.289	2.066	95.491						
7	0.197	1.41	96.901						
8	0.157	1.123	98.024						
9	0.117	0.836	98.86						
10	0.076	0.542	99.403						
11	0.043	0.304	99.707						
12	0.023	0.167	99.874						
13	0.011	0.078	99.952						
14	0.007	0.048	100						

As shown in Table 7, the factor analysis produced two sets of elements:

Table 7. Factor loading matrix after rotation related to D.

Index	Component	
	F1	**F2**
S5	0.976	0.104
R1	0.963	0.087
S4	0.955	−0.02
N5	0.932	0.133
S1	0.89	−0.102
R3	0.874	0.117
I1	0.856	0.07
S2	0.823	0.309
N2	0.814	0.113
S6	−0.774	−0.268
N3	0.707	0.047
E3	0.123	0.963
E1	−0.062	0.946
E2	0.224	0.917

4.3. Multiple Linear Regression Analysis Results

- Multiple linear regression of RD

The main component factors obtained after factor dimensionality reduction were input into the multiple linear regression analysis as the independent variables, and the results obtained are shown in Table 8. The multiple regression analysis of RD obtained an R^2 of 0.612, the significance of the coefficients was good, and VIF values showed that there was no multicollinearity in the regression model.

Table 8. Coefficient in the final model of the RD equation.

Model	Standardized Coefficients		t	Sig.	Collinear Statistics	
	Standard Error	**Beta**			**Permission**	**VIF**
(constant)	0.024		57.324	<0.001		
F_1	0.025	−0.373	−3.117	0.003	1.000	1.000
F_2	0.025	−0.406	−3.393	0.002	1.000	1.000
F_3	0.025	−0.329	−2.746	0.009	1.000	1.000

A multiple linear regression equation for RD was obtained (Equation (4)). RD is negatively correlated with F1, F2, and F3. The influence of the three principal components on RD is F2 > F1 > F3, in descending order, which shows that the density of GC road network elements has the greatest influence on the connectivity of the internal road network. The basic information and the entrances and exits of the GC have the least influence on the connectivity of the internal road network.

$$RD = 1.389 - 0.083F2 - 0.076F1 - 0.067F3 \quad (4)$$

- Multiple linear regression of D

The main component factors obtained after dimensionality reduction of the factors were input into the multiple linear regression analysis as independent variables, and the results obtained are shown in Table 9. The multiple regression analysis of D yielded an R^2 of 0.731, the significance in the coefficients was good, and VIF values showed that there was no multicollinearity in the regression model.

Table 9. Coefficient in the final model of the D equation.

Model	Standardized Coefficients		t	Sig.	Collinear Statistics	
	Standard Error	Beta			Permission	VIF
(constant)	7.006		30.397	<0.001		
F_1	7.085	0.702	8.675	<0.001	1.000	1.000
F_2	7.085	−0.482	−5.962	<0.001	1.000	1.000

The multiple linear regression equation for RD was obtained (Equation (5)). D is positively correlated with F1 obtained by dimensionality reduction of the elements of the basic form and the internal road network of the GC, and negatively correlated with F2 obtained through dimensionality reduction of the indicators of the entrances and exits of the settlement. In addition, F1 was obtained by downscaling the 11 indicators with correlations with D, and the coefficient in the regression equation was 61.467, and F2 was obtained by downscaling the three entrance- and exit-related elements, and the coefficient in the regression equation was −42.243, which shows that the entrance- and exit-related indicators had a great influence on D.

