

Article

Multi-Scale Gradient Patterns of Building Morphology in Town Peripheries and Their Association with Economic Development: A Case Study of 13 Prefecture-Level Cities in Jiangsu Province, China

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Abstract

This study examined the building morphology of 1491 town-level administrative units across 13 prefecture-level cities in Jiangsu Province, China, within inner-boundary belts of 50, 100, 150, and 200 m. Four indicators including mean building spacing, mean building height, mean building volume, and mean building shape index were calculated, and their gradients, correlations, economic associations, and inter-town similarity networks were analyzed. Northern Jiangsu exhibits greater within-city variation in peripheral building morphology than Southern Jiangsu. With increasing belt width, building volume increased and spacing decreased; while height and shape index showed no consistent monotonic trends across all cities. Mean spacing was negatively correlated with height, volume, and shape index, whereas height, volume, and shape index are positively interrelated. In higher per-capita GDP cities, the negative correlation between spacing and shape index and the positive correlation between height and shape index were more pronounced, although this finding is exploratory given the 13-city sample. Similarity network analysis reveals clear clustering by prefecture-level city, with within-city similarity significantly higher than between-city similarity across all belt widths. Similarity ranking remained consistent across belt widths, although some local restructuring occurs between the immediate boundary zone and interior. These findings contribute to urban morphology research and planning policy.

Keywords: building morphology; town periphery; multi-scale gradient; economic development; morphological similarity network



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1. Introduction

Urbanization profoundly transforms the functionality and vitality of cities [1–3]. As the most fundamental structural units of urban form [4,5], buildings are an important entry point for interpreting urban complexity [6]. Characteristics such as spatial distribution, height, volume, and footprint shape of buildings directly reflect the construction density and spatial order of a given area.

Buildings, together with the urban street spaces they subdivide and define, are fundamental components of urban form and essential elements of urban morphological research [7,8]. The spatial distribution and combinations of buildings with specific functions,

including residential buildings, facilitate an understanding of the spatial morphology of a given area [9]. In many studies, the relationship between building form and spatial distance has served as an important lens for interpreting urban morphology [10,11]. Building morphology is frequently analyzed in conjunction with land use and transportation networks to examine the urban structure of a locality [12,13]. Meanwhile, examining urban morphological characteristics from a similarity perspective has become an important analytical strategy [14,15].

Employing appropriate indicators and computational methods can enable building characteristics to be quantified within a given area [16]. Two-dimensional descriptors of building morphology include building density [17], mean radius of the building footprint (i.e., the average distance from the vertices of the building footprint to its centroid) [18], and shape index of the building footprint [19]. Building height is one of the most important three-dimensional indicators. Average height can be used to characterize the spatial form of an area [20,21], or as part of a more complex analytical framework [22]. Building height is closely related to volume [23].

Generally speaking, the relationship between urban construction and socioeconomic factors is highly significant [24], and the development of the latter strongly promotes urban expansion [25]. With respect to urban spatial structure and building morphology, their association with the economy is also notably close [26]. Reasonable spatial structures and building layouts generally facilitate the efficient operation of urban economic activities [27]. The relationship between building morphology and the economy can facilitate the classification [28] and interpretation [29] of urban spaces with different morphological characteristics. For example, Wurm et al. and Li et al. conducted in-depth analyses of slums within the framework of urban morphology [30,31]. Building height, an important indicator of building morphology, is clearly influenced by economic development [32] and is closely related to urban economic and social vitality [33,34]. On the other hand, some studies suggest that China's economic development has stabilized since 2018, leading to a slowdown in the growth rate of comprehensive urban development intensity, which is partly constituted by building volume and other factors [35].

Urban and building morphology often need to be understood in relation to specific spatial locations. Among these locations, the fringe belt, which is characterized by highly complex elements [36] and serves as a key counterpart to the central area, has long been a research focus in land planning, urban planning, and urban geography. The concept of the fringe belt was first proposed by Conzen in the 1960s [37,38] and further developed by Whitehand [39]. Studies on fringe belts have concentrated mainly on ecological landscapes [40], changes in land use structure [41], and the distribution of industrial activities [42]. These studies have been conducted predominantly at the city scale [43], with limited attention to town-level units and even less focus on the building morphology of fringe belts. Another important concept that frequently intersects with fringe-belt research is the urban–rural interface. Located at the expanding edge of cities, the urban–rural interface faces challenges, such as the loss of agricultural land [44] and land-use conflicts [45]. With socioeconomic development, the location of the urban–rural interface also changes [46]. Together, these different perspectives indicate that the fringe belt is a geographical location that warrants in-depth analysis.

Previous studies have often treated the fringe belt as a transitional zone at the city scale. However, in the process of China's urbanization, town-level administrative units, which function as grassroots nodes of the administrative hierarchy, contain fringe belts that are simultaneously frontier zones and relatively well-preserved rural areas, making them a suitable scale for observing building morphology. Indeed, the fringe belts of town-level units are both frontiers of urban expansion and areas where rural landscapes

remain comparatively intact. Under different levels of economic development, building morphology at town peripheries may vary substantially; the edges of towns in economically advanced regions may already exhibit peri-urban characteristics, whereas those in less-developed regions may still maintain traditional rural settlement patterns. Such differences are likely to be manifested not only in the absolute values of individual morphological indicators, but also in the structural relationships among them. Specifically, the strength of inter-indicator correlations is related to the level of economic development. For these reasons, town peripheries constitute an ideal setting for examining the relationships among building morphology, economic development, and spatial location.

In summary, although considerable progress has been made in research on building morphology, its relationship with economic development, and fringe belts, three research gaps remain. First, existing studies have mostly taken cities as the core analytical unit, with limited systematic characterization and cross-city comparison of building morphology at the town scale. Second, fringe-belt research has focused primarily on macro-level elements, such as land use and ecological landscapes, with limited attention on building morphology. Third, the strength of inter-indicator correlations and their relationship to economic development have not been adequately examined at the town periphery scale.

Therefore, this study focused on 1491 town-level administrative units across 13 prefecture-level cities in Jiangsu Province, China, and examines their peripheral building morphology in relation to multi-scale gradients, inter-indicator correlations, associations with economic development, and inter-town morphological similarity. The research framework is illustrated in Figure 1.

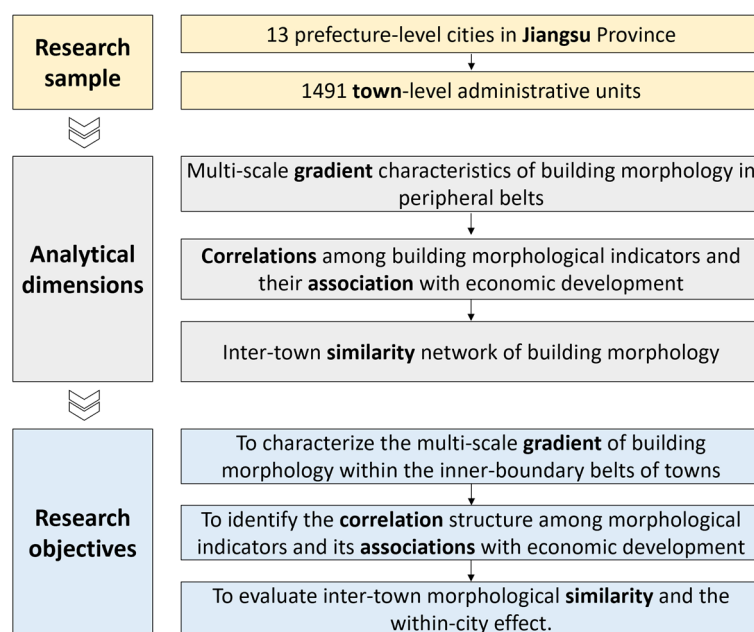


Figure 1. Research framework.

The following hypotheses were proposed:

- H1.** Building morphology exhibits a regular gradient from the town boundary toward the town center.
- H2.** The structural relationships among building morphological indicators are stronger in more economically developed cities.
- H3.** Towns within the same prefecture-level city exhibit greater similarity in peripheral building morphology than towns in different cities.

2. Materials and Methods

2.1. Study Area

This study focused on 13 prefecture-level cities in Jiangsu Province, China: Nanjing, Zhenjiang, Changzhou, Wuxi, and Suzhou in Southern Jiangsu; Yangzhou, Taizhou, and Nantong in Central Jiangsu; and Xuzhou, Lianyungang, Suqian, Huai'an, and Yancheng in Northern Jiangsu. Jiangsu Province is located on the eastern coast of China in the core area of the Yangtze River Delta (Figure 2), and is one of the most economically developed and highly urbanized provinces in the country. In 2025, the per-capita GDP (GDPPC) of the five Southern Jiangsu cities exceeded 170,000 yuan, whereas that of the five Northern Jiangsu cities fell mostly within the range of 100,000–130,000 yuan, revealing a pronounced economic gradient between the south and north. This characteristic of uneven intra-provincial development provides a valuable window through which to examine the differentiation patterns of town-edge spatial morphology at different levels of economic development.

