International Journal for Housing Science and Its Applications
Publish August 3, 2025. Volume 46, Issue 3 Pages 639-652

https://doi.org/10.70517/ijhsa46347

Quantitative research on spatial morphology topology of Fujian mountain settlements by integrating graph theory algorithm and spatial syntactic analysis and GIS visualization implementation

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Abstract This study takes Fujian Putian mountain settlement as the object, integrates the graph theory algorithm and spatial syntax analysis, constructs a multi-scale quantitative index system, and systematically researches the topology and functional attributes of the spatial form of the settlement by combining with GIS technology. By integrating multi-source data and extracting 782 samples of settlements, five types of quantitative indexes, namely, aspect ratio λ, modified shape index S, compactness W, average width of edge space L and dispersion K, are proposed, which are combined with the parameters of spatial syntax, such as integration and comprehensibility, to analyze the law of spatial differentiation of settlements. The empirical analysis shows that: the foothills and riverbanks type of clusters have the mean value of shape index up to 2.89 ($S \geq 2$), and the aspect ratio $\lambda = 2.39$, which shows a significant banding feature, and the river valley and flat dam type of clusters have a larger area, such as 188,899.85m² in Village V, but the shape index is medium, $S = 1.54$. The mountain type of clusters have the lowest integration degree, with the mean value of 0.618, and the degree of spatial discretization is high. The study was visualized by GIS with linear fitting, and the goodness of fit $R^2 \geq 0.98$ revealed the strong correlation between geographic constraints and colony shape, providing data-driven theoretical support for the protection and planning of mountainous colonies.

Index Terms fusion graph theory algorithm, spatial syntax, mountain settlement, spatial morphology topology

I. Introduction

As a spatial carrier of human settlement, the form of rural settlements carries the long history and cultural value of the region [1]. However, with the acceleration of urbanization and modernization and the gradual dilution of people's awareness of the protection and inheritance of traditional culture [2], the existing studies on the spatial morphology of rural settlements are mostly confined to qualitative methods. Most of the existing studies on the spatial morphology of rural settlements are confined to the shallow characterization and regular description of qualitative methods, and the quantitative analysis of in-depth spatial morphology at the genetic level is very lacking [3], [4]. Fujian Province is characterized by mountainous areas and gullies, with mountainous areas accounting for more than 85% of the province's land area, and the overall spatial pattern of mountains and basins is intertwined [5]. Due to the richness of geomorphological types in mountainous areas, under the support of the historical background of multicultural interlacing and fusion, the rural settlement pattern presents diverse and three-dimensional characteristics that are obviously different from those in plain areas, which makes the description of spatial morphological features and interpretation of spatial generative laws more complex [6]-[9]. Therefore, to carry out the study of rural settlement spatial morphology in the mountainous region of Fujian, it is necessary to firstly extract the spatial laws scientifically, interpret the current phenomenon, and complete the accurate cognition of the complex spatial morphology of the settlement [10], [11]. It is also necessary to utilize the laws to deduce or judge the spatial patterns for spatial planning [12]. It can be seen that the current depth and accuracy of rural settlement morphology, which is dominated by a single qualitative study, is not sufficient to support rural construction planning in the mountainous areas of Fujian [13], [14]. Through the use of relevant quantitative analysis methods and parametric means, quantitative research on its spatial morphology from the macro, meso and micro view, exploring the deep law of settlement morphogenesis, providing data support and theoretical guidance for the protection, inheritance and sustainable development of local rural settlement spatial culture [15]-[18].

This study systematically constructs a research framework from the definition of research object, data acquisition, quantitative index construction to spatial syntax analysis. Firstly, it clarifies the research scope, defines the uniqueness of Putian mountain settlements based on the perspective of geography and humanistic zoning, and realizes the precise extraction of research samples through the integration of multi-source data. Then five types of quantitative indexes, namely, aspect ratio λ, modified shape index S, compactness W, average width of edge space L and dispersion K, are proposed, which are combined with multi-scale boundary contour analysis to break through the single dimension of the traditional morphological description. The theory of spatial syntax is also introduced to analyze the topological logic and functional association of the spatial structure of the settlement through the quantitative description of comprehensibility, spatial grouping and configuration. By calculating the correlation coefficient between local variables and global variables, the comprehensibility is quantified. Then the three-dimensional space is simplified into a two-dimensional topological relationship map, i.e., the relationship diagram, to study the connection and compactness between spatial points. Finally, the spatial configuration is quantitatively described by topological morphological variables (connectivity, integration, and comprehensibility) to reveal the functional attributes and dynamic characteristics of the settlement space. The combination of the three layers, data support and algorithmic modeling provides a methodological basis for revealing the spatial differentiation law and evolution mechanism of mountain settlements.

II. Definition of research objects, construction of quantitative indicator system and spatial syntactic analysis methods

II. A. Objective and scope of the study

The study of the spatial morphology of Putian mountain settlements needs to first clarify its geographical and humanistic boundaries. In this section, we define the research object from the three perspectives of administrative divisions, natural geographic features and cultural divisions, and construct a research sample library through the fusion of multi-source data to lay the foundation for subsequent quantitative analysis and spatial topological modeling.

