Exploring the spatial pattern of historic Chinese towns and cities: A syntactical approach

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Abstract This study explores the spatial pattern of Historic Chinese Towns and Cities (HCTC) by using a syntactic approach. The HCTC is an important element of the built environment and exhibits a variety of unique spatial characteristics. Although previous research has been focused on qualitative analysis, a quantitative approach to exploring this issue is scarce, leading to insufficient understanding of the spatial characteristics of HCTC. This study presents a quantitative approach to analyzing the spatial pattern of HCTC by utilizing the space syntax method. Four well-preserved historic towns were selected as case studies, each representing a typical spatial type of historic town in China. A series of mathematical measures from space syntax were used to explore the spatial characteristics of HCTC, facilitating expanded interpretation of traditional Chinese ideologies. Results contribute to a more critical understanding of the spatial pattern of HCTC.

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1. Introduction

China throughout its long history contains over 2000 historic towns and cities (Ruan et al., 1999). With different spatial layouts and characteristics, these Historic Chinese Towns and Cities (HCTC) reflect the nation’s rich history and culture, thus exhibiting high conservation values (Ruan, 1993). Specific spatial configurations have shaped different spatial patterns of...
HCTC. For instance, a typical Chinese city built by the Han people, the largest ethnic group within China, is often characterized by an urban form of walled enclosures, orthogonal spatial layout, and an ordinal spatial hierarchy (Gu, 2001; Whitehand and Gu, 2006; Wu, 1986). The spatial layout represents the ancient Chinese ideology known as an “ideal city”.

Heritage conservation in China has been studied from various perspectives. For example, The Theories of Historical Urban Preservation (in Chinese), which aimed to provide a foundational understanding of HCTC and theories of urban conservation (Ruan et al., 1999), has become a key textbook for architecture students. Wang (2019) emphasized the significance of traditional Chinese urban planning principles and analyzed how they respond to nature and society based on more than 3700 maps of HCTC. Some other studies focused on an in-depth analysis of individual historic towns and cities, such as the Old Town of Pingyao and Lijiang (Su, 2010; Wang, 2012). However, current studies mostly focus on the qualitative analysis of HCTC. Some limited quantitative studies, such as Zhu (2004), explored the planning strategies of imperial Beijing with the aid of quantitative analysis, and its results were limited to the capital city of China in the Ming and Qing dynasties only. Shen and Karimi (2016) analyzed the spatio-functional patterns of Tianjin by using space syntax with social media check-in data. They later turned their attention to central Shanghai by using the same methodology (Shen and Karimi, 2018). However, these quantitative studies in the Chinese context are focused more on urban area in specific cities only. Li et al. (2016) analyzed the spatial configuration and the tourist space of Kulansu by using space syntax method. However, such work is limited to one historic town, and the findings lack generalization. A quantitative analysis of HCTC is still lacking. This study noticed a lack of HCTC analyses based on formal mathematical measures that would enable direct benchmarking, comparison, and integration between different analyses on cases that could be used to reveal innate spatial knowledge and logics that cannot be objectively measured and understood through qualitative analyses.

This study examines the spatial pattern of HCTC by using space syntax, which is a powerful mathematical technique for quantitatively analyzing spatial configurations. Space syntax has demonstrated its effectiveness and reliability in analyzing spatial patterns of urban spaces through mathematical means, including a large number of studies that analyze and compare spatial patterns of towns and cities in different contexts, such as England and Iran (Karimi and Vaughan, 2014), Turkey (Asami et al., 2001), and Israel (Omer and Zafir-Reuven, 2015). This research applies space syntax to Chinese cultural context to explore the spatial pattern of HCTC.

Two phases were undertaken during our research to discover the spatial pattern. The first phase is to decode the spatial structure by using street centrality measures via the star model (Hillier et al., 2012). Those measures include Normalized Angular Choice (NACH) and Normalized Angular Integration (NAI). The analysis based on those two measures will reveal the planning and design principles of urban spaces. The second phase is to categorize and analyze quantitative spatial patterns by mapping against five measures representing the key spatial characteristics of HCTC: axiarchy, curvature, intelligibility, synergy, and organic spatial layout.