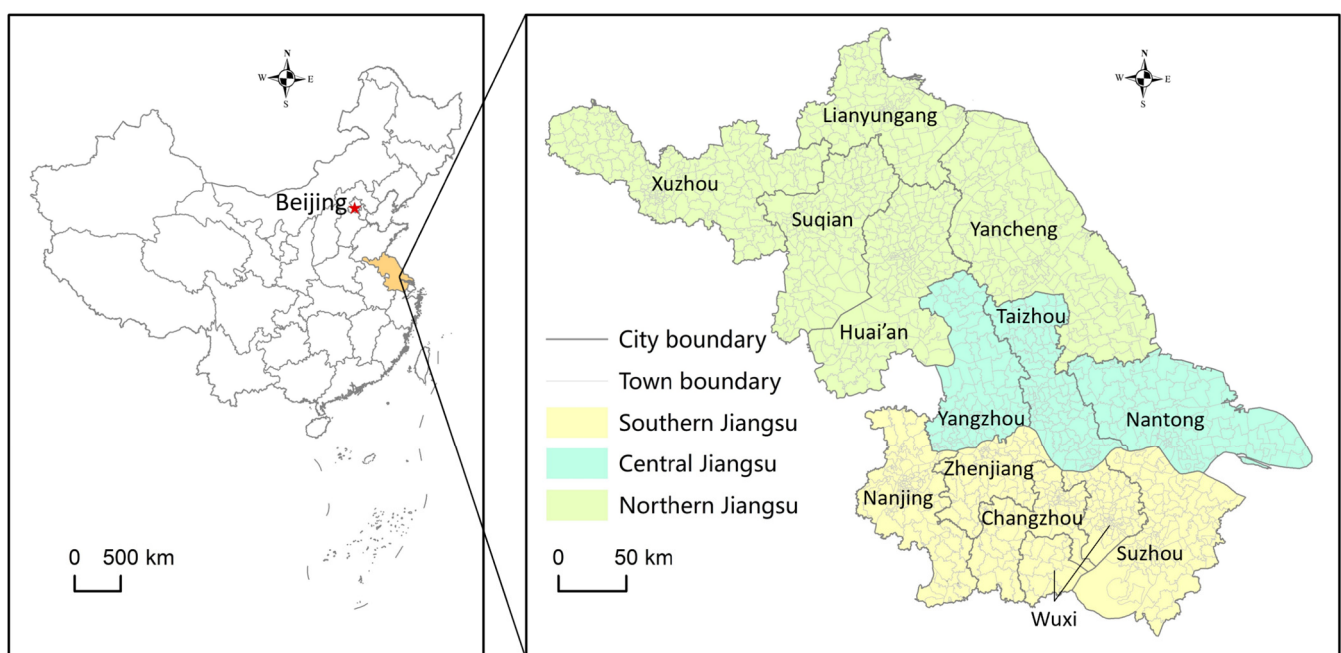


Figure 2. Jiangsu's location in China and its internal administrative divisions.

The basic spatial unit of this study was the town-level administrative unit (including designated towns and subdistricts). The town is one of the lowest tiers of China's administrative hierarchy. The peripheral space of town-level administrative units is both the frontier of urban expansion and an area where rural building forms remain relatively intact.

2.2. Data

The building footprints and heights used in this study were obtained from the 3D-GloBFP dataset (<https://doi.org/10.5281/zenodo.11397014>) (accessed on 3 June 2026), which provides the first global three-dimensional building footprint map for the year 2020 [47]. The building footprints were derived primarily from Microsoft Building Footprints, with an average precision of about 95% and an IoU (Intersection over Union) of about 65%. For China, because Microsoft Building Footprints does not fully cover East Asia, the footprints were obtained from Shi et al. [48], whose deep-learning-based extraction achieved precision and recall above 80% across different cities. Building heights in 3D-GloBFP were estimated at the individual building level by integrating multisource remote-sensing features—including Sentinel-1 SAR, Sentinel-2 optical imagery, SRTM DEM, ALOS DSM, and auxiliary socioeconomic variables—and building morphological features

within an XGBoost (eXtreme Gradient Boosting) regression framework. The height estimation models were developed for 33 global subregions and evaluated using 10-fold cross-validation, yielding R^2 values ranging from 0.66 to 0.96 and RMSEs (Root Mean Square Errors) from 1.9 to 14.6 m. These figures indicate that the building height data are generally reliable for regional-scale morphological analysis, although some uncertainty remains.

2.3. Belt Construction

For each subdistrict-level unit within each city, a belt can be created by stepping a certain distance inward from its boundary. The number of buildings within this belt varies with belt width. This study considered four belt widths: 50 m, 100 m, 150 m, and 200 m (Figure 3). This belt-width configuration was determined based on the spatial scale of town-level units and existing research [49–51] on fringe belts. Details regarding the selection of 200 m as the maximum belt width, 50 m as the interval, and the use of cumulative rather than independent belts can be found in the Appendixes A–C.

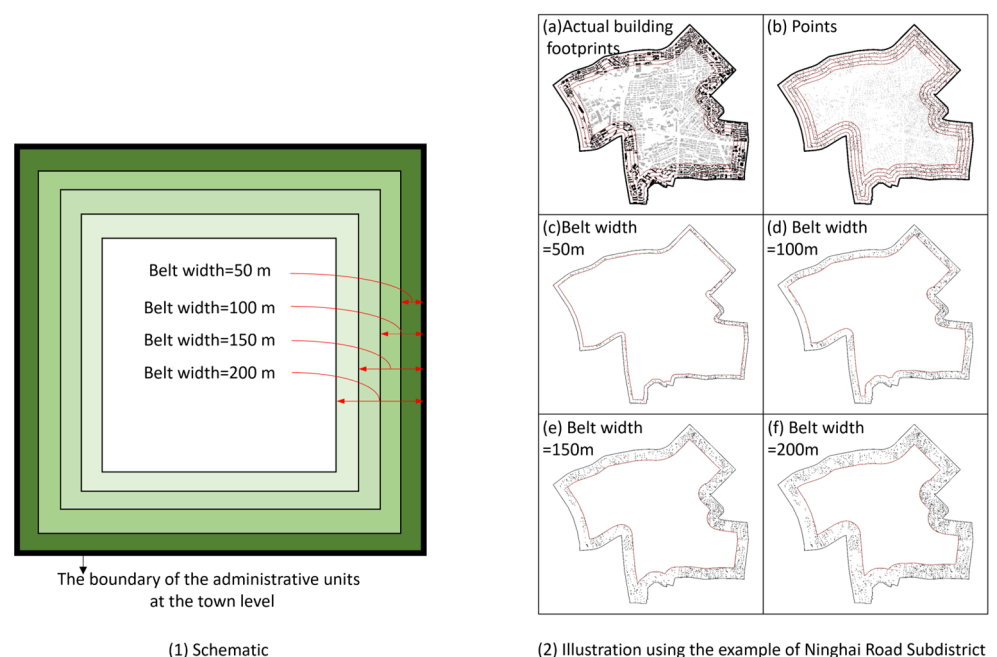


Figure 3. Belts of different widths inside the town boundary.

Note that to facilitate generation of spatial statistics and analysis, all building polygons were converted into point features, specifically, their planar geometric centroids. At smaller belt widths (e.g., 50 m), it is possible that no buildings are present within the inner-boundary belt of a town-level administrative unit. In such cases, the relevant morphological indicators cannot be calculated. In this study, the descriptive statistics of building morphology at town peripheries across different cities (i.e., the box plots presented later) included all 1491 town-level units. In the similarity analysis, however, 28 town-level units were excluded to ensure valid town pairs (Appendix D). The exclusion criterion was that a town-level unit was removed if any morphological indicator at any belt width had a missing value. The proportion of town-level units affected by this circumstance was very low; therefore, the exclusion did not affect the subsequent calculations or analytical conclusions.

2.4. Core Indicators

Mean building spacing (x_{1-ave}) was defined as the average of all pairwise Euclidean distances between the planar geometric centroids of buildings within a given inner-boundary belt (unit: meters). Mean height (x_{2-ave}) was defined as the average height

of different buildings within the belt (unit: meter). Mean volume (x_{3-ave}) was defined as the average volume of different buildings within the belt (unit: m^3). Building volume was calculated as the building footprint area multiplied by the building height. Mean shape index (x_{4-ave}) was defined as the average shape index of different buildings within the belt. To eliminate the influence of building size on shape measurement, the normalized shape index was calculated as $P / (2\sqrt{\pi A})$, where P is the perimeter and A is the area of the building footprint [5]. This index equals 1 for a circle and approximately 1.13 for a square; larger values indicate more irregular plan shapes, whereas smaller values indicate more regular plan shapes.

2.5. Correlation Coefficients

Examining the correlations among different indicators is a common and effective approach in building morphology studies [52]. We calculated Spearman rank coefficients [20] among the four core indicators for all 13 prefecture-level cities in Jiangsu for each of the four belt widths. Furthermore, we analyzed the correlations between these pairwise correlation coefficients and the level of economic development (expressed in terms of GDPPC, with the data year set to 2020 to maintain consistency with the building data).

2.6. Morphological Similarity in the Inner-Boundary Belts of Town-Level Administrative Units

2.6.1. Similarity Calculation

To quantify the similarity of building morphology between any two towns at a given belt width, a feature vector was first constructed for each town based on the four building-form indices (x_{1-ave} , x_{2-ave} , x_{3-ave} and x_{4-ave}), after which pairwise similarities were computed as follows.

For a belt width of $b \in \{50, 100, 150, 200\}$ m, the building morphological profile of town i was represented by the four average indices within that belt:

$$v_i(b) = (x_{1-ave,b}, x_{2-ave,b}, x_{3-ave,b}, x_{4-ave,b})_i \quad (1)$$

To eliminate differences in scale and unit, the morphological index of each building was standardized within each belt as follows:

$$z_{i,k,b} = \frac{v_{i,k,b} - \mu_{k,b}}{\sigma_{k,b}} \quad (2)$$

Here, $\mu_{k,b}$ and $\sigma_{k,b}$ are the mean and standard deviation, respectively, of index k across all towns at belt width b .