II. A. 1) Scope of the study: mountain settlements in the Puxian region

The Putian region includes Putian City and Xianyou County in terms of administrative division. Putian region is located in the south of central Fujian, north of Fuzhou and south of Quanzhou, is the main point of land and sea transportation between the two places, west of the Daiyun Mountains east of the Taiwan Strait, the geographical pattern of the mountains and the sea makes it relatively independent of the surrounding, Putian region has a unique dialect of the Putian language and a strong cultural temperament. Changqing academician will be dialect and language group as the main basis for distinguishing the terroir, Dai Zhijian synthesized the geographical, administrative and language group based on the three, will be extracted for the Minhai system of residential houses in the independent class, to the Puxian dialect and the culture of science and technology as a feature, and will be divided into two types of residential houses in the Putian region, respectively, for the “Coastal Plain Area” (Mainly located in Chenggang District, Licheng District, Hanjiang District, Xiuyu District) and “Xianyou Mountainous Area”, from the type of residential point of view there is no obvious distinction between Putian and Xianyou, but more the difference between the plains and mountainous areas. Due to the convenient transportation and economic development of the coastal plains, the residential patterns are similar to those in other areas of Fujian, while the residential patterns in the mountainous areas of Putian are more special, reflecting a unique terroir. In this paper, a small number of settlements in the plains are selected as a control, and the scope of the study is dominated by mountain settlements.

Mountain as a geographical concept refers to the terrain with an absolute height of more than 500 meters and a relative height of more than 200 meters. The study broadly understands mountainous areas from the perspective of settlement and landscape, which can be regarded as “lots with a height of undulation greater than 200m are collectively referred to as mountainous areas, which also include plateaus, hills, valleys and basins.” Putian region pillow mountains facing the sea, mountainous settlements in the 200m to 1200m range of elevation fluctuations in the area, through the Arcgis Putian dem elevation data and administrative divisions are superimposed, resulting in an elevation of more than 500m and undulating mountainous areas mainly 14 townships (townships), respectively, Hanjiang District: Dayang Township (1), Xinxian Township (2), Zhuangbian Township (3), Baisha Township (4), Hagi Lutsu Township (5); Chenggang District: Changtai Township (6); Licheng District: Xitianwei Township(7); Xianyou County: Zhongshan Township (8), Shufeng Township (9), Xiyuan Township (10), Youyang Township (11), Shicang Township (12), Caixi Township (13), and She whetstone Township (14), and the study mainly selects the settlements in the figure 1. The geographic definition of Putian hill settlements is the reference basis of this study. The hill is not only an entity of material space, but as part of the built environment of the terroir settlement, its settlement pattern is the main research content of this paper.

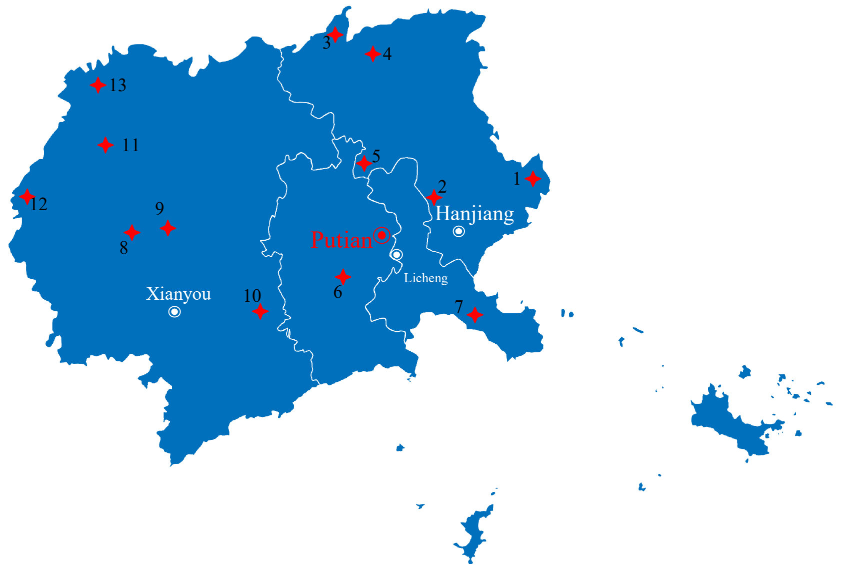

Figure 1: Research area

II. A. 2) Data acquisition and processing

The administrative division data of Putian area are obtained from the Atlas of Administrative Division of Fujian Province and the public data of the Natural Resources Bureau of Putian City and Xianyou County; the information of the settlement's orientation, toponymy, and historical evolution is obtained through the Records of Putian City, the Records of Xianyou County, and the Geographical Names Information Database of Fujian Province (http://fujian.dmfw.mca.gov.cn/). After counting the toponymic information, the settlement boundaries were vectorized and extracted using the Google Earth platform combined with field research, and the GCJ-02 coordinate system was converted to the WGS84 coordinate system. The formation age and historical change information of the settlements were verified by comparing the literature such as “Putuyang Culture Examination” and “Minzhong Terroir Architecture”. The elevation and topographic slope data of each township were extracted based on Putian 30-meter resolution DEM data (source: Geospatial Data Cloud), and the population and economic data were obtained from Putian Statistical Yearbook and Xianyou County National Economic and Social Development Statistical Bulletin. A total of 782 samples of Putian hill settlements were obtained in this study, covering 18 townships.

II. B.Indicators for quantitative analysis of colony boundaries

Based on the standardized processed dataset, this study further constructs a multi-dimensional quantitative index system, aiming to break through the limitations of the traditional morphological description, and to analyze the topology of the colony morphology from multiple perspectives, such as geometric features, spatial compactness and boundary dynamics.

II. B. 1) Aspect ratio λ

The aspect ratio is the ratio of the length of the long axis to the short axis of the outer boundary graph, which describes its narrowness. In order to complete the quantitative analysis of the outer boundary graph, it is also necessary to obtain the outer rectangle of the general plane of the colony, and determine the length of the long axis and the short axis of the colony plane from the values of the length and width of this rectangle, so as to further calculate the aspect ratio of the boundary graph of the colony λ. When drawing the outer rectangle of the general plane of the colony, the boundary graph of the colony can be used as a reference to obtain a suitable outer rectangle.