Only a few such historic sites have been properly preserved due to the demolition of ancient sites and buildings throughout the years as a result of rapid industrialization and modernization in China, thus making them precious. The selected case studies include four historic towns, three of which are UNESCO World Heritage (WH) sites. The towns are Pingyao (WH site, 1997), Lijiang (WH site, 1997), Kulansu (WH site, 2017), and Wuzhen (tentative WH list, 2008). Each site represents a typical spatial type of historic Chinese town. The historical maps of those four towns were obtained to examine their morphological change over time. This study includes four ancient capital cities from the dynasties of Wei (ca. 220–265), Tang (ca. 618–907), Song (ca. 960–1279), and Yuan (ca. 1271–1368) and the ideological plan of an ancient “ideal city” illustrated in Kaogongji to achieve a more comprehensive understanding of the spatial pattern of HCTC. These case selections ensure a complete and systematic analysis of the spatial pattern of HCTC that considers differences in time and scale.

The results and comparisons of the selected cases provide a comprehensive understanding of the innate spatial structure of HCTC through a quantitative analysis. The research demonstrates the potential of a formal methodology that can be applied to other cases in the broader built environment, contributing to heritage conservation in China.

2. Review of HCTC

The spatial layouts of HCTC often incorporate patterns that reflect the philosophical and ideological characteristics of the ethnic groups from the past who lived on the site. Confucianism is the most recognized Han ideology since the Han dynasty (ca. 202 B.C.E.–220); it is regarded as the state religion and is structurally dominated by the dealings of sage rulership toward the creation of harmony (Taylor and Arbuckle, 1995; Zhu, 2004). Confucianism influences the institutional structure, social life, and the spatial and functional aspects of city planning. The principles and practice of feng shui is another Chinese cosmology that has long influenced traditional urban planning and architectural design in China (Li et al., 2019); it addresses the accord of heaven and humanity (tianrenheyi) and the harmony between yin and yang, heaven and earth, and humans and nature.

The first known Chinese urban planning publication Kaogongji, a title that translates to "The Craftsmen's Record" (ca. 475 B.C.E.–221 B.C.E.), describes the ancient Chinese planning ideology for an "ideal city". The spatial structure of an "ideal city" is a good example to illustrate how ancient Han cities were planned and built. The "ideal city" has an elementary form with a rectangular shape; on each side of the rectangle, three main gates are accessing the city, forming nine main crossing streets wherein the center is the imperial palace. Although this pattern is somewhat simplified, and not all historic cities have strictly followed its details due to other influences and restrictions, it has had a significant impact on urban planning history in China.
Most ancient capital cities have somewhat followed the pattern of the “ideal city”. The capital city of the State of Wei (ca. 220–265) called Ye is related to the “ideal city” pattern. Ye was the first ancient city that had a rectangular shape as the city form, with a clear functional design and a north–south axis in its layout. The spatial structure was symmetrical. Meanwhile, the distribution of the gates was asymmetrical at each side due to the actual site, which led to the variations from the typical “ideal city”.

In the Tang dynasty (ca. 618–907), the capital city Chang’an (the ancestor of current Xi’an city) was significantly larger than the previous capital cities due to the prosperity of imperial China during the time. Chang’an was the largest city in ancient Chinese history with a grand size of 84.1 km² (Hou and Li, 2002). Restricted neighborhoods (lifang) were used as the basic modules in the planning of Chang’an, thus influencing its spatial layout of regular blocks and streets.

During the Song dynasty (ca. 960–1279), the size of the capital city Dongjing was smaller than that of Chang’an. Some deviations in terms of orientations were observed. The restricted neighborhoods were replaced with lively and open streets. Dongjing’s development included rivers, featuring an advanced water-transportation system that boosted its business development.

The capital of the Yuan dynasty (ca. 1271–1368), Dadu, was the predecessor of the Forbidden City in Beijing. The area had a rectangular shape and incorporated river-related considerations for the planning of the city. A clear north-south axis can be observed across the city dominating the spatial layout. The capital of Ming and Qing dynasties expanded from Dadu, ultimately forming the Beijing City as we know it today.

The above-mentioned ancient capital cities did not strictly follow the “ideal city” pattern and have their different spatial characteristics. However, some similarities to the “ideal city” pattern can be observed. The original and detailed spatial layouts of ancient capital cities are difficult to obtain due to the unavailability of historic data. Therefore, this study selects historic towns that have been well preserved as case studies for analysis. Meanwhile, the spatial layouts of the ancient capital cities are only utilized for comparison purpose.

With a long history, China also has a large number of historic towns that have evolved with different spatial characteristics. Different types of Chinese towns have displayed various spatial patterns reflecting their own cultural and social characteristics. For example, the towns in northern China often exhibit a regular plan constructed by courtyard houses. In southern China, numerous waterfront towns are organized around river delta systems. These traditional settlements are more organic, with free-flowing curved streets that respond to the undulating topography. The typical spatial properties of the waterfront towns along the Yangtze River can be described as “bridges, rivers, and dwellings (xiaqiao, liushui, and renjia)” (Zhang, 2002).