After standardization, the building morphological distance between towns A and B at belt width b was defined as the Euclidean distance:

$$d_b(A, B) = \sqrt{\sum_{k=1}^4 (z_{A,k,b} - z_{B,k,b})^2} \quad (3)$$

The distance was converted to a building morphological similarity index in the $(0, 1]$ interval using a Gaussian kernel, as follows:

$$S_b(A, B) = \exp[-\lambda_b \cdot d_b(A, B)] \quad (4)$$

The scaling parameter λ_b was set as the reciprocal of the median pairwise distance for the belt:

$$\lambda_b = \frac{1}{\text{median}(d_b)} \quad (5)$$

This choice ensured comparable similarity distributions across belts while preserving reasonable sensitivity to distance. Self-similarity was defined as a score of 1.

2.6.2. Similarity Network and Key Network Metrics

To emphasize the strongest building morphological affinities, for each belt we constructed a weighted undirected network G_b , in which nodes represented towns, and each town was connected to only its top-3 most similar neighbors in terms of building morphology. The choice of $k = 3$ was based on a sensitivity analysis showing that modularity remained high and stable for $k = 1$ –5 and declined substantially for larger k (see Appendix E). Edge weights corresponded to the Gaussian kernel similarity $S_b(A, B)$.

The following topological metrics were computed to characterize the building-form similarity structure:

The weighted degree of node i was defined as:

$$w_i = \sum_{j:(i,j) \in E} S_b(i, j) \quad (6)$$

where $j : (i, j) \in E$ denotes all nodes j such that the edge (i, j) belongs to the edge set E ; that is, iterating over all neighbor nodes j that are directly connected to node i . Thus, w_i equals the sum of similarities $S_b(i, j)$ between node i and all of its directly connected neighbors. This metric indicates how strongly a town's building morphology resembles that of its closest neighbors, serving as a measure of morphological typicality or centrality.

Weighted network modularity quantifies the strength of a community structure when cities are used as predefined communities:

$$Q = \frac{1}{2m} \sum_{i,j} [S_{ij} - \frac{w_i w_j}{2m}] \delta(c_i, c_j) \quad (7)$$

where $m = \frac{1}{2} \sum_{i,j} S_{ij}$ and c_i is the prefecture-level city to which town i belongs. High magnitude Q (close to 1) indicates that the network decomposes sharply into city-based groups, implying that intracity towns share greater building morphological similarity.

The weighted clustering coefficient measures the local cohesiveness of the network [53]:

$$C = \frac{1}{n} \sum_i \frac{1}{w_i(w_i - 1)} \sum_{j,k} (S_{ij} S_{ik} S_{jk})^{\frac{1}{3}} \quad (8)$$

A large clustering coefficient implies that towns of comparably built forms tend to aggregate into tightly knit local triangular groups.

The assortativity coefficient is the Pearson correlation between the weighted degrees of connected nodes. It reveals whether high-degree nodes preferentially connect to other high-degree nodes, suggesting a core–periphery organization in building-form space.

2.6.3. Within-City Effect Testing

To test whether towns within the same prefecture-level city exhibited more similar building morphology than those in different cities, all town pairs were split into two groups: within-city (both towns belonged to the same city) and between-city (towns from different cities). For each belt, the mean similarity values of the two groups were compared using the Mann–Whitney U test [54,55].

2.6.4. Comparison Across Belt Widths

To investigate whether the building morphological similarity structure varied with the inward depth from the town boundary, cross-belt comparisons were conducted.

First, the mean and standard deviation of all pairwise building morphological similarities were computed for each belt, and their trends with increasing belt width were examined.

Second, the difference $\Delta S_b = \bar{S}_{within} - \bar{S}_{between}$ was calculated for each belt. The widening or narrowing of this gap with belt width indicated whether the intra-city convergence of building morphology strengthened or weakened deeper inside the town.

Finally, for each belt, the upper-triangle similarity values were extracted as a vector, and the Spearman rank correlation coefficient ρ computed each pair of belts. A ρ value close to 1 indicated that the relative ordering of pairwise building morphological similarities was highly consistent across depths, demonstrating strong spatial continuity of similarity patterns. A decrease in the ρ value with greater belt-width separation would signal a gradual reorganization of the similarity structure.

3. Results

3.1. Building Morphological Characteristics of the Inner-Boundary Belts at the Town Level

3.1.1. Mean Spacing

Box plots (Figure 4) illustrate the conditions of each town-level administrative unit across 13 cities in Jiangsu Province. Figure 4 presents the average straight-line distance between buildings within belts of varying widths, created by stepping inward from the town administrative boundary by 50, 100, 150, and 200 m, denoted as x_{1-ave} .

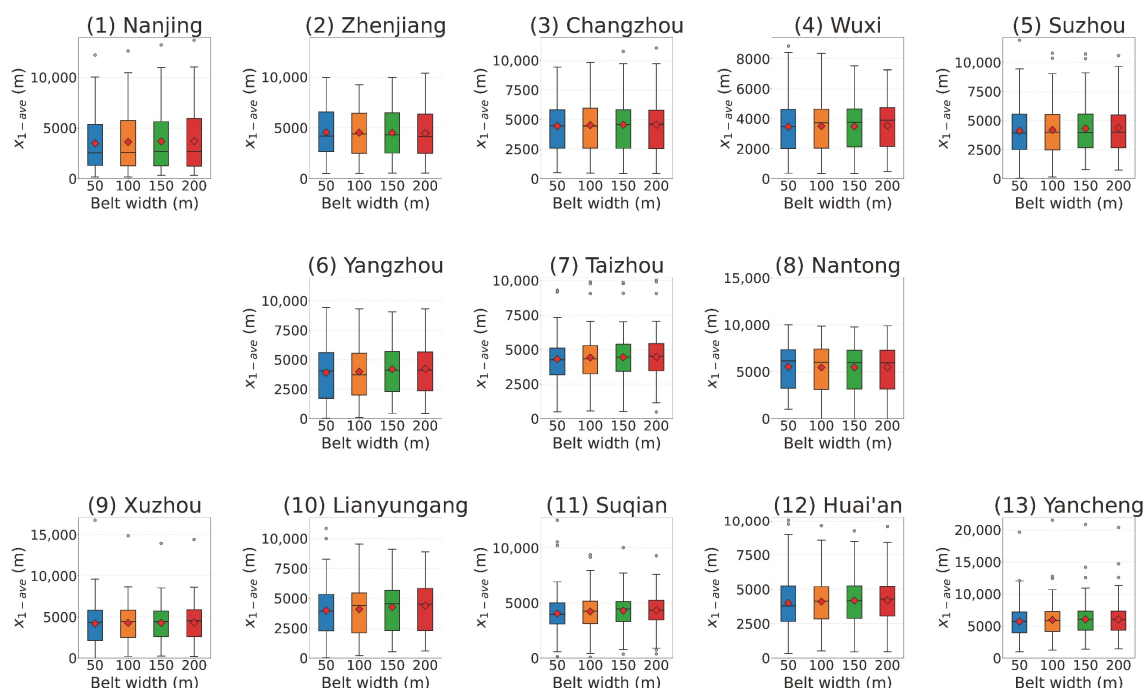


Figure 4. Box plots of mean spacing for each city at different belt widths. (Red diamonds indicate mean values, and gray circles indicate outliers beyond 1.5 times the interquartile range (IQR)).

The overall distribution of x_{1-ave} values changed slightly as the belt width increased. In most cities, high-value outliers that clearly exceeded the upper whiskers of the box were present. For example, in Xuzhou, at a belt width of 50 m, one town-level administrative unit (Gaolou Town) appeared as an outlier, with its x_{1-ave} value reaching 16,887.51 m, which is 76.03% higher than that of the second-ranked unit (Yaoji Town). However, some cities exhibited no outliers, such as Zhenjiang, Yangzhou, and Nantong. This phenomenon indicates that within these three cities, the distribution of the mean building-to-building distances in the inner boundary belts of the town-level administrative units is relatively uniform.

Another interesting comparison is between Nanjing and Nantong. As shown in Figure 4, the mean values (red diamonds) of the box plots for Nanjing lay above the median lines across all four belt widths, whereas the opposite was true for Nantong. This indicates that the x_{1-ave} values of Nanjing's town-level administrative units are more concentrated in the high-value range (e.g., the presence of some outliers increases the mean), whereas those of Nantong are more concentrated in the low-value range. Within the inner boundary belts of some town-level administrative units in Nanjing, buildings exhibited a higher degree of spatial dispersion.

3.1.2. Mean Height

Figure 5 exhibits outliers in the box plots of x_{2-ave} for all cities. Upon closer inspection, the five cities in Northern Jiangsu (Xuzhou, Lianyungang, Suqian, Huai'an, and Yancheng) exhibited a greater number of outliers than the three cities in Central Jiangsu (Yangzhou, Taizhou, and Nantong) and the five cities in Southern Jiangsu (Nanjing, Zhenjiang, Changzhou, Wuxi, and Suzhou). This indicates a pronounced polarization in Northern Jiangsu, namely, within the inner boundary belts of some town-level administrative units, the average building height far exceeds that of other units. For example, in Yancheng, Wuxing Town and Xinghe Town have average building heights of 16.97 m and 15.57 m, respectively, within the 50 m belt, substantially higher than the overall mean of 6.89 m. Thus, among the town-level administrative units of Northern Jiangsu, there exists a pronounced disparity in building height morphology, at least for buildings situated within the inner boundary belts.