$$D = 212.96 + 61.467F_1 - 42.243F_2 \quad (5)$$

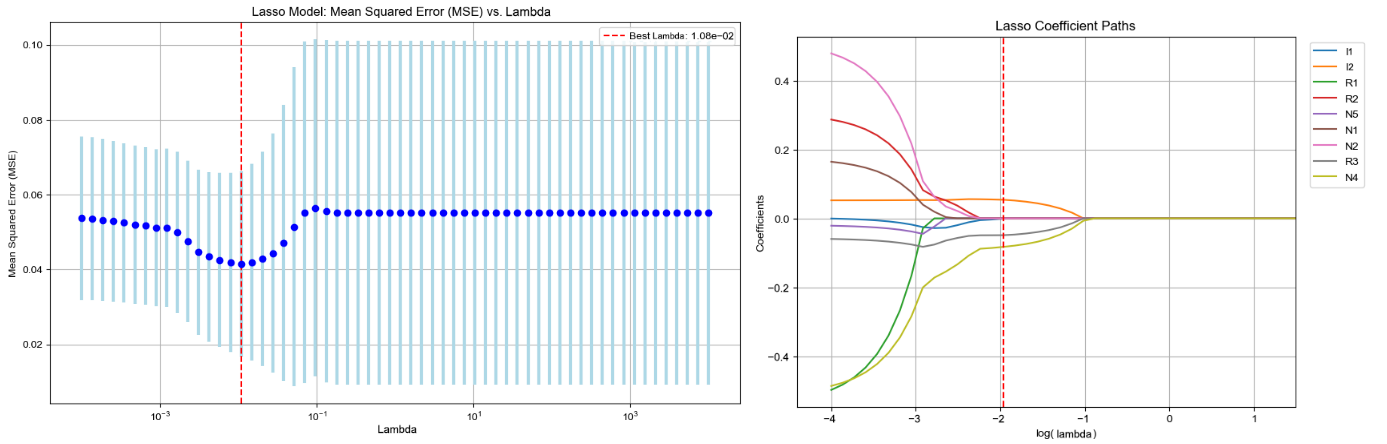
4.4. LASSO Regression Analysis Results

LASSO regression aims to identify the variables and corresponding regression coefficients that lead to a model that minimizes the prediction error. This is achieved by imposing a constraint on the model parameters that "shrinks" the regression coefficients towards zero, that is by forcing the sum of the absolute value of the regression coefficients to be less than a fixed value (λ) [68].

- LASSO regression of RD

The independent variables that correlated with RD were input into the LASSO regression analysis, and the R^2 obtained was 0.715. As shown in Figure 7, the red dashed line represents the lambda value (λ = 0.01081) with the minimum MSE in Figure 7a and the corresponding coefficients for the LASSO model in Figure 7b. From Figure 7b, I_2, R_3, and N_4 are the only independent variables selected, with coefficients of 0.054, −0.049, and −0.083, respectively. The coefficient for all remaining latent factors is zero. Therefore, a prediction model using the LASSO variable selection method can be expressed as:

$$RD = 1.393 + 0.054I_2 - 0.049R_3 - 0.083N_4 \quad (6)$$



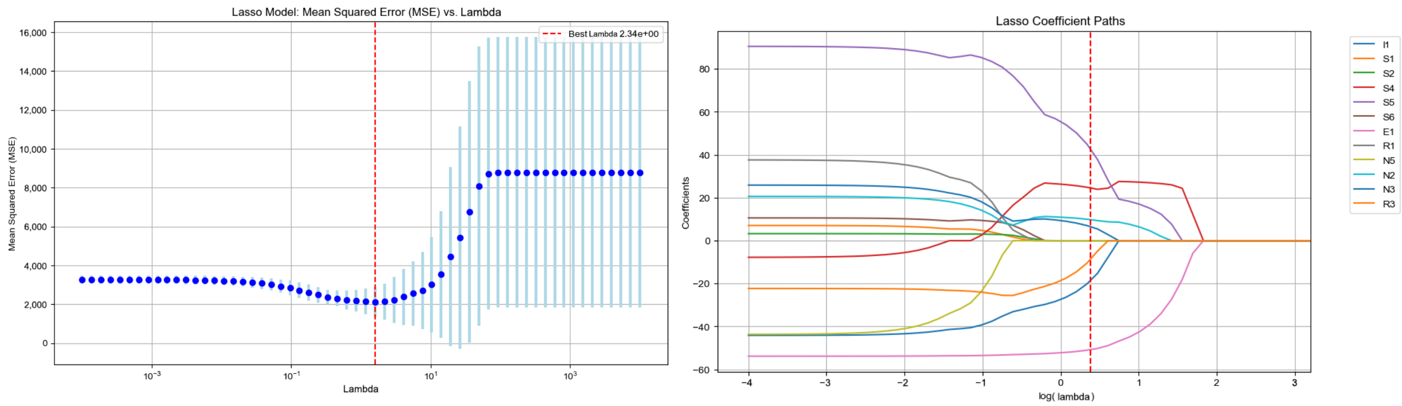
(**a**) (**b**)

Figure 7. The cross-validation for the Lasso model of RD. (**a**) MSE dependence on lambda. (**b**) Coefficient path dependence on lambda.