Although some ethnic minority groups follow the building ideology of the Han people, their towns often have their unique cultural characteristics, let alone some other towns that are also influenced by the modernist movement. Typical cases must be selected to understand the spatial pattern of HCTC for ensuring that the spatial type can be well analyzed, categorized, and compared.

3. Methodology

3.1. Applying the space syntax method to analyses urban spaces

This study proposes and demonstrates a quantitative approach to understanding the spatial pattern of HCTC from a mathematical perspective. Space syntax (Hillier and Hanson, 1984) is adopted as the main method in this study due to its recognized syntactic theory and associated mathematical measures that are appropriate for the spatial analysis of the selected HCTC. Most space syntax techniques commence by abstracting spatial relationships into a graph, in which each space is seen as a node, and the connections between them are edges (Yu et al., 2015). The distance from one node to another is called depth. The different types of depth are topological, geometric, and metric. Once the depth can be quantitively computed, a series of mathematical measures is calculated.

The three main space syntax analytical techniques are as follows: Convex Analysis, Axial Line Analysis, and Visibility Graph Analysis. Axial Line Analysis uses the fewest and longest straight lines to cover every convex space while ensuring that lines that can be connected are connected, and all nontrivial circulation loops are made (Ostwald and Dawes, 2011; Hillier and Hanson, 1984). This technique has been applied to a wide range of urban spaces (Al-Sayed and Penn, 2016), including historic towns (Karimi and Vaughan, 2014), and it is a potential tool to study the spatial pattern of HCTC.

Two key measures from space syntax should be noted: integration and choice, which are applied to explore the spatial pattern of HCTC in this study. Integration is a “normalized measure of distance from any a space of origin to all others in a system”, (Hillier and Hanson, 1984, p 108–109). This mechanism measures how close one space is to all the other spaces in a system, which represents the extent that one space connects with other spaces. Choice measures “how likely an axial line or a street segment it is to be passed through on all shortest routes from all spaces to all other spaces in the entire system or within a predetermined distance (radius) from each segment” (Hillier et al., 1987, p 237).

Recent space syntax research has turned its attention to Angular Segment Analysis (ASA) developed by Turner (2001). ASA uses the least angular turns to describe the relationship among each axial segment that is broken from axial lines based on each junction. In graph theory, segments broken from axial lines are still considered nodes, while the numbers of angular turns are regarded as edges. Specifically, a turn of 90° is denoted as one turn, 180° is equal to two turns, and 0° equates to zero turns. Specifically, the number of turns is a weighed topological relationship. A further development of this system, NACH and NAIN, was developed from ASA, enabling comparisons of the spatial configurations of urban spaces regardless of scale (Hillier et al., 2012), thus providing a theoretical
foundation of this study to thoroughly analyze the spatial pattern of HCTC.

Although Road Centerline Analysis is another alternative way to analyze the spatial configuration of urban spaces (Kolovou et al., 2017), it is not the focus of this study. The rationale of using ASA rather than Road Centerline Analysis is that the generated NACH and NAIN measures from ASA can be compared with other similar existing studies, thus creating a reference point for benchmark regarding HCTC. In this respect, Axial Line Analysis and ASA have been adopted in the study with the appropriate measures used to identify the spatial pattern of HCTC.

Space syntax has been widely applied in analyzing urban spaces with different focuses, such as pedestrian movement (Hajrasouliha and Yin, 2015), spatial transformation (Yang, 2004), urban morphology (Dabbour, 2020), relationships between typology and others, including block density (Ye et al., 2018), land use distribution (Shen and Karimi, 2016), and the utilization of tourist spaces (Li et al., 2016). The spatial configuration of architectural design may have influences on the physical indicators (e.g., the ventilation and energy performance) (Du et al., 2019). Space syntax can be used to decode a spatial structure using the NACH and NAIN measures. Some patterns categorized in academic papers are particularly helpful in identifying the spatial pattern of HCTC. Asami et al. (2001) analyzed the spatial patterns of traditional Turkish cities by using three indices: graph theoretical indices, image analytical-related indices, and space syntax-associated indices. The measures in Omer and Zafrir-Reuven (2015) include curvature, fragmentation, connectivity, continuity, and differentiation. These studies have demonstrated the effectiveness of space syntax in analyzing the spatial pattern of urban spaces in different cultural contexts. The research framework is shown in Fig. 1.