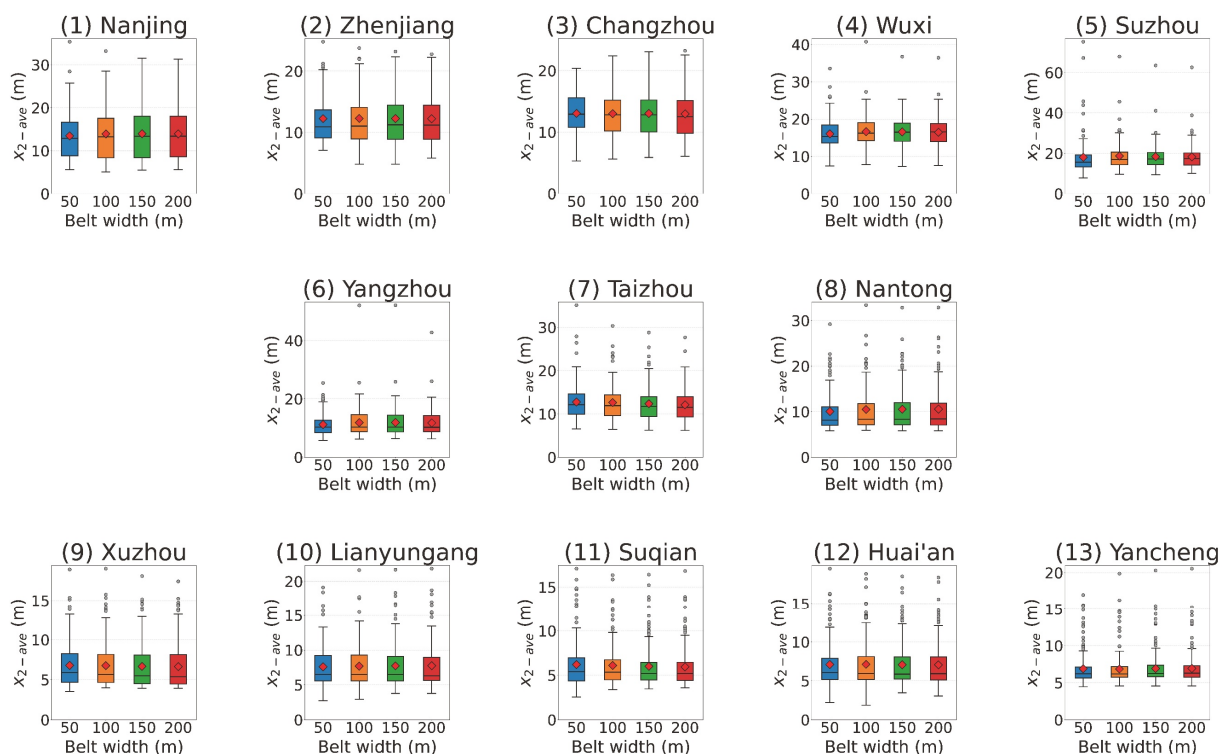


Figure 5. Box plots of mean height for each city at different belt widths. (Red diamonds indicate mean values, and gray circles indicate outliers beyond 1.5 times the interquartile range (IQR)).

Note that, across all cities, the mean values, x_{2-ave} , lay above the medians (except for Wuxi at belt widths of 150 and 200 m). This observation is consistent with the presence of high-value outliers, as both features indicate a right-skewed distribution of building heights.

3.1.3. Mean Volume

As the belt width increased, the number of buildings encompassed within the inner boundary belt of the town-level administrative units also increased. The average building volume (x_{3-ave}) also increased in many cities (Figure 6). For instance, in Changzhou, the mean values of x_{3-ave} at belt widths of 50 m, 100 m, 150 m, and 200 m were 6640.73 m³, 7406.21 m³, 7720.34 m³, and 7808.10 m³, respectively. This reflects an intuitive pattern: within a town-level administrative unit, buildings tend to have relatively larger volumes closer to the town center.

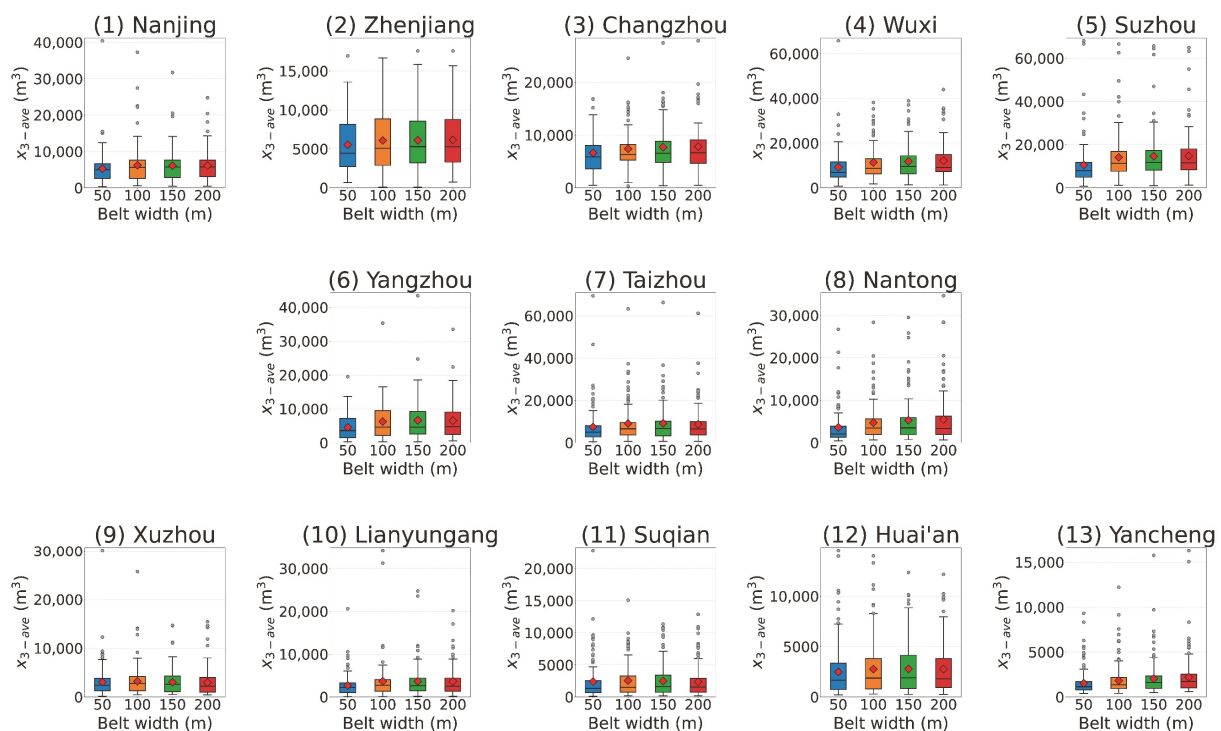


Figure 6. Box plots of mean volume for each city at different belt widths. (Red diamonds indicate mean values, and gray circles indicate outliers beyond 1.5 times the interquartile range (IQR)).

Similar to x_{2-ave} , many cities also exhibited varying numbers of high-value outliers that increase the mean. As shown above, the mean values were predominately located above the median values. This phenomenon was particularly pronounced in Nanjing, Changzhou, Wuxi, Suzhou, Taizhou, Nantong, Xuzhou, Lianyungang, Suqian, Huai'an, and Yancheng. This indicates that in these cities, the inner boundary belts of many town-level administrative units contain large-volume buildings, such as residential tower blocks and industrial factory buildings. In contrast, Zhenjiang and Yangzhou displayed relatively fewer outliers, suggesting that in these two cities, the average building volume within the inner boundary belts of the town-level administrative units varies to a lesser degree.

3.1.4. Mean Shape Index

Compared with Southern Jiangsu, cities in Northern Jiangsu had more town-level administrative units whose x_{4-ave} values were high-value outliers (Figure 7). In Central Jiangsu, Yangzhou exhibited high-value outliers at belt widths of 100, 150, and 200 m, all of which were well above the upper whiskers of the boxes. This is mainly because the building footprints within the inner-boundary belts are relatively irregular in some town-level administrative units. Additionally, in Central and Northern Jiangsu, the mean points of x_{4-ave} were mostly located above the median points, indicating that the distributions

of x_{4-ave} values among town-level administrative units in these regions are more clearly right-skewed.