- LASSO regression of D

The independent variables that correlated with RD were input into the LASSO regression analysis, and the R^2 obtained was 0.81. As shown in Figure 8, the red dashed line represents the lambda value ($\lambda = 2.34$) with the minimum MSE in Figure 8a, with the corresponding coefficients for the LASSO model in Figure 8b. From Figure 8b, I_1, S_4, S_5, E_1, N_2, N_3 and R_3 are the independent variables selected, with coefficients of −18.537, 24.563, 42.622, −50.776, 9.768, 6.500, and −8.649, respectively. The coefficient for all remaining latent factors is zero. Therefore, a prediction model using the LASSO variable selection method can be expressed as

$$D = 209.031 - 18.537I_1 + 24.563S_4 + 42.622S_5 - 50.776E_1 + 9.768N_2 + 6.5N_3 - 8.649R_3 \quad (7)$$



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

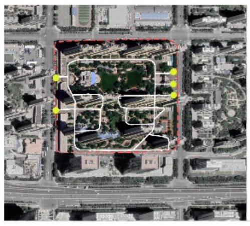
Figure 8. The cross-validation for the Lasso model of D. (**a**) MSE dependence on lambda. (**b**) Coefficient paths dependence on lambda.

5. Discussion and Conclusions

5.1. Discussion

Randall found that neighborhoods with grid street typologies and short blocks had PRD values of 1.4 to 1.5 [48,54]. David Walters used the "connectivity index" to evaluate the connectivity of urban streets, and pointed out that the connectivity index of a perfect grid of roads is 1.4 [69]. LU Jian and WANG Wei believed that the RD should be controlled below 1.3 in cities where the geographic conditions are not constrained [70]. Since this paper focused on the connectivity of GCs in cities, 1.3 was taken as the critical value of RD to judge the connectivity of the internal road network of GCs. In the "urban residential planning and design standards" [61], the scale of a "residential neighborhood" is 150–250 m. In 2016, the "Opinions on Further Strengthening the Management of Urban Planning and Construction" pointed out that the average density of a road network in a built-up area of a city is increased to 8 km/km^2 with a block width of 250 m. In this paper, 250 m was used as the threshold value of D to judge the accessibility of travel of residents in the GCs through the connectivity to the external urban roads. The 120 GCs studied were categorized into four types (Table 10).

Table 10. Examples of four types of GCs.

Type	Condition	Case 1	Case 2	Case 3
T1	RD > 1.3 D > 250	 Meili Xinju	 Shengfu Garden	 Guohua Yinxiang
T2	RD > 1.3 D < 250	 Golden Age	 Xingfu Jiayuan	 Hengda garden-east
T3	RD < 1.3 D > 250	 Dongli Garden	 Jianda Garden	 Shida new Village
T4	RD < 1.3 D < 250	 Steel Garden-east	 Ginza Garden	 Emerald Bund

- T1: RD > 1.3, D > 250.

The number of GCs of this type accounted for 11.1% of the total samples. This type has poor internal road networks and poor travel convenience, which should be solved in terms of the internal road networks and internal–external connections. Combined with the LASSO regression equations for RD and D, the solution should not only involve strengthening the intersection density (N_4), but also increasing the number of entrances and exits (E_1)

and controlling the size of GCs (S5, S4). This comprehensive approach will improve the connectivity of such GCs.

- T2: RD > 1.3, D < 250.

The number of GCs of this type accounted for 48.9% of the total samples. The internal road network connectivity of this type is not good and should be improved, as shown by the LASSO regression equation of RD. Efforts should focus on the intersection density (N_4), and, secondly, the road area (R_3) should be increased.

- T3: RD < 1.3, D > 250.

The number of GCs of this type accounted for 13.3% of the total samples. The internal road network meets requirements, but the travel convenience is not good, and the connections with external urban roads should be increased. Combined with the LASSO regression equation of D, the number of entrances and exits (E_1) can be increased and the size of GCs (S5, S4) should be controlled.

- T4: RD < 1.3, D < 250.

The number of GCs of this type accounted for 26.7% of the total samples. These GCs have strong internal connectivity and excellent connectivity to external urban roads.

5.2. Conclusions

This paper used GIS to collect data on the morphological elements and connectivity (RD and D) of GCs. Subsequently, SPSS was used to conduct a series of analyses, culminating in the development of regression prediction models of GC connectivity. After a categorical discussion, the findings can be summarized as follows:

(1) From the correlation analysis of RD, according to the order of correlation from the largest to the smallest, it can be seen that the correlation between RD and the internal road network indicators is the highest. The strongest correlation is for intersection density (N_4), with a correlation coefficient of 0.464 ** ($p < 0.01$). This indicates that a higher intersection density results in a lower RD and better internal connectivity. The calculation of RD was applied to the data from the five points of the GC to all the entrances and exits, reflecting the connectivity situation of the internal road network.