3.2. Case selection

To examine the spatial pattern of HCTC, their typical cases were selected for analysis. Towns and cities are defined by their administrative level in China, namely, province—city—town/county, which is often determined by geographic size and population. The selected historic cities in the study refer to the ancient capital cities that do not exist nowadays or have significantly changed. Towns were selected to represent the typical spatial types in historic Chinese towns. Three groups of cases were studied: firstly, the four historic Chinese towns — Pingyao, Lijiang, Kulangsu, and Wuzhen — were selected as the main focus of this study. Secondly, the historical maps of the aforementioned four towns were analyzed to provide a comprehensive view for examining the morphological change over time. Thirdly, four ancient Chinese capital cities — Ye, Chang’an, Dongjing, and Dadu — and the “ideal city” pattern denoted in Kaogongji were analyzed for comparison purposes. The four ancient capitals and Kaogongji were introduced above, while Pingyao, Lijiang, Kulangsu, and Wuzhen are described in the following sections.

3.2.1. Pingyao

The Old Town of Pingyao, inscribed on the World Heritage (WH) List in 1997, is a prototypical example showcasing traditional planning at a county level, which can be understood as an “ideal city” pattern. The town is located in northern China, and it retains typical planning, building, and construction characteristics of the traditions of the Han people from the Ming and Qing dynasties (WHC, 2018). The spatial layout of the town is a typical reflection of Chinese ancient towns/cities with unified characteristics, such as walled enclosures, north–south orientation, and axiality (Fig. 2). The spatial layout of Pingyao closely replicates the “ideal city” pattern, therefore supporting the case study as an appropriate focus for research in this study.
3.2.2. Lijiang
The Old Town of Lijiang, also inscribed on the World Heritage List in 1997, is another example that can show the influences of the ethnic minorities in China. The above-mentioned capital cities and Pingyao were mainly built by the Han people. Meanwhile, Lijiang was built by the ethnic minority called Naxi during the Ming dynasty. Lijiang is located in southern China and surrounded by mountains, trees, and rivers. The town presents a natural topography that creates a harmonious human settlement between humans and nature. In contrast with Pingyao, the development of Lijiang was influenced by a blend of different cultures of the Han people and ethnic minorities (WHC, 2018). Accordingly, the spatial layout of Lijiang exhibits unique spatial properties that reflect this dynamic cultural and social mix of demographics (Fig. 2).

3.2.3. Kulangsu
Kulangsu, inscribed on the World Heritage List in 2017, is a typical historic town that was influenced by the Western architectural modernist movement. This town is a historic international human settlement, and it was formed since 1903 followed by the opening of Xiamen as a commercial port (WHC, 2018). Kulangsu expresses more modern architectural characteristics compared with Pingyao and Lijiang, especially from influences outside of China. In contrast with Pingyao and Lijiang, Kulangsu represents a mixture of different cultural contexts and forms (Fig. 2). The spatial layout of Kulangsu is well-preserved because it is isolated from Xiamen. Kulangsu is a good example to illustrate a spatial layout under the influence of the Western modernist movement (Zhu, 2009).

3.2.4. Wuzhen
Waterfront towns are another type of historic town in China. Most waterfront towns are located in southern China, forming the so-called "southern style" in which the city’s structure tends to be more organic and responsive to geographical features than towns in northern China. Wuzhen is one of the four waterfront towns that are inscribed on the WH tentative list as "The ancient waterfront town in the south of Yangtze River" proposal. Given that the area is located in the south of Yangtze River, water in these towns not only influences the spatial layout but also serves as the primary transportation system to promote the economic growth. Wuzhen possesses a unique urban plan that is organized by rivers and topography (Fig. 2), which illustrates urban spatial planning layouts that are typical in southern China.

The maps of the four historic towns (group 1) and their historical maps (group 2) are shown in Fig. 3. The maps of the four capital cities and the form of the "ideal city" pattern (group 3) are shown in Fig. 4. Note "old" in the following figures refers to the historical map of each selected town.