II. B. 2) Shape index S

The concept of shape index was developed from the perimeter-area ratio, but since the perimeter-area ratio alone is not sensitive to the characterization of shape changes, it has been further improved, usually using a compact shape as a reference standard. The most widely used is the shape index using a circle as a reference, which is calculated as the ratio of the perimeter of the object to the perimeter of a circle of equal area, reflecting the extent to which the object deviates from the circle in shape, and is calculated by the formula:

$$S = \frac{P}{2\sqrt{\pi A}} \tag{1}$$

where P denotes the perimeter of the target figure and A denotes the area of the target figure. The minimum value of the shape index S is 1. The closer the value is to 1, the closer the target graph is to a circle, and the larger the value is, the larger the difference between the target graph and a circle is, and the more complex and irregular the shape is. However, it is worth noting that, for a two-dimensional graph, the reason why its shape index value becomes larger may be due to the change of the degree of concavity and convexity of the outer boundary, or due to the proportion of its own shape has become "flatter", and thus simply using the original shape index can not be a good characterization of the colony boundary pattern. Therefore, the original shape index alone does not characterize the settlement boundary pattern well, and a correction of the shape index is needed. The method used for this correction is to take the aspect ratio λ into account, and use equal area ellipses (with the same aspect ratio) to calculate the shape index, and the modified shape index formula is:

$$S = \frac{P}{\left(1.5\lambda - \sqrt{\lambda} + .5\right)}\sqrt{\frac{\lambda}{A\pi}} \tag{2}$$

In the present research methodology, due to the use of three different scale tiers of outer boundary contours, these three tiers of boundaries cascade downwards, with the small boundaries continuing the dominant features of the medium boundaries and trivializing them even further, while the large boundaries are more closely related to the clusters or strips, which differ from the medium boundaries to a certain extent. These three layers of boundaries correspondingly produce three different shape indices S, and for the combined, weighted average shape index, the formula is:

$$\begin{aligned} S_{\text{Equal rights}} &= S_{\text{Large}} \times 1.4010 \times 0.25 + S_{\text{Medium}} \times 0.5 \\ &+ S_{\text{Small}} \times 0.5611 \times 0.25 \end{aligned} \tag{3}$$

where S_{Large}, S_{Medium}, and S_{Small} denote the shape indices computed for large, medium, and small boundaries, respectively.

II. B. 3) Compactness W

As mentioned before, the boundary of the settlement is composed of the solid boundary constituted by buildings, natural environment and other real substances and the imaginary boundary defined by their enclosure. The denseness of the outer boundary of a settlement, i.e., the proportion of the solid boundary in the outer boundary of the settlement, reflects the degree of aggregation of building units on the boundary of the settlement. Similar to the shape index, the compactness W also exists three values corresponding to three different scale levels, and the compactness formula after weighted average is expressed as:

$$W_{\text{Equal rights}} = W_{\text{Large}} \times 0.16 + W_{\text{Medium}} \times 0.34 + W_{\text{Small}} \times 0.5 \tag{4}$$

where W_{Large}, W_{Medium}, and W_{Small} denote the cluster boundary densities computed for large, medium, and small boundaries, respectively.

II. B. 4) Average width of edge space L

Based on the three different scale levels set by the three kinds of colony external boundary colony graphic adjacent to the two layers of two-two enclosure, the formation of two layers of colony edge space. Among them, the outer layer is called the colony external edge space, and the inner layer is called the colony internal edge space, so that the colony from outside to inside is also divided into four levels: external environment space, external edge space, internal edge space, and colony internal space. The edge space reflects the degree of aggregation of the space at the boundary of the colony, if this edge is smaller, it means that the boundary of the colony is more compact, on the contrary, it is more discrete.

Combining the three scale levels of large, medium, and small of the settlement's outer boundary with the two levels of inner and outer edge space has spawned three definitions for the edge space of the settlement:

$$L_{\text{Outside}} = \frac{A_{\text{Outside}}}{P_{\text{Large}}} \tag{5}$$

$$L_{\text{Inside}} = \frac{A_{\text{Inside}}}{P_{\text{Medium}}} \tag{6}$$

$$L_{\text{Total}} = \frac{A_{\text{Outside}} + A_{\text{Inside}}}{P_{\text{Medium}}} \tag{7}$$

where L_{Outside}, L_{Inside}, L_{Total} denote the average widths of the outer edge space of the colony, the inner edge space of the colony, and the overall edge space of the colony, respectively, P_{Large}, P_{Medium} denote the perimeter of the large and medium boundaries, respectively, and A_{Outside}, A_{Inside} denote the area of the outer edge space and inner edge space, respectively.

II. B. 5) Discrete degree K

Dispersion is a variable derived from the shape index of a graph. In the three scale levels of the outer boundary of the colony, as the scale level continues to get smaller its area also decreases, while the perimeter will increase, which means that its complexity is also increasing, this process is actually a change in the spatial limitation of the boundary of the colony, and this process of change can be examined by the relationship between the two shape indices. If the difference between the shape index of the two layers of graphics is greater, it means that the space between them is richer and richer, and the ratio of the shape index between the two layers of boundary graphics K is defined as the degree of dispersion of the outer boundary graphics of the colony, similar to the average width of the space of the boundary of the colony L, the degree of dispersion of the outer boundary graphics of the colony of the three ways of expression:

$$K_{\text{Outside}} = \frac{S_{\text{Medium}}}{S_{\text{Large}}} \tag{8}$$

$$K_{\text{Inside}} = \frac{S_{\text{Small}}}{S_{\text{Medium}}} \tag{9}$$

$$K_{\text{Total}} = \frac{S_{\text{Small}}}{S_{\text{Large}}} \tag{10}$$

where K_{Outside}, K_{Inside}, K_{Total} denote the dispersion of the outer edge space of the settlement, the inner edge space of the settlement, and the overall edge space of the settlement, respectively, and S_{Large}, S_{Medium}, and S_{Small} denote the shape indices of large, medium, and small boundaries, respectively.