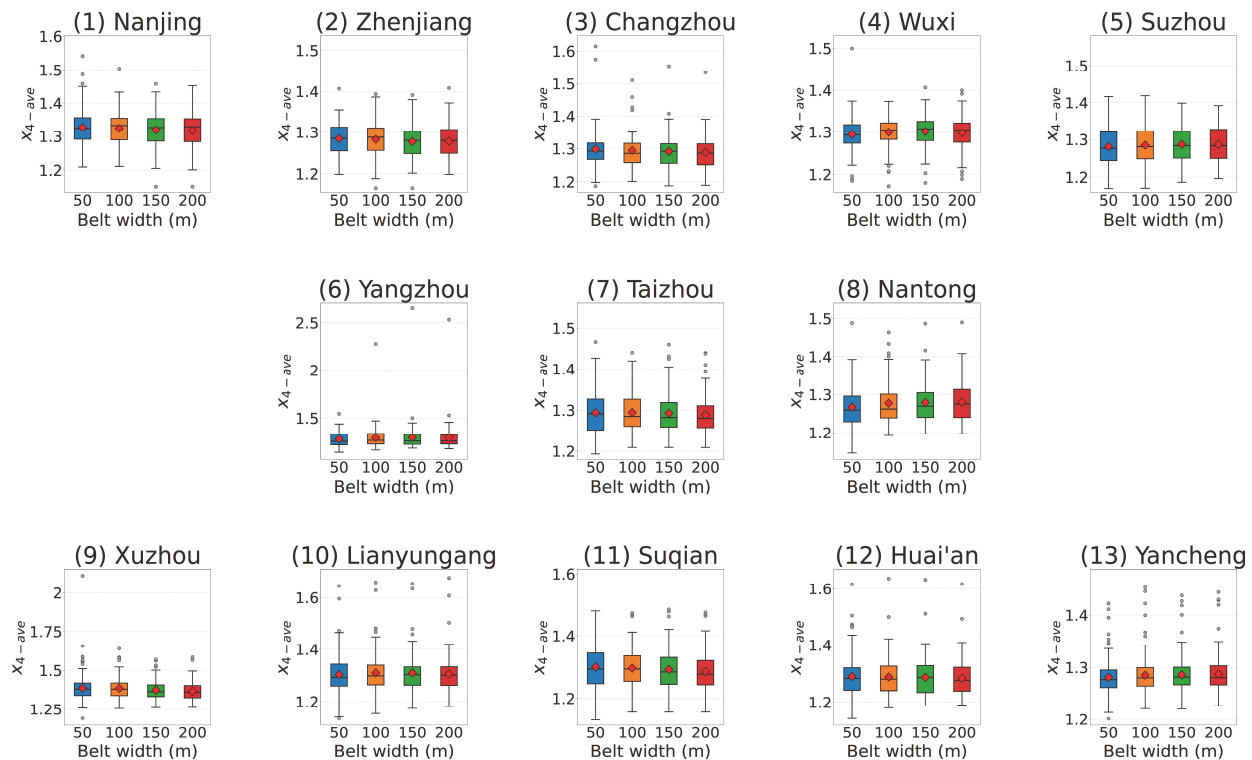


Figure 7. Box plots of mean shape index for each city at different belt widths. (Red diamonds indicate mean values, and gray circles indicate outliers beyond 1.5 times the interquartile range (IQR)).

3.2. Correlations Among Building Form Indicators Within the Inner-Boundary Belts and Their Relationship with Local Economic Development

3.2.1. Correlations

Figure 8 shows that the pairwise correlations among the four building morphology indicators were broadly consistent across belt widths. Specifically, x_{1-ave} was negatively correlated with x_{2-ave} , x_{3-ave} , and x_{4-ave} , whereas x_{2-ave} , x_{3-ave} , and x_{4-ave} were positively correlated with one another.

These correlations reflect the mixed characteristics of building morphology within the inner-boundary belts of town-level units. This zone is typically occupied by a variety of building types, where traditional rural houses and scattered auxiliary structures coexist with relatively taller and denser newly built residences or small workshops. In areas with larger building spacing, buildings tend to be simple rectangular farmhouses or sheds, resulting in lower shape indices. Conversely, in areas with smaller spacing, buildings are often constrained by irregular plot boundaries and mixed functions, leading to more complex footprints and higher shape indices. This helps explain the negative correlation between x_{1-ave} and x_{4-ave} .

These relationships remained stable across the four belt widths, suggesting that they are not driven by variations in belt width but instead reflect persistent associations between building types and spatial adaptation within the town periphery.

3.2.2. Relationship Between Correlations and Urban Economic Development

To avoid the limitations of small sample size and heteroscedasticity, we used Spearman rank correlation to assess the monotonic associations between indicator-pair correlations and GDPPC (Table 1). The correlation between x_{1-ave} and x_{4-ave} showed a significant

negative association with GDPPC (ρ ranged from -0.7473 to -0.7967 , $p < 0.01$ across all belt widths). Conversely, the correlation between x_{2-ave} and x_{4-ave} showed a significant positive association with GDPPC (ρ ranged from 0.6099 to 0.8187 , with $p < 0.05$ in all four belts). These results suggest that in more economically developed cities, larger building spacing is associated with more regular footprints, whereas taller buildings are associated with more irregular footprints. No significant associations were found for the remaining indicator pairs.

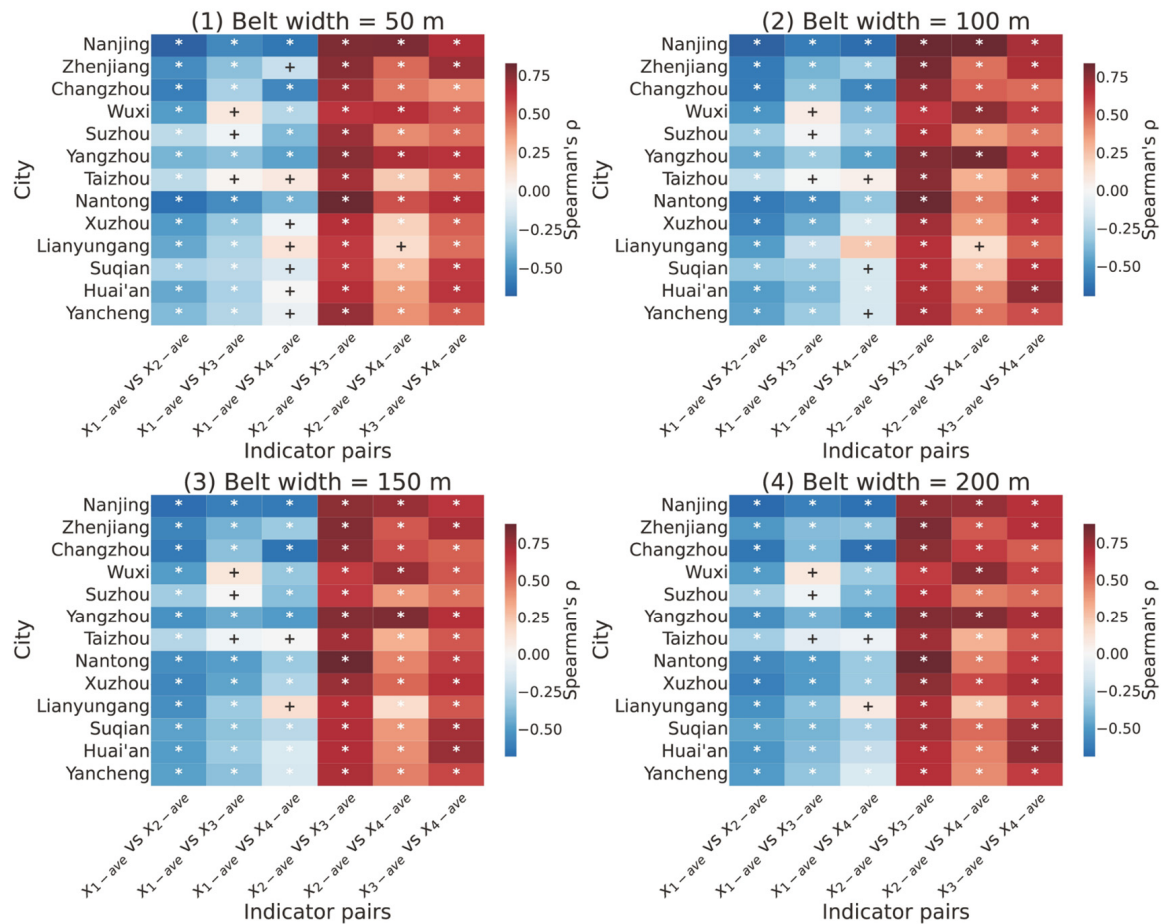


Figure 8. Heatmap of correlation coefficients among indicators. * $p < 0.1$, + $p > 0.1$. (When calculating the Spearman rank correlation coefficient for each pair of indicators, we used pairwise deletion to handle missing values; that is, for each pair of indicators, only towns with non-missing values for both indicators were used in the calculation.).

Table 1. Relationship between inter-indicator correlations of building morphology and GDPPC across different belt widths.

Pair	Belt Width = 50 m	Belt Width = 100 m	Belt Width = 150 m	Belt Width = 200 m
x_1-ave – x_2-ave & GDPPC	−0.3297	−0.3077	−0.2143	−0.1264
x_1-ave – x_3-ave & GDPPC	−0.0879	0.0879	0.0000	0.1648
x_1-ave – x_4-ave & GDPPC	−0.7473 ***	−0.7912 ***	−0.7967 ***	−0.7637 ***
x_2-ave – x_3-ave & GDPPC	0.5055 *	0.2473	0.0824	−0.0165
x_2-ave – x_4-ave & GDPPC	0.8187 ***	0.7473 ***	0.6099 **	0.6154 **
x_3-ave – x_4-ave & GDPPC	0.0879	−0.1154	−0.4505	−0.4121

Note: ***, $p < 0.01$; **, $p < 0.05$; *, $p < 0.1$.

3.3. Similarity of Building Morphology Among Inner-Boundary Belts of Towns and Its Relationship with Same-City Affiliation and Belt Width

3.3.1. Similarity

To quantify morphological similarity among town-level administrative units, we constructed weighted similarity networks for each belt width using all pairwise similarities derived from the four indicators. Following a sensitivity analysis of the number of nearest neighbors k (see Appendix E), the top-3 network was selected as the representative configuration, because the modularity Q remained high and stable for $k = 1\text{--}5$ and declined sharply as k increased, approaching zero for the full network. This pattern indicates that weak similarity edges obscure the community structure, and that retaining only the strongest connections is necessary to reveal the underlying morphological grouping.