3.3. Decoding spaces using the star model
In this section, normalized angular measures, namely, NACH and NAIN, are applied to compare the similarities and differences among the case studies. Hillier et al. (2012) used a star model that standardizes NACH and NAIN to ensure that the differences between different cities can be scaled up. The star model is a diamond-shape graph with four values: mean NACH (of one city/town), mean NAIN, max NACH (the max value among all the NACH values in one city/town), and max NAIN. A sample star model diagram can be seen in the Results section. The calculation of NACH and NAIN is demonstrated in Equations (1) and (2), respectively.

\[
\text{NACH} = \frac{\log(CH+1)}{\log(TD+3)},
\]

where \(CH\) is the angular choice value of a node, and \(TD\) is the total angular depth of that node in a graph.

\[
\text{NAIN} = NC^{1.2} / (TD+2),
\]
Fig. 3  Group 1: four historic Chinese towns; group 2: historical maps of the four towns.
where $NC$ is the total number of nodes, and $TD$ is the total angular depth of a node in a graph. The standardized NACH and NAIN values ($z$ scores) range from $-3$ located at the center of the star model diagram to $3$ located at the edge of the diagram. The formula is shown in Equation (3):

$$z = \frac{z - \mu}{\sigma};$$

where $\mu$ is the mean value of a group, and $\sigma$ is the Standard Deviation (SD) of that group.

The mean NACH and NAIN values are related to the background network, while the max NACH and NAIN values are related to the foreground network. In the star model, foreground networks are more structural forms with higher max values; while background networks are more or less regular forms without excessive movement (Hillier et al., 2012). The star model provides a method through which to decode the spatial structure of HCTC, which can be compared between each other via the standardized measures. Such measures can be applied to compare and interpret the spatial structure of different HCTC to understand whether a town/city is organic or planned.

3.4. Mapping the spatial characteristics using categorized spatial measures

Various spatial measures have been discussed and applied to explore the spatial patterns of cities (Asami et al., 2001; Omer and Goldblatt, 2016; Silva and Medeiros, 2019). However, the spatial pattern that is appropriate for each specific cultural background of HCTC must be contextualized. The two main types of spatial layouts of HCTC are as follows: the first one is the orthogonal spatial layout, which we called “ideal city” from Kaogongji. Such a spatial layout reflects an idealistic spatial order originated from Confucianism. The other one is the organic spatial layout where the towns/cities were developed around the water systems and nature. This type of spatial layout suggests a harmony between humans and nature and the influences of feng shui practices on urban and spatial planning. Hence, axiality and curvature are used to measure the degree of rigidity of an urban form’s spatial structure, which is suitable to reveal the spatial characteristic of the former. The organic spatial layout is used to measure the degree to which it conforms to a regular formal structure or shape. Intelligibility and synergy are applied to measure the specific features that are more relevant to contemporary planning purposes today. This approach may be suitable for heritage planning and tourism management to identify how easily a visitor can find their way around and identify important tourist locations within a historic Chinese town’s or city’s urban form. Therefore, the five measures of axiality, curvature, intelligibility, synergy, and organic spatial layout are used in this study to interpret the spatial pattern of HCTC.

The proposed methods were developed by adopting and integrating relevant space syntax method from current literature for studying the spatial pattern of urban spaces to map the spatial characteristics of HCTC (Asami et al., 2001; Hillier et al., 2012; Omer and Goldblatt, 2016).
These methods have shown effectiveness in similar research purposes. Hence, the validity and reliability of the proposed methods can be ensured.

3.4.1. Axiality
Axiality is a typical spatial characteristic in HCTC influenced by the Han people. Pingyao, Xi’an, and Beijing possess an orthogonal street pattern with a rectangular shape. Hillier and Hanson (1984) used the term grid axiality to describe this spatial feature with Equation (4):

\[ G_A = \frac{2I^2 + 2}{L}, \]  

(4)

where \( I \) represents the number of islands (the voids defined by the boundary of streets), and \( L \) represents the number of axial lines in street network \( A \). The result is a value between 0 and 1 whereby the closer to 1 indicates stronger grid axiality. The result of grid axiality is directly associated with the number of islands and axial lines regardless of the scale of that grid, thus allowing the comparison of axiality of different cases in unique shapes and scales. A grid axiality value of approximately 0.25 or above indicates a grid-like pattern system, while the value below 0.25 indicates a more or less deformed spatial system (Hillier and Hanson, 1984).