II. C.Main analytical methods of spatial syntax

Although quantitative indicators can characterize morphological features, it is difficult to reveal the internal logic of spatial systems. Therefore, this study introduces the theory of spatial syntax to transform morphological data into functional interpretation of spatial structure through variables such as topological depth, integration degree and comprehensibility, and ultimately realizes the analysis of the whole chain of “form-structure-function”.

II. C. 1) Quantitative analysis of spatial syntax based on intelligibility

In the most superficial and intuitive way, “space” refers to the dimensions of the plane, the proportionality of the façade, the arrangement and combination of walls and columns, etc. At a deeper level, it refers to the spatial structure behind the surface form of the space. The deeper meaning is the spatial structural property behind the surface form of space, which refers to an inner spatial structure derived from the relative position and connection relationship between various elements in the spatial system.

Spatial comprehensibility is the ability to judge people's logical understanding of spatial structure in the theory of spatial syntax, the higher the spatial comprehensibility, the easier the spatial layout is recognized and understood, and the spatial comprehensibility illustration is actually a way to help people understand the spatial illustration in a more intuitive way.

II. C. 2) Quantitative analysis approach based on spatial grouping

Spatial conformation is a way of thinking that describes and interprets space from an innovative perspective. Spatial configuration refers to ignoring the three-dimensionality of the research object, only in the plane relationship, the research space is reduced to points, and then study the structural relationship between the points of the diagram, this process is called spatial configuration, the resulting diagram is called the relationship illustration. The relational illustration is a structural illustration of a spatial topology that emphasizes only the relationships within the space. Spatial conformation in this way is a prerequisite for quantitative spatial analysis.

The relational illustration describes the topological depth of the space in the abstract. Figure 2 shows the relational illustration, the two diagrams are different in appearance, but in fact, the relational illustration is obtained by observing the same space from two different perspectives, namely, spatial form and functional relationship, from which it can be seen that a change in the angle of observation will lead to differences in the relational illustration of the object of study.

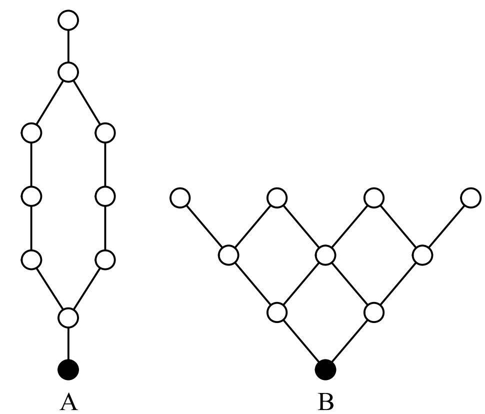

Figure 2: Justified Graph

The graphical representation of visual integration expresses the relationship of space through the warmth or coldness of the color, the warmer the color the wider the range of the viewing area, and similarly, the colder the color the smaller the range of the viewing area and the more intimate the space. All corners of the studied space are given colors, and the warmer the color, the more dense the space is. This approach serves as an important metric for spatial systems, and it makes it easier to identify the relationship between the space and the various system elements.

II. C. 3) Quantitative description of conformations

Describing the configuration through quantitative way is the so-called quantitative description, describing the relationship between space and space, space and system is the most common way to get the diagram to interpret the judgment through the topological morphology variables, the change metric value abstracted in this way is not only a quantitative description, but also an important analytical reference value in the whole research process. The arithmetic process of metric value actually reflects the quantitative description of spatial relations, and different spatial relations correspond to different metric values:

(1) Connectivity:

Spatial connectivity refers to the connection status between points in space, the warmer the color in the illustration, the higher the value of spatial connectivity in this area, the closer the relationship with the surrounding space, on the contrary, the lower the value of connectivity, the lighter the color, the weaker the relationship with the surrounding.

(2) Integration degree:

The degree of spatial integration refers to any point in space, how much space you need to cross to reach another point, the warmer the color, it means that there are multiple alternative ways to reach the destination, the better the spatial compactness.

(3) Intelligibility:

The comprehensibility value, also known as the R^2 value, describes the relationship between the degree of connectivity of a local variable and the degree of integration of the overall variable. When the comprehensibility is greater than 0.5, it indicates a higher degree of connection between the two, and also implies a higher spatial accessibility, the easier it is for people to pass through the spatial local structural features that can be seen.

III. Physical analysis of the morphology of the planar boundaries of settlements

Based on the theoretical elaboration of the definition of the research object, the systematic construction of the quantitative index system, and the spatial syntax analysis method in Chapter 2, Chapter 3 will combine the specific sample data to empirically analyze the topology and functional attributes of the mountain settlements in Fujian in terms of the three dimensions of boundary morphology, accessibility, and spatial typology division.

III. A. Comprehensive analysis of aspect ratio and shape index of settlements

In this paper, we try to use the shape index model with equal area and same aspect ratio ellipse as reference to further study the shape of Fujian mountain settlements. After the initial screening of the aspect ratio of the settlement boundaries, we analyze the shape index of the morphology of the space of Fujian mountain settlements, and the shape index statistics of the boundary graphs of 30 settlements are shown in Table 1.