Table 2 reports the key network metrics for the top-3 networks. Across all four belt widths, the modularity Q ranged from 0.1881 to 0.2355, substantially higher than expected by chance, indicating that towns are clearly clustered by prefecture-level city in terms of peripheral building morphology. The assortativity coefficient was positive across all belt widths, indicating that morphologically typical towns tend to connect with one another and form a core group. The average weighted clustering coefficient remained relatively stable across belt widths, indicating that locally tight clusters of highly similar towns exist regardless of observation depth.

Table 2. Network attributes ($k = 3$).

Belt Width	Average Weighted Clustering Coefficient	Modularity (Q)	Assortativity
50 m	0.3240	0.1881	0.1182
100 m	0.3259	0.2126	0.0814
150 m	0.3258	0.2178	0.0653
200 m	0.3196	0.2355	0.0856

3.3.2. Relationship Between Similarity City Membership

Mann–Whitney U tests revealed that within-city similarity ($\bar{S}_{within}$) was significantly higher than between-city similarity ($\bar{S}_{between}$) across all four belt widths ($p < 0.001$), indicating strong morphological convergence at the prefecture-city level (Table 3).

Table 3. Results of Mann–Whitney U tests.

Belt Width	$\bar{S}_{within}$	$\bar{S}_{between}$	ΔS_b	p Value
50 m	0.4523	0.3772	0.0752	0
100 m	0.4612	0.3770	0.0843	0
150 m	0.4634	0.3763	0.0872	0
200 m	0.4642	0.3767	0.0875	0

Note: All values are rounded to four decimal places.

Collectively, the network metrics and similarity comparisons demonstrate that the building morphology of town peripheries is organized into clear city-based similarity groups and that this organization is robust to the choice of network parameters. The observed patterns of modularity and assortativity, along with the significant within-city effect, support the conclusion that prefecture-level city boundaries play a strong constraining role in shaping peripheral building morphology.

3.3.3. Relationship Between Similarity and Belt Width

Figure 9 shows that all Spearman's ρ values exceeded 0.74 and were significant, indicating that the rank ordering of inter-town morphological similarity was highly consistent across the four belt widths.

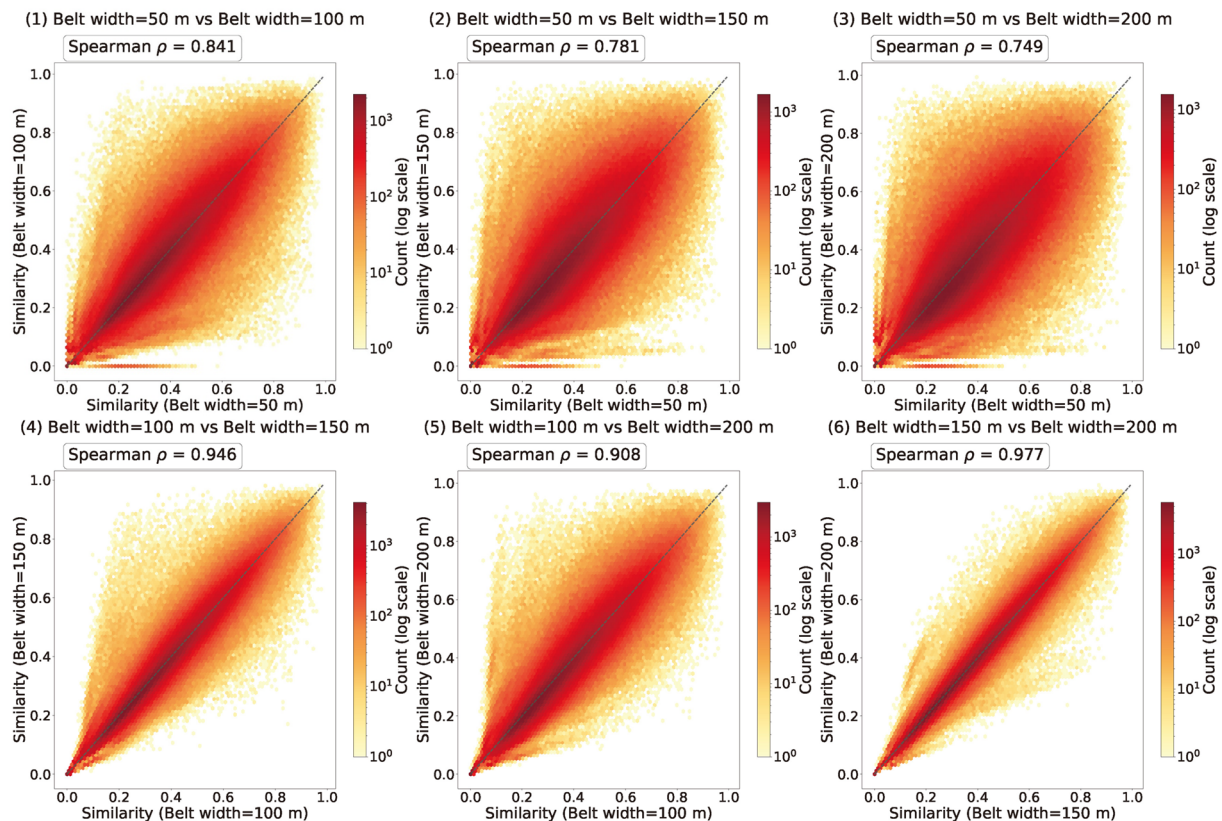


Figure 9. Cross-belt similarity correlations.

Upon closer examination, adjacent belts exhibited higher correlations. The correlation coefficient between belt widths of 100 m and 150 m was 0.946, that between belt widths of 150 m and 200 m reached 0.977, whereas the coefficient between belt widths of 50 m and 100 m was relatively lower at 0.841. Evidently, the closer to the town center, the more consistent the similarity structure became between adjacent depths. Differences remained between the immediate boundary zone (50 m) and the adjacent depth (100 m), reflecting the relatively distinctive nature of the morphological similarity pattern in the edge belt.

The greater the inter-belt distance, the lower the correlation. The correlation coefficient between belt widths of 50 and 200 m was 0.749. This suggests that although the overall similarity ranking framework remains largely stable from the immediate boundary at 50 m to the deep interior at 200 m, some local restructuring occurs between the edge and the interior. Certain town pairs that are highly similar in terms of edge morphology may no longer be similar in the interior, and vice versa.

4. Discussion

4.1. Summary of Hypothesis Testing

We proposed three hypotheses. H1 predicted that building height and volume would increase, while spacing and shape index would decrease, from the town boundary inward. The results provide partial support for H1: mean building volume increases with belt width in most cities, and mean spacing tends to decrease, but mean height and shape index do not show consistent monotonic trends across all cities. H2 predicted that inter-indicator

correlations would be stronger in more economically developed cities. This hypothesis is partially supported for the $x_{1-ave}-x_{4-ave}$ and $x_{2-ave}-x_{4-ave}$ correlations, which showed significant associations with GDPPC, but not for the remaining indicator pairs. H3 predicted that towns within the same prefecture-level city would be morphologically more similar than towns from different cities. This hypothesis was strongly supported by both network metrics and Mann–Whitney U tests.

4.2. Regional Differences in Peripheral Building Morphology

At the scale of town-level administrative units, within-city differences in mean building spacing and mean building height in peripheral belts were greater in Northern Jiangsu than in Southern Jiangsu cities. Possible explanations include differences in urbanization stages, construction modes, and planning regulations; however, these factors were not directly measured in this study, and these interpretations remain suggestive.

4.3. Mean Volume and Shape Index

Regarding mean volume and mean shape index, the former exhibited a centripetal increase pattern, whereas the latter demonstrated polarization, especially in Northern Jiangsu. These patterns may be related to varying land use intensity and construction modes, but these mechanisms require further validation using direct land use and regulatory data.

4.4. Inter-Indicator Correlations

The following four indicators were significantly correlated: mean spacing was negatively correlated with height, volume, and shape index, while the latter three were positively correlated with one another. This pattern reflects the mixed character of building types within the peripheral belts, but this interpretation is based on morphological inference rather than direct land use data.

4.5. Relationship Between Correlations and Economic Development

The $x_{1-ave}-x_{4-ave}$ correlation was significantly negatively associated with GDPPC, and the $x_{2-ave}-x_{4-ave}$ correlation was significantly positively associated with GDPPC. These results suggest a possible link between economic development and the structural organization of peripheral building morphology. However, because governance capacity and planning strictness were not directly measured and because the sample comprises only 13 cities, this interpretation should be considered exploratory.

4.6. Similarity Networks and Within-City Convergence

The top-3 similarity networks exhibited modularity Q values ranging from 0.1881 to 0.2355 across the four belt widths, indicating a clear tendency for the peripheral belts of town-level units to cluster by prefecture-level city in terms of building morphology. Assortativity was positive at all belt widths, but its trajectory was nonlinear, first decreasing and then increasing. This pattern suggests that the morphological organization of the town periphery tends to become more ordered from the boundary inward. The Mann–Whitney U tests further confirmed that within-city similarity was significantly higher than between-city similarity across all four belt widths, providing additional evidence that the prefecture-level city, as an administrative unit, exerts an important constraining effect on the peripheral building morphology of towns.

4.7. Policy Implications

These findings have practical implications for urban planners, town-level administrators, and regional development policymakers. In less developed townships, incremental planning interventions may help reduce morphological fragmentation—for example, by

formulating design guidelines for towns that have already adopted standardized construction, and by promoting standardized housing catalogues for towns still dominated by traditional rural houses. However, the applicability of these suggestions beyond the Chinese context remains a topic that warrants further investigation, given China's distinctive urban–rural zoning system, hukou system, and land tenure structure as well as nature. Comparative studies in different institutional settings are therefore important for assessing the transferability of these conclusions.