3.4.2. Curvature
Curvature describes the form of streets through their degree of curvature, where the term straight is the absence of curvature. Some Chinese towns have straight streets as a result of their geographic orientation. Thus, curvature can be an indicator to identify the degree of street-grid deformation a town possesses. In contrast with the measure of grid axiality that focuses on grids alone, curvature indexes the relative curvature of the grid’s streets and is measured by the ratio between the number of axial lines and the number of streets (Omer and Zafrr-Reuven, 2015). Given the same number of streets, more axial lines are required for a curved street. Therefore, a curved street pattern has a higher ratio between the number of axial lines and the number of streets than a straight street pattern, as shown in Equation (5):

\[ Cur_A = \frac{L}{S}, \]  

(5)

where \( L \) is the number of axial lines in a given street network \( A \), and \( S \) is the number of streets in the network. Omer and Zafrr-Reuven (2015) did not demonstrate how the number of streets was counted. The current study follows a method of transforming curved streets into street segments to calculate the number of streets (natural streets), which is adopted by Liu and Jiang (2012). The natural street is determined by the continuity of centerlines of streets with an angle threshold (normally 45°). The segments for each intersecting centerline segment were joined with the smallest angle deviation possible (called every best-fit algorithm). This study sets 60° as the threshold angle instead of 45°, which is an attempt to more accurately represent the “real-world” street network of the case studies because 45° is considerably sharp for breaking the continuing centerlines of streets. The centerlines are generated using computer-aided design software, while the natural streets are generated using Arcwoman, a plug-in of ArcGIS (Jiang, 2015). The axial line maps and natural streets can be automatically generated (Jiang and Liu, 2010; Turner et al., 2005), while an axial line map can be unique with a defined algorithm (Ostwald and Dawes, 2011). In this way, the study has adopted a quantitatively robust method to evaluate the curviness of streets in HCTC to better encapsulate the spatial deformations of the urban form under investigation.

3.4.3. Intelligibility
Intelligibility indexes the degree to which the number of immediate connections a line has and is a reliable guide to the importance of that line in the system as a whole (Hillier et al., 1987). Stronger intelligibility implies that a visitor unfamiliar to the system can easily navigate the whole system. Intelligibility is related to the ability of a visitor to orient them within the urban system. Higher intelligibility values may indicate that the social life of citizens can be controlled by government officials, expressing the dominance of imperial power structures embedded within historic towns/cities. Intelligibility has been widely used in space syntax research, and it is a potential indicator for this research to see how intelligible a historic Chinese town/city is.

The measures needed to calculate intelligibility are the connectivity of each node and global axial integration. Intelligibility (axial intelligibility) is the Pearson correlation between axial connectivity and global axial integration, as described in Equation (6):

\[
\text{Intelligibility} = \frac{n \Sigma \text{Con}_i \cdot \text{Int}_i - \Sigma \text{Con}_i \Sigma \text{Int}_i}{\sqrt{(n \Sigma \text{Con}_i)^2 - (\Sigma \text{Con}_i)^2} \sqrt{n \Sigma \text{Int}_i^2 - (\Sigma \text{Int}_i)^2}},
\]  

(6)

where \( \text{Con}_i \) is the connectivity value of node \( i \) in a graph, and \( \text{Int}_i \) is the integration value of node \( i \) in that graph.

3.4.4. Synergy
Synergy is defined as the correlation between radius-3 and radius-n integration. This parameter measures the degree to which the internal structure of an area relates to the larger-scale system in which it is embedded (Hillier, 1996). Synergy is also called axial synergy that is an axial measure utilizing Axial Line Analysis. This study also considers angular synergy utilizing Angular Segment Analysis. The correlation of global angular integration (radius \( n \)) and local angular integration (radial 500 and 750 m) are used in this study to interpret angular synergy. Readers should refer to Hillier and Iida (2005) and Turner (2001) for the differences between axial and angular integration. The calculation of axial synergy is described in Equation (7):

\[
\text{Synergy}_{\text{axial}} = \frac{n \Sigma \text{Int}_{i,n} \cdot \text{Int}_{3,i} - \Sigma \text{Int}_{i,n} \Sigma \text{Int}_{3,i}}{\sqrt{n \Sigma \text{Int}_{i,n}^2 - (\Sigma \text{Int}_{i,n})^2} \sqrt{n \Sigma \text{Int}_{3,i}^2 - (\Sigma \text{Int}_{3,i})^2}}.
\]  

(7)

where \( \text{Int}_{i,n} \) is the integration value of node \( i \) at the global scale, and \( \text{Int}_{3,i} \) is the integration value of node \( i \) at a topological step of three (local scale). \( \text{Int}_{i,n} \) should be replaced with the angular integration at the global scale, and \( \text{Int}_{3,i} \) should be replaced with the angular integration at the local scale.
at the scale of 500 and 750 m to calculate Synergy_500 and Synergy_750. The co-pre-sence of high global and local angular integration demonstrates that a visitor has easier access to a local site without the spatial interference of visual congestion, thus a visitor’s visual navigation is less likely to be inhibited (Li et al., 2016). Vehicles are strictly limited within the tourist spots of the selected historic towns where the visual navigation of tourists needs to be carefully designed to protect the historical heritage site. Therefore, synergy can be used as a potential indicator for planning to make those spots with high heritage significance more visually present. The study considers three different synergy measures and compares them with other categorized patterns to associate with the aforementioned measures: axiality, curvature, and intelligibility.