Table 1: Shape index statistics of boundary graphs of 30 settlements

Village	Area (A)/m^2	Perimeter (P)/m	Aspect ratio (λ)	Shape Index (S)
A	332901.4152	2927.5523	2.2776	1.4317
B	140010.6796	2033.5703	2.0379	1.5335
C	188899.8502	2780.2755	1.5815	1.8050
D	249260.4517	2749.4421	2.9928	1.5539
E	278060.8930	3023.1713	1.9703	1.6177
F	77042.0510	1205.6118	1.8569	1.2256
G	195112.5580	2654.9924	4.4697	1.6960
H	278241.4657	2671.9550	1.7775	1.4293
I	543416.0118	3279.2458	2.9263	1.2552
J	416077.2044	2382.9569	1.8194	1.0424
K	353638.7902	3367.6300	2.5241	1.5979
L	105941.3946	1216.9707	1.9901	1.0550
M	14937.4968	693.6824	2.6898	1.6015
N	152780.5226	2242.7231	3.0149	1.6190
O	139492.3339	1849.2579	5.0315	1.3971
P	111662.2160	3723.2026	2.3054	3.1439
Q	143437.0255	2083.6707	4.9128	1.5524
R	59329.1090	1249.1002	2.8269	1.4470
S	198883.0962	2882.5110	2.7261	1.8238
T	126384.7807	2229.0466	2.7602	1.7692
U	86534.9441	1160.6540	2.8766	1.1133
V	52220.1750	1932.1009	1.9177	2.3857
W	303926.5941	3431.8423	1.9811	1.7565
X	458416.7504	3277.9894	2.4096	1.3661
Y	124999.9398	1519.1325	2.1439	1.2124
Z	790585.9057	3562.6925	3.3973	1.1306
AB	199627.8664	4179.5264	2.4841	2.6395
AC	1140999.8652	4298.9560	4.8094	1.1356
AD	56526.7480	1140.5443	2.0594	1.3536
AE	136017.1894	2312.8224	1.0320	1.7695
Average			2.6534	1.5820

After calculation and statistics, the mean value of shape index of 30 clusters is 1.5820, the smallest village J is 1.0424, and the largest village P is 3.1439, the larger the shape index, the more obvious the shape characteristics. According to the principle of statistics, since in any normal distribution, according to the statistical analysis of the shape index data of these 30 settlements, the mean value is 1.5820, and the standard deviation is 0.4752. Based on the 68-95-99.7 rule of normal distribution: $\mu - \sigma = 1.1068$, $\mu + \sigma = 2.0572$, i.e. 68% of the data should fall within the medium value interval of [1.1068, 2.0572]. Data greater than 2.0572 fall in the high value interval, showing obvious finger-like characteristics.

For ease of analysis, S = 2 can be used as a simplified critical value for the finger-like feature (close to the actual calculated $\mu + \sigma = 2.0572$). The morphology of three clusters ($S \geq 2$) in the data showed significant finger-like features, while most of the remaining clusters (S<2) had weak or insignificant finger-like features. When S ≥ 2, it is a fingered colony, of which when λ < 1.5, it is a fingered colony with clumping tendency; when λ ≥ 2, it is a fingered colony with banding tendency; and when 1.5 ≤ λ < 2, it is a fingered colony with no clear tendency. When S < 2, λ < 1.5, it is a clustered cluster; when S < 2, 1.5 ≤ λ < 2, it is a clustered cluster with a banded tendency. When S < 2, λ ≥ 2, it is a banded cluster. Based on the aspect ratio λ and shape index S the 30 cluster samples were classified morphologically, and the morphological classification of the cluster boundaries is shown in Table 2.

Table 2: Settlement classification based on aspect ratio λ and shape index S

S	λ	Village	Aspect ratio (λ)	Shape Index (S)
Finger-like settlement S≥2	A finger-like settlement with a zonal tendency λ≥2	P	2.3054	3.1439
		AB	2.4841	2.6395
	Finger-like settlement without definite orientation 1.5≤λ<2	V	1.9177	2.3857
S<2	Band settlement λ≥2	S	2.7261	1.8238
		T	2.7602	1.7692
		G	4.4697	1.6960
		N	3.0149	1.6190
		M	2.6898	1.6015
		K	2.5241	1.5979
		D	2.9928	1.5539
		Q	4.9128	1.5524
		B	2.0379	1.5335
		R	2.8269	1.4470
		A	2.2776	1.4317
		O	5.0315	1.3971
		X	2.4096	1.3661
		AD	2.0594	1.3536
		I	2.9263	1.2552
		Y	2.1439	1.2124
		AC	4.8094	1.1356
		Z	3.3973	1.1306
		U	2.8766	1.1133
	A cluster settlement with a zonal tendency 1.5≤λ<2	C	1.5815	1.8050
		W	1.9811	1.7565
		E	1.9703	1.6177
		H	1.7775	1.4293
		F	1.8569	1.2256
		L	1.9901	1.0550
		J	1.8194	1.0424
	Cluster settlement λ<1.5	AE	1.0320	1.7695

III. B. Accessibility analysis

After initially revealing the geometric characteristics of the settlement form through the integrated analysis of aspect ratio and shape index, this section further introduces the spatial syntax of accessibility analysis to explore the dynamic vitality and functional connection of the settlement spatial structure from the perspective of topological relationship.

In the research method of spatial syntax, the accessibility of a settlement is mathematically calculated by abstracting the connection of spatial structure into topological structure, which is expressed by the integration degree; the higher the integration degree, the higher the accessibility, and the higher the flow of people, the higher the vitality of its settlement. The global integration degree (R=N) and local integration degree (R=3) of Fujian mountain settlement space are calculated separately, and the global integration degree and local integration degree present consistent results.

The correlation between the global integration (Rn) and local integration (R3) is considered here by using a special concept “synergy”. Positive and negative correlations have different meanings: (1) when the positive correlation is positive, when Rn and R3 are both low, such areas are very unfavorable, and the possibility of people being able to reach them is very low; when Rn and R3 are both high, then these clusters are geographically close to the center of the city, and people's accessibility is high, and they are relatively prosperous; if they are close to the center of the city and in a prosperous location, but Rn and R3 are low, it indicates that the cluster is geographically very closed, and people can reach them. If the location is close to the center of the city and prosperous, but Rn and R3 are both low values, it indicates that the settlement is very closed geographically, and people's accessibility is low; (2) when negative correlation, one of the values of Rn and R3 is oddly high, and the other one is oddly low, which indicates that these settlements are the distinctive areas in the city, or the problematic areas.