4.8. Limitations and Future Research

This study has several limitations that should be acknowledged. First, the cross-sectional design does not allow causal inference; future research employing a longitudinal design could help examine causal mechanisms. Second, the city-level GDPPC analysis is based on only 13 cities, which limits statistical power; future studies could expand the sample to more cities or regions to improve the robustness of the economic association analyses. Third, the town periphery was delineated using administrative boundaries. Although a building density-based validation showed that 89% of the towns had lower building density in the peripheral belts than in the whole town (Appendix F), this approximation may not fully capture the actual urban–rural transition, particularly in highly urbanized subdistricts. Future research could adopt more refined edge delineation methods, such as night-time light data or land use transition indicators. Fourth, the building height and footprint data derived from the 3D-GloBFP dataset are not entirely free from measurement imperfections; future work could validate these data against field surveys or higher-resolution imagery. Fifth, planning regulations and construction standards were not directly measured, and building types were inferred primarily from morphological characteristics rather than land use data. Future research could integrate land use and planning control data to directly examine the proposed mechanisms. In addition, future studies could incorporate the distributional characteristics of morphological indicators, such as quantiles and skewness, and extend the analysis to different institutional contexts to further assess the generalizability of the findings.

5. Conclusions

This study examined the peripheral building morphology of town-level units from three complementary perspectives: morphological gradients, inter-indicator correlations and their associations with economic development, and inter-town similarity networks.

First, within-city variation in peripheral building morphology was greater in Northern Jiangsu than in Southern Jiangsu. This difference may be related to differences in urbanization stages and construction modes.

Second, the four indicators exhibited a stable correlation structure across the four belt widths: mean building spacing was negatively correlated with mean building height, mean building volume, and mean shape index, whereas the latter three indicators were positively correlated with one another.

Third, the strength of inter-indicator correlations was associated with the level of economic development. Specifically, in cities with higher GDPPC, the negative correlation between mean building spacing and mean shape index in town peripheral belts was stronger, as was the positive correlation between mean building height and mean shape index. However, this finding is based on only 13 cities in Jiangsu Province and should, therefore, be regarded as exploratory.

Fourth, the building morphology of town peripheral belts was clearly clustered by prefecture-level city. Within-city similarity was significantly higher than between-city similarity, and the similarity ranking remained highly consistent across belt widths. These

results indicate that the prefecture-level city boundary is strongly associated with the peripheral building morphology of towns.

This study also has several limitations, including its cross-sectional design, the limited number of cities in the economic analysis, and the use of administrative boundaries as an approximation of town peripheries.

Overall, this study demonstrates that the inner-boundary belts of town-level units provide a meaningful spatial scale for examining the interplay among building morphology, economic development, and administrative boundaries. The findings also offer practical implications for differentiated spatial governance in rapidly urbanizing regions, although their transferability to other institutional contexts requires further investigation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land15091756/s1>.

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Abbreviations

The following abbreviations are used in this manuscript:

GDP	Gross domestic product
GDPPC	Per-capita gross domestic product

Appendix A

This appendix validates the reasonableness of the 200 m maximum belt width based on calculation results for all town-level administrative units across the province. We sequentially extended the belt widths to 50 m, 100 m, 150 m, 200 m, 250 m, 300 m, 350 m, and 400 m, and compared the indicator increments between adjacent belt widths (Figure A1). The results show that the largest increase in mean volume occurred within 0–150 m, with the increment from 150–200 m already approaching zero; beyond 200 m, the increments became negative or fluctuated. The increments in mean building spacing continued to decrease and leveled off beyond 200 m. Mean building height entered a state of small fluctuations after 100 m, with only minor changes beyond 200 m (all less than 0.1 m). The mean shape index showed increments of less than 0.002 after 200 m, indicating that it remained essentially stable. Collectively, the morphological gradient at the town periphery is concentrated mainly within the 0–200 m belt range, and further increases in belt width would have only a limited effect on the indicators. Therefore, 200 m represents a reasonable maximum belt width that balances the completeness of the edge gradient with the need to avoid interference from the town center.

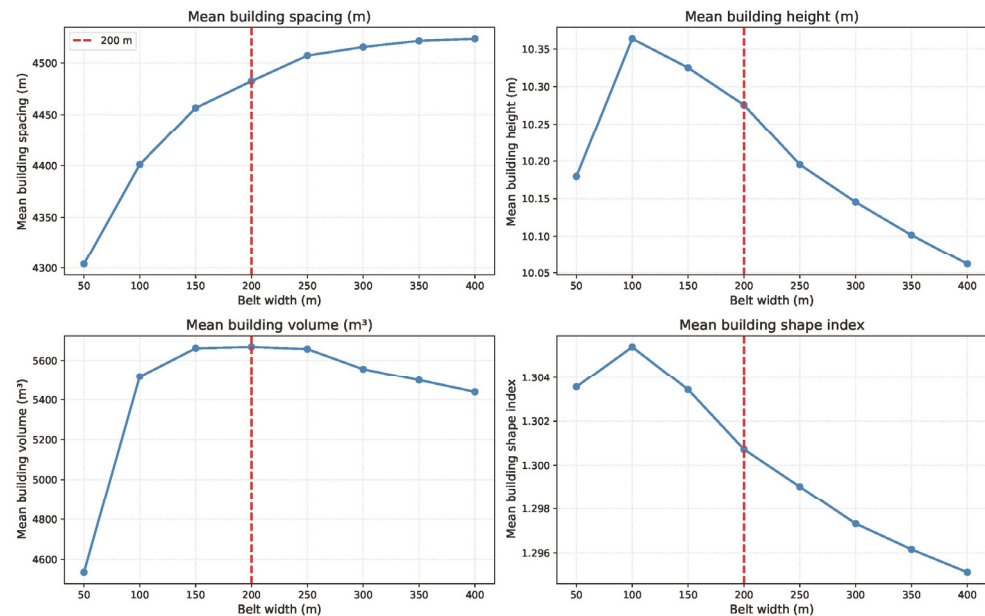


Figure A1. Trends of four building morphological indicators under different cumulative belt widths.

Appendix B

To validate the reasonableness of the cumulative belt approach, we calculated the four building morphological indicators using cumulative belts (0–50, 0–100, 0–150, 0–200 m) and independent belts (0–50, 50–100, 100–150, 150–200 m), and compared their trends with increasing belt width (Figure A2). The results show that the mean indicator values derived from the two methods are highly consistent: the correlation coefficients for mean building spacing, mean building height, mean building volume, and shape index are 0.956, 0.888, 0.940, and 0.999, respectively. This indicates that the belt definition does not affect the main morphological gradient patterns, and the cumulative belt approach is a more robust choice because it provides a sufficient sample size and smoother trends.

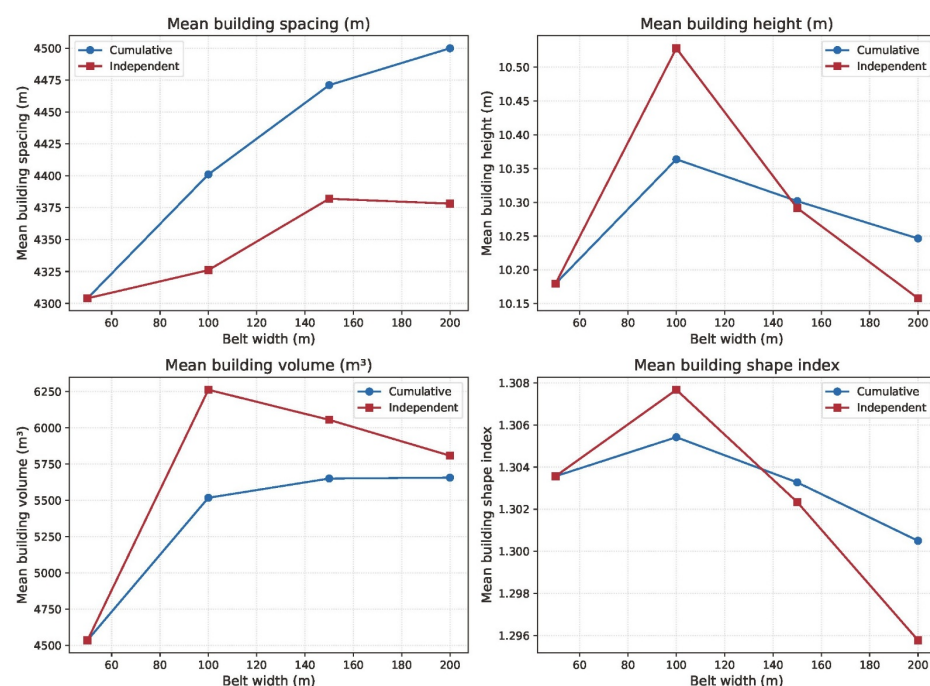


Figure A2. Comparison of four building morphological indicators between cumulative and independent inner-boundary belts across different belt widths.

Appendix C

To validate the reasonableness of the 50 m belt interval, we calculated four building morphological indicators using cumulative belts at intervals of 25 m, 50 m, and 100 m, and compared their trends and missing-data rates with increasing belt width (Figure A3). The results show that the directions of change for the four indicators are consistent between the 25 m and 50 m intervals, and the missing-data rate for the 50 m interval (0.74%) is lower than that for the 25 m interval (0.97%), indicating better sample completeness. The 100 m interval yields only two cumulative belt widths (100 m and 200 m), which are insufficient to characterize the gradient shape and lead to substantial information loss. Overall, the 50 m interval preserves sufficient gradient detail while maintaining sample completeness and statistical stability, and is therefore a reasonable choice.