3.4.5. Organic spatial layout

In space syntax, an organic spatial layout reveals that an urban form lacks any obvious geometry (Hillier, 2012). In a city with an organic spatial pattern, in terms of the axial line map of that city, a longer axial line is often connected to another longer one by an almost straight connection, while shorter lines are connected by near right angles (Hillier, 2012). The organic development shapes the dual layer system of a city containing a foreground network and a background network (Hillier, 2016).

This study follows the main idea of organic spatial layouts in space syntax theory. However, historic towns/cities have their own urban and spatial characteristics that are a reflection of ancient Chinese ideologies and approaches to urban planning and design. For example, feng shui practices emphasize that the planning of HCTC should be facing south (zuobeichaonan), surrounded by rivers and mountains that supplied “life breath” (qi) (Li et al., 2019). This study takes waterfront towns as an example. Such towns were organized around rivers that served as their main transportation mode necessary to boost their economy in ancient times. Therefore, the location of rivers and bridges did have direct configurational outcomes and impacts in terms of the town’s or city’s spatial layout. In this study, axial lines flowing around (i.e., rivers) and through rivers (i.e., bridges) are considered as decisive axial lines in the spatial layout. The analysis cannot address the reasons behind the site selection of a city/town. Therefore, we are only considering the syntactic role that rivers have in Chinese waterfront towns.

The five measures have been calculated and mapped which can be quantitatively analyzed. Accordingly, an ANOVA test was conducted to check if a statistical significance exists within the three groups. The ANOVA test was conducted using SPSS.

The hypothesis of the research regarding the five spatial measures is summarized in Table 1. The analyzed results can help in examining the hypotheses, which can be used to direct the mapping of the spatial characteristics of HCTC interpreted through traditional Chinese ideology and cosmology.

Supplementary documents to this paper contain our original raw data of this research to ensure data transparency. Readers can utilize necessary resources and examine or expand the results by applying the given equations together with depthmapX (the space syntax analysis tool).

4. Results

4.1. Phase 1: star model analysis

Fig. 5 (left) illustrates the star model of the four historic towns in their historical and current urban forms. Fig. 5 (right) describes the star model of the ancient capital cities. This figure demonstrates that the ancient capital cities (group 3) tend to have a higher mean NACH (for Chang’an, Dadu, and Ye), mean NAIN, and max NAIN value than the four historic towns (groups 1 and 2). Accordingly, the spatial layouts of ancient capital cities are overall more integrated (due to the higher integration values) and regular (due to the higher mean NACH values). However, the max NACH values of group 3 are quite low (except Dadu). The spatial layout of Dadu has been broken by the central gaps (the location of the imperial palace), and its spatial layout is not as regular as other capital cities. The max NACH values of group 3 are basically lower than 1.4, which is contradicted by the claim that “no real system has a maximum (max NACH value) below 1.4” (Hillier et al., 2012). However, the results are consistent with the theories of regular grids and confirm that such grids in ancient Chinese capital cities do exist as real systems that have a max NACH value lower than 1.4. Specifically, ancient capital cities have a strong background network and lack a visible foreground network; they were planned primarily to create a spatial hierarchy rather than self-evolving into organic cities.

The historical forms of the four selected towns (group 2) have a higher max and mean NAIN value than their counterpart current forms (group 1). This notion indicates that the historical forms of the four towns are more integrated. Pingyao is a town with regular grids (higher mean NACH value) and strong structure (represented by higher max value). Lijiang and Kulangsu have a similar spatial structure with only a slight max NACH value difference. Wuzhen has a more structural form due to a higher max NACH value; however, it has the smallest mean NACH values among the four historic towns, indicating an outcome of its deformed spatial layout because of the river system.

The results have shown that ancient capital cities are overall more integrated than historic towns due to their regular spatial layouts. The historical spatial layouts of historic towns are more integrated than their current spatial layouts, and the spatial layouts of the four towns are more deformed, yielding a higher max NACH value compared with the ancient capital cities.

4.2. Phase 2: categorized spatial measures

Figure 6 shows the categorized spatial measures of the selected three groups of case studies.