According to the results of spatial syntax software analysis: from the coordinate system R^2=0.430528, Rn and R3 show strong positive correlation, when targeting a certain spatial element in the system, the values of Rn and R3 are the same as the high and the same as the low, and it has been pointed out above that the higher the values of Rn and R3 are, the more favorable the location is in economic geography. Figure 3 shows the scatter distribution of synergistic degree of Fujian mountain settlement.

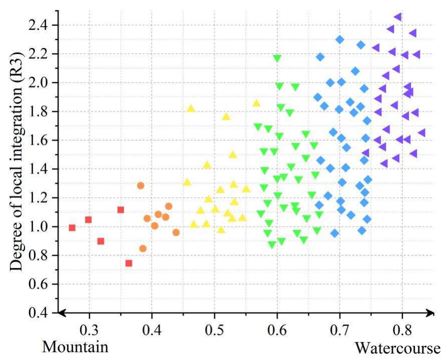

Figure 3: Dispersal distribution of synergistic degree of Fujian mountain settlements

From the scatter plot of synergism degree, it can be seen that the higher its value is less, then its center location is easy to judge. Combined with the integration degree graph, the settlements along the river and those distributed vertically along the river have higher integration and synergy degrees, and are the main settlements in the Fujian region, as well as the main areas for their economic and public activities. It is consistent with the results inferred from the geographic environment, that is, the area by the river has convenient transportation and is the main area engaged in trading, and the more it extends towards the mountains, the less convenient its transportation is, the worse its accessibility is, and the less its economic activities are.

III. C. Spatial typing and morphological characterization of settlements

On the basis of clarifying the correlation between settlement accessibility and its economic and geographic characteristics, this section combines the spatial classification of settlements, and systematically analyzes the differentiated characteristics of settlement patterns in different geographic environments at the levels of external boundary morphology and internal structure.

III. C. 1) Morphological analysis of external spatial boundaries of settlements

According to the location of the settlement, Fujian mountainous settlement is divided into three spatial types: mountainous, foothills and riverbanks, and river valleys and dams. Most of the mountain type settlements are distributed in the mountains on the west side of the main river basin, and the dwellings are built on the hillside or mountain passes, etc., and the settlements are built in a trapezoidal shape from the top to the bottom. Because of the high terrain of the dwellings, the ventilation and lighting conditions are better, and the living comfort is also higher, overlooking the farmland and streams in the valleys. However, they are located in a complex terrain with high elevation, far away from the main river, with little water in the surrounding area, low accessibility, and poor connectivity with the outside world, and they account for the least proportion in the watershed.

The foothills and riverbank type settlement is mainly distributed on both sides of the tributaries, and the residential houses are set up at the foot of the mountain, because of the strong restriction of the boundary of the river water, the building is dense, and the area of the village is relatively small, and the comfort is low, but the defense is strong, and because of the proximity to the mountain and the water it is easy to get materials nearby, and it is the most common type in the watershed.

River valley dam type settlement layout selection of river confluence or alluvial formation of flat and open basin, located in the terrain is flat, the line of sight is open, suitable for settlement, so the scale is larger, the layout is more regular, often forming a decentralized layout pattern. This type of village is mostly located in the main river channel of the basin, with better accessibility to the outside world, accounting for a higher percentage.

The analysis of the boundary morphology of the settlement space in Fujian mountainous areas is shown in Table 3.

Table 3: Analysis of boundary morphological characteristics of mountain settlement

Spatial type	Boundary morphology	Village	Area (A)/m^2	Perimeter (P)/m	Aspect ratio (λ)	Shape Index (S)
Piedmont riparian type	A finger-like settlement with a zonal tendency	P	332901.4152	2927.5523	2.3054	3.1439
		AB	140010.6796	2033.5703	2.4841	2.6395
Valley flat dam type	Finger-like settlement without definite orientation	V	188899.8502	2780.2755	1.9177	2.3857
Mountain type	Band settlement	S	249260.4517	2749.4421	2.7261	1.8238
		T	278060.8930	3023.1713	2.7602	1.7692
		G	77042.0510	1205.6118	4.4697	1.6960
		N	195112.5580	2654.9924	3.0149	1.6190
		M	278241.4657	2671.9550	2.6898	1.6015
		K	543416.0118	3279.2458	2.5241	1.5979
		D	416077.2044	2382.9569	2.9928	1.5539
		Q	353638.7902	3367.6300	4.9128	1.5524
		B	105941.3946	1216.9707	2.0379	1.5335
		R	14937.4968	693.6824	2.8269	1.4470
		A	152780.5226	2242.7231	2.2776	1.4317
		O	139492.3339	1849.2579	5.0315	1.3971
		X	111662.2160	3723.2026	2.4096	1.3661
		AD	143437.0255	2083.6707	2.0594	1.3536
		I	59329.1090	1249.1002	2.9263	1.2552
		Y	198883.0962	2882.5110	2.1439	1.2124
		AC	126384.7807	2229.0466	4.8094	1.1356
		Z	86534.9441	1160.6540	3.3973	1.1306
		U	52220.1750	1932.1009	2.8766	1.1133
Valley flat dam type	A cluster settlement with a zonal tendency	C	303926.5941	3431.8423	1.5815	1.8050
		W	458416.7504	3277.9894	1.9811	1.7565
		E	124999.9398	1519.1325	1.9703	1.6177
		H	790585.9057	3562.6925	1.7775	1.4293
		F	199627.8664	4179.5264	1.8569	1.2256
		L	1140999.8652	4298.9560	1.9901	1.0550
		J	56526.7480	1140.5443	1.8194	1.0424
Mountain type	Cluster settlement	AE	136017.1894	2312.8224	1.0320	1.7695

The foothill riparian-type settlements, such as P and AB, had an average shape index of 2.89, which was significantly higher than the other types, indicating that they were restricted by the rivers and mountains and showed a narrow and long belt-like character, and the aspect ratio λ averaged 2.39, which further supported this trend.