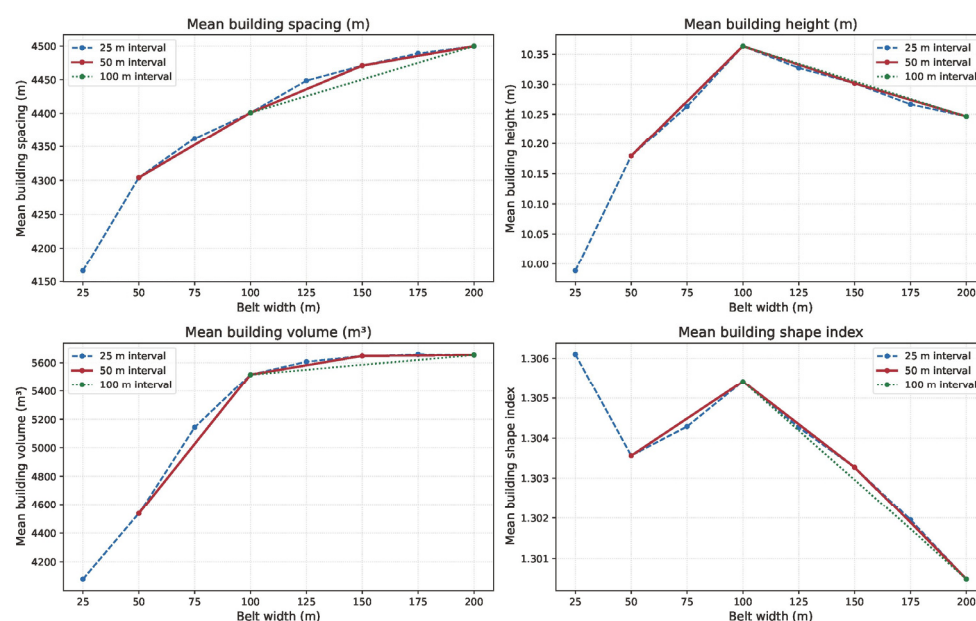


Figure A3. Sensitivity of four building morphological indicators to different belt intervals.

Appendix D

Table A1. Towns excluded when constructing the similarity network.

City	Excluded Town-Level Administrative Units
Nanjing	Baguazhou Subdistrict, Nanjing Jingang Science and Technology Entrepreneurship Center
Zhenjiang	Shiye Town, Xinminzhou Port-side Industrial Park, Jiangxinzhou Eco-agricultural Park, Xilaiqiao Town, Gaoqiao Town
Changzhou	None
Wuxi	Jianghai Subdistrict
Suzhou	Dongshan Town, Suzhou High-tech Innovation and Entrepreneurship Service Center
Yangzhou	Original Seed Farm, Aquaculture Experimental Farm
Taizhou	None
Nantong	Qidong Offshore Engineering and Shipbuilding Industrial Park, Yuantuoqiao Tourist Resort, Rudong Coastal Economic Development Zone, Rudong Yangkou Port Economic Development Zone, Huiping Town, Huanben Farm
Xuzhou	Economic Development Zone, Hubushan Huilongwo Historical and Cultural District Management Center
Lianyungang	Lingang Economic Development Zone, Lianyungang Soda Plant
Suqian	Bancheng Town, Sihe Township, Longji Town, Linhuai Town
Huai'an	Fanji Town, Tiefu Town
Yancheng	None

Appendix E

The sensitivity analysis shows that modularity Q remains high and stable for $k = 1$ –5, then declines sharply as k increases and approaches zero in the full network. These results indicate that weak similarity edges obscure the community structure. We selected $k = 3$ because it retains more similarity information than $k = 1$ or $k = 2$ while maintaining a modularity comparable to the smallest k values, and because larger k values increasingly dilute the city-based clustering structure.

The assortativity coefficient also responds systematically to the number of nearest neighbors k . At $k = 1$, assortativity is negative across all four belt widths, indicating that the single most similar neighbor of a town is often not a node of similarly high strength. As k increases, assortativity becomes positive and rises steadily, reaching approximately 0.4 for $k = 20$ –50. However, in the full network, assortativity drops to nearly zero (approximately -0.001), because the inclusion of all weak edges eliminates the selective connectivity among high-strength nodes. The positive assortativity observed at intermediate k values indicates that morphologically typical towns tend to connect to one another, forming a core group. The near-zero value in the full network again confirms that weak similarities obscure the network structure. The top-3 network already yields positive assortativity in all four bands, and together with its high modularity, it provides a clear and stable representation of city-based morphological clustering.

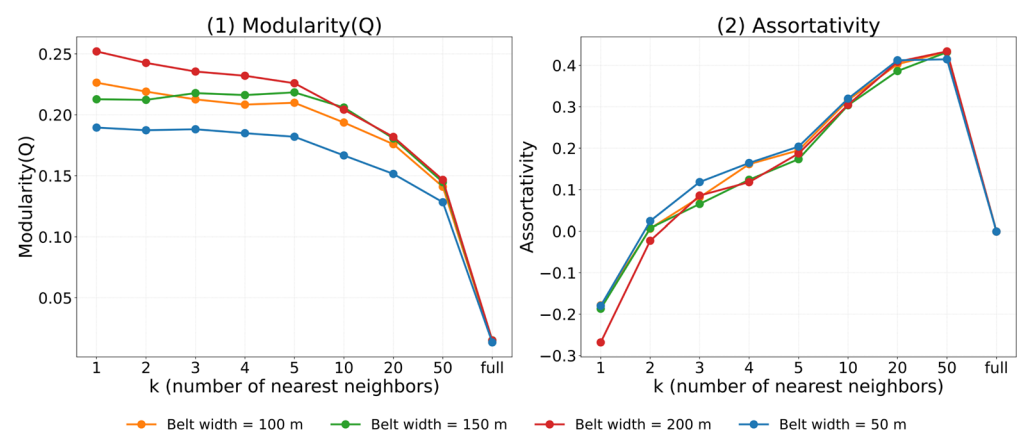


Figure A4. Sensitivity of modularity Q and assortativity to the number of nearest neighbors k in the morphological similarity network.

Appendix F

To test whether the inner boundary belts derived from town-level administrative boundaries can reasonably approximate the urban–rural transition at town peripheries, we compared building density in the entire town with that in the inner 0–200 m belt. Building density was defined as the number of buildings per unit area (buildings/km²). If building density in the boundary belt is generally lower than that of the town as a whole, this would indicate that the belt is, on average, closer to a rural or low-intensity development state, thereby supporting the use of the administrative boundary as an approximation of the town periphery.

Figure A5 presents two complementary views of this comparison. The left panel displays the relationship between whole-town density and edge-belt density for each town. Most data points fall below the 1:1 reference line, indicating that, for the majority of towns, building density in the 0–200 m belt is lower than the town-wide average. The right panel further summarizes this pattern by showing the distribution of the density ratio (edge belt/whole town). The density ratio is less than 1.0 for 89.0% of towns, with a median value of 0.593 and a mean value of 0.632.

These results indicate that the inner boundary belt typically contains only about sixty percent of the building density of the town as a whole, and is therefore relatively less urbanized and more rural in character. This provides empirical support for using the administrative boundary to delineate the town periphery. It should be noted, however, that approximately 11% of towns have density ratios greater than 1.0. These cases likely correspond to highly urbanized subdistricts or situations where built-up areas extend across the administrative boundary. For such towns, the approximation should be interpreted with caution, but at the provincial scale, the administrative boundary remains a reasonably effective and operational means of identifying the town periphery.

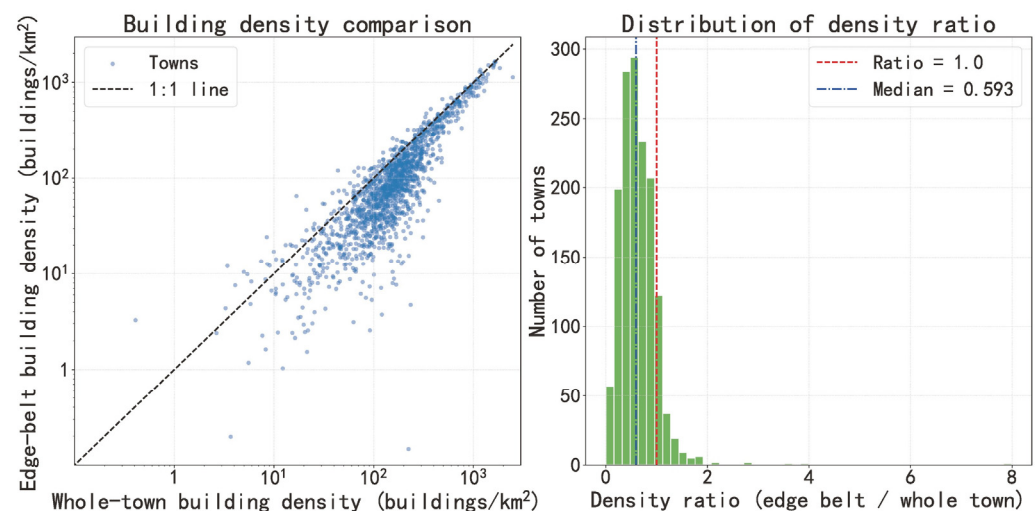


Figure A5. Validation of the administrative boundary as a proxy for the town periphery using building density.

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