(2) In the correlation analysis of D, sorted from the largest to the smallest, D has the highest correlation with the perimeter (S_4) in the basic form of the GC, with a correlation coefficient of 0.692 *** ($p < 0.001$). This is followed by the area (S_5) at 0.651 ***($p < 0.001$) and length of the GC (S_1) at 0.645 *** ($p < 0.001$), indicating that the size of a GC has the strongest influence on the convenience of travel. The perimeter–area ratio (S_6) is negatively correlated with all other independent variables, suggesting that a more regular boundary pattern of GCs improves travel convenience for residents within the GCs.

(3) D is negatively correlated with all the indicators for entrances and exits. This indicates that as the number of entrances and exits (E_1) increases, the width of entrances and exits (E_2) expands, and the urban road width (E_3) connecting the entrances and exits becomes wider, and D decreases, making it more convenient for residents within the GC to travel. The number of entrances and exits (E_1) has the most significant correlation with D, indicating that it has the greatest influence on travel convenience.

(4) From the value of R^2, it can be seen that LASSO regression had a better fitting effect compared with the multiple linear regression. Lasso regression has a significant advantage over traditional multiple linear regression in dealing with high-dimensional data, reducing overfitting, handling multiple covariance, performing automatic feature selection, improving model stability, and simplifying the model.

(5) According to the LASSO regression equation of RD, intersection density (N_4) has the greatest impact on RD, followed by building density (I_2) and road area (R_3). Intersection density (N_4) and road area (R_3) are negatively correlated with RD, and building density (I_2) is positively correlated with RD. Since a smaller RD indicates better internal

connectivity, it is advisable to increase intersection density and road area, while decreasing the building density.

(6) According to the LASSO regression equation of D, the number of entrances and exits (E_1) has the greatest impact on D, followed by area (S_5) and perimeter (S_4). Therefore, the number of entrances and the size of GCs have the greatest influence on D, while N_2, N_3, and R_3 in the internal road network have relatively little influence on D. The number of entrances (E_1) is negatively related to D, while the area (S5) and perimeter (S4) are positively related to D. Since a smaller D indicates higher convenience for internal residents' travel, it is advisable to increase the number of entrances and exits and to control the size of the GCs to enhance the connectivity between the inside and outside of the GCs, to facilitate the travel of the internal residents.

(7) In T3, when RD < 1.3 and D > 250, the connectivity between the GC and the outside is poor, making travel inconvenient. From Case 2, it is evident that not only should more entrances and exits be added, but these entrances and exits should also be connected to multiple urban roads.

(8) Comparing Case 1 of T2 with Case 3 of T4, both have an inner ring road. However, T2 exhibits poor internal road network connectivity, whereas T4 demonstrates good connectivity. This difference is due to Case 1 of T2 lacking intersections within the inner ring road and primarily consisting of cul-de-sacs, while Case 3 of T4 has no cul-de-sacs and features connections between the inner and outer ring roads, enhancing the connectivity of the internal road network of the GC.

(9) Regarding travel convenience, T2 and T4 meet requirements, whereas T1 and T3 are less conducive to travel. The comparison of the cases revealed that a more regular boundary pattern for GCs improves the travel convenience for internal residents. This conclusion was also supported by the correlation analysis of D.

This paper has several innovative points: (1) Unlike previous methods that only used the center point as the starting point, this paper focused on the connectivity of the GCs and proposed a new method that calculates connectivity using the center point along with four corner points as the starting points. This approach resulted in more accurate connectivity calculations. (2) By calculating two dependent variables of GC road network connectivity, this paper established a set of indicators to provide a reference and quantitative basis for the future sustainable urban street layout of "small neighborhoods and dense road network". (3) The D dependent variable introduced in this paper provides a quantitative basis for assessing the ease of travel for residents within GCs. A D value greater than 250 indicates that travel is inconvenient for residents within the GC.

This paper also has several shortcomings. This paper did not propose the optimal ranges for each independent variable under conditions where D < 250 and RD < 1.3, indicating good connectivity. There are many practical difficulties in optimizing road connectivity within GCs in China, such as land ownership, traffic safety, traffic pollution, and noise [4]. Follow-up studies could validate the findings of this paper through simulation and actual measurement, combined with the case of GC renovation.

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