River valley flat dam type settlements, such as V and C, are generally larger in area, e.g., V=188,899.85m², C=303,926.59m², but the shape index S is medium on average at 1.54, suggesting that their spatial development is more free, but they still retain a certain amount of geometrical regularity due to the flatness of the terrain.

Mountain-type settlements, such as villages S, T, and G, have generally higher aspect ratio λ, with an average of 2.99, but lower shape index S, with an average of 1.47, reflecting that they are restricted by complex topography, and their boundary morphology tends to be discrete or irregular, e.g., the village G, with an aspect ratio λ = 4.4697 and a shape index S = 1.6960, presents extreme narrowness and length characteristics.

Overall, band and finger-like boundaries are the dominant patterns. The foothills and riverbank type settlements (e.g., AB, P) have high aspect ratios and high shape indices due to geographic constraints, while the valley and dam type (e.g., V) has a larger area but is less affected by natural conditions, and the boundary expands more freely. Mountain-type settlements (e.g. S, T), on the other hand, tend to have a decentralized spatial structure due to complex topography and low integration.

III. C. 2) Quantitative analysis of the internal spatial structure of settlements

Through the quantitative classification and feature summary of external boundary morphology, this section further focuses on the internal spatial structure of the settlements to reveal the functional logic and spatial organizational efficiency of different settlement types with the help of spatial syntactic parameters such as integration degree and comprehensibility degree. The quantitative analysis values of syntactic parameters of each sample village are shown in Table 4.

Table 4: The quantized analysis values of syntactic parameters of each sample village

Spatial type	Village	Number of axes	Average global integration degree	Average global selectivity	Intelligibility	Average depth	Link value
Piedmont riparian type	P	41	0.912	184.77	0.901	2.08	2.81
	AB	36	0.879	146.48	0.911	3.77	2.33
Valley flat dam type	V	48	0.840	259.04	0.909	4.56	2.16
Mountain type	S	48	0.818	365.11	0.866	4.65	2.76
	T	51	0.812	391.35	0.836	4.68	2.90
	G	51	0.808	557.45	0.830	5.67	2.12
	N	56	0.769	628.81	0.794	6.15	2.23
	M	64	0.718	657.11	0.736	7.10	2.28
	K	70	0.713	692.30	0.735	7.31	2.17
	D	71	0.703	737.61	0.723	8.09	2.62
	Q	81	0.700	924.37	0.693	8.21	2.29
	B	90	0.692	1120.76	0.689	8.89	2.75
	R	90	0.709	1167.75	0.679	9.42	2.27
	A	104	0.631	1204.57	0.599	10.08	2.18
	O	108	0.599	1312.32	0.522	10.49	2.44
	X	118	0.584	1654.60	0.379	10.65	2.61
	AD	123	0.538	1658.96	0.358	10.70	2.65
	I	125	0.494	1669.79	0.333	10.86	2.12
	Y	145	0.486	1671.71	0.306	11.04	2.43
	AC	133	0.465	1707.14	0.295	11.71	2.75
	Z	143	0.405	1745.38	0.282	11.99	2.52
	U	143	0.405	1835.79	0.225	12.41	2.26
Valley flat dam type	C	152	0.371	2031.92	0.221	13.17	2.54
	W	153	0.353	2161.55	0.189	13.27	2.84
	E	155	0.247	2213.44	0.188	14.81	2.55
	H	169	0.324	2217.42	0.167	15.01	2.51
	F	176	0.322	2246.61	0.164	15.55	2.38
	L	181	0.317	2346.70	0.154	15.64	2.14
	J	185	0.316	2350.33	0.137	16.09	2.26
Mountain type	AE	195	0.308	2376.58	0.122	17.64	2.37

The foothill riparian type settlement has the highest global integration, with the global integration of village P and village AB being 0.912 and 0.879 respectively, and the comprehensibility of 0.901 and 0.911, which is close to 1. This indicates that its spatial logic is clear, and it is easy to infer the overall structure through the local features. The number of axes of village P is less, 41, and the average depth is 2.08, further verifying its spatial compactness.

The integration degree of river valley flat dam type settlements is in the middle, such as 0.840 for village V and 0.371 for C, but the difference in the number of axes is significant. The low integration degree of 0.371 and high average depth of 13.17 of village C reflect its spatial discrete, which is consistent with the medium its large area of 303,926.59m² and low shape index of S=1.8050.

Mountain type settlements have the lowest integration with an average of 0.618 and comprehensibility with an average of 0.551, decreasing with the number of axes. For example, Village G has 51 axes and an integration of

0.808, while Village N has 56 axes integration decreases to 0.769, suggesting that increased road network complexity in a mountainous environment leads to decreased accessibility.

In general, foothills and riverbank type settlements form compact space due to geographic constraints, with both high integration and comprehensibility; valley and dam type settlements have large spatial scales but loose structures due to free land use; and mountain type settlements have a large number of axes and low integration due to complex topography, making spatial logic difficult to be perceived locally.

III. D. Quantitative results for colony space

A village was selected as the study object from each boundary pattern and its linear fit was plotted, the linear fits for village P, village V, village S, village C and village AB are shown in Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8.

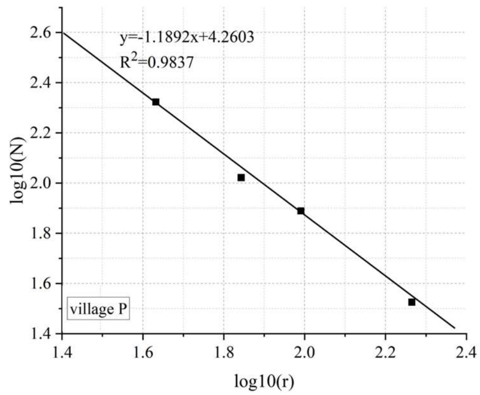

Figure 4: Linear fitting of village P

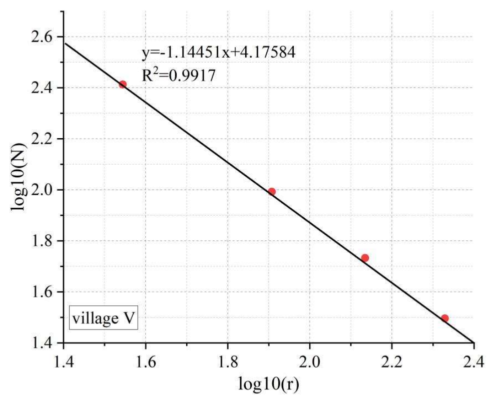

Figure 5: Linear fitting of village V

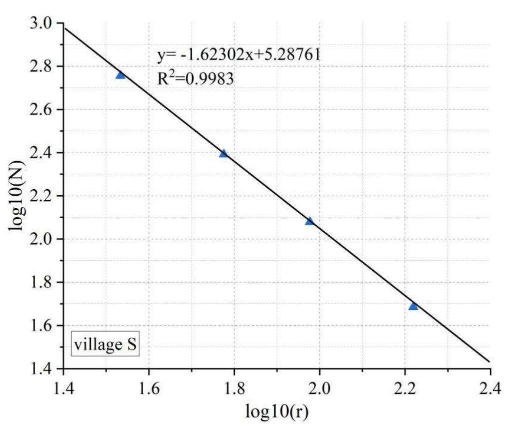

Figure 6: Linear fitting of village S

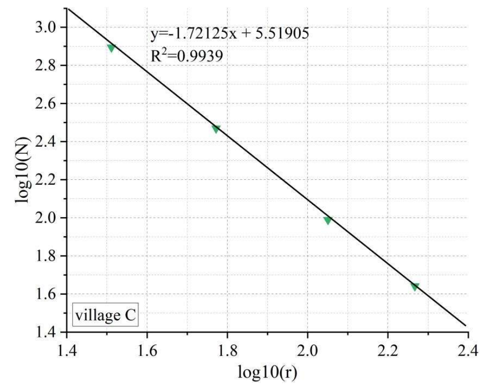

Figure 7: Linear fitting of village C

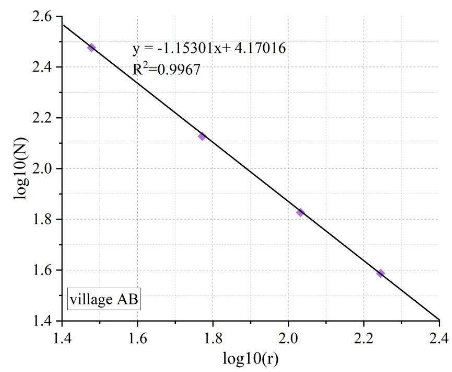

Figure 8: Linear fitting of village AB

The lattice dimension of the foothill riparian-type cluster P, which is a finger-like cluster with a banding tendency, is 1.1892; the R^2 of the goodness-of-fit is 0.9837; the lattice dimension of the valley flat dam-type cluster V, which is a finger-like cluster with no clear tendency, is 1.1445; the R^2 of the goodness-of-fit is 0.9917; the lattice dimension of the mountainous-type cluster S, which is a banding cluster, is 1.6230; the R^2 of the goodness-of-fit is 0.9983; the lattice dimension of the valley-flat dam-type colony C with clustered aggregates with a tendency to banding is 1.7213; the R^2 for the goodness-of-fit is 0.9939; and the lattice dimension of the mountain-type colony AB with clustered aggregates is 1.1530; the R^2 for the goodness-of-fit is 0.9967.

IV. Conclusion

Through quantitative analysis and spatial syntactic modeling, this study systematically reveals the spatial morphological characteristics and functional logic of mountain settlements in Fujian. The main conclusions are as follows.

Based on the statistical analysis of 30 samples, the mean value of the settlement shape index is 1.58, and the critical value S=2 distinguishes finger-like and cluster-like settlements. The foothill riverbank type settlements, such as P and AB villages, present high aspect ratio λ=2.39 and high shape index S=2.89 due to geographic constraints, while the mountain type settlements, such as G village, have a low degree of integration as low as 0.808 due to complex topography, with significant spatial discrete features.

Spatial syntactic analysis shows that the foothills and riverbank type settlements have the highest global integration degree, with P village reaching 0.912, comprehensibility close to 1, and clear spatial logic; river valley and flat dam type settlements such as C village have a large scale, with an area of 303,926.59m², which leads to a low degree of integration of 0.371, and a high complexity of axes, with 152 axes; and the degree of integration of the mountain type settlements decreases significantly with the increase in the number of axes, such as N village with 56 axes, and a high shape index of S=2.89, with significant spatial discrete features. For example, N village has 56 axes with 0.769 integration degree.

The study verified the applicability of the combination of quantitative indicators and spatial syntax through multi-scale boundary contour analysis, spatial topology modeling and GIS visualization, providing scientific basis for the spatial optimization and cultural heritage protection of mountainous settlements.

Funding:

This research was funded by the National Natural Science Foundation of China (NSFC) (Grant No. 32401642); Fujian Provincial Project of Xi Jinping Thought on Socialism with Chinese Characteristics for the New Era (No. FJ2022XZB069); Fujian University of Technology 2023 University-level Undergraduate Education and Teaching Research Project (No.2023JG012); Zhejiang University of Science and Technology 2024 International Education Research Special Course (No.2024IERC004).

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