4.2.1. Axiality

Ancient Chinese capital cities (group 3) built by the Han people exhibit a stronger axiality (except Dadu). The
spatial layout of Dadu is broken by gaps at its center where the imperial palace is located. Dadu is not considered as a city with a clear axiality, even though it was built on the basis of a central geometric axis. The grid axiality values of group 1 from high to low are Pingyao, Wuzhen, Lijiang, and Kulangsu, although the differences between the last three towns are minor. When we examine their historical forms in group 2, Pingyao has the highest axiality value among the four towns, followed by Wuzhen. Thus, the analysis suggests that towns built by the Han people (i.e., Pingyao and Wuzhen) have a higher axiality value due to the influence of Confucianism’s emphasis on hierarchical spatial order in planning and creating urban forms.

Axiality is a typical spatial feature of the ancient capital cities with values over 0.25 indicating the presence of a grid-like urban-pattern system. In the four selected towns, only the historical map of Pingyao has a higher axiality value (0.369). With regard to the other three towns, Kulangsu has the lowest axiality value (0.040). Our analysis shows that the axiality value may be used to understand and analyze the spatial layouts that are either centric or concentric.

### 4.2.2. Curvature

In Fig. 6, all selected ancient capital cities (group 3) have a curvature degree less than or equal to one. Kulangsu’s urban form possesses the highest curvature value (over 2.5) among the 13 cases, which is followed by Lijiang. In group 1, Kulangsu is the most curved town (2.58), while Pingyao is the least curved among the four towns (1.58). The results

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**Table 1: Hypotheses regarding the categorized spatial measures of HCTC.**

<table>
<thead>
<tr>
<th>Spatial measures</th>
<th>Hypotheses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axiality</td>
<td>Towns and cities built by the Han people often show centric spatial layout with clear axes throughout the layout yielding an unified spatial form, which emphasizes Confucianism that addresses a hierarchical order between the monarch and his subjects. As ancient capital cities (group 3) were built by the Han people, they show an overall higher axiality value than the four historic towns (group 1 and group 2). In group 1, Pingyao should have the highest axiality value while Kulangsu has the lowest.</td>
</tr>
<tr>
<td>Curvature</td>
<td>The main difference of the spatial layout of HCTC built by the Han people compared to those built by ethnic minorities could be curviness of streets which can be measured using Curvature. The hypothesis is that Pingyao has the lowest curvature value in group 1. Also, ancient capital cities (group 3) should have the lowest curvature values compared to group 1 and group 2.</td>
</tr>
<tr>
<td>Intelligibility</td>
<td>Intelligibility demonstrates the degree of orientation whether a city/town is understandable from a particular location. A HCTC may be intelligible due to a plain urban fabric so that the life of citizens can be controlled by government officials. In group 1, Kulangsu should have a lower intelligibility value than the others due to the impact of modernism on its urban planning. The historical forms of the four towns (group 2) are more intelligible than their current forms (group 1). Meanwhile, the ancient capital cities (group 3) should have the overall highest intelligibility values.</td>
</tr>
<tr>
<td>Synergy</td>
<td>Synergy indicates the degree to which the syntactic measures of the parts relate to those of the whole street network. It is assumed that the synergy values of the historical spatial layouts of the four towns (group 2) are higher than their current spatial layouts (group 1). In group 1, Kulangsu has the lowest synergy value while Pingyao has the highest synergy value. Also, Group 3 (ancient capital cities) has the overall highest synergy values.</td>
</tr>
<tr>
<td>Organic spatial layout</td>
<td>The feng shui practices address the role of rivers aimed at creating harmony between man and nature. The spatial arrangements of the HCTC may have syntactic meanings regarding the role of rivers. The hypothesis is that rivers in Wuzhen and Lijiang are located in a higher integrated area.</td>
</tr>
</tbody>
</table>

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**Fig. 5** Left: star model of the four historic towns in the historical and current forms; right: star model of the ancient capital cities.
support the hypothesis that Han-based towns (i.e., Pingyao and Wuzhen) and cities (all selected ancient capital cites) are less curved than Lijiang and Kulangsu whose settlements and development were heavily influenced by other cultural and ethnic minority groups in China. Given that the ancient capitals have a regular spatial layout, they often express an extremely rigid street pattern.

4.2.3. Intelligibility

The intelligibility value describes the relationship between the parts and the whole in a street network. Three of the ancient capital cities (group 3, except Dadu) that have regular grids show a higher intelligibility value than the selected historic towns. Dadu does not have a higher intelligibility value due to the central gaps explained earlier that block the connectivity of some axial lines in its spatial layout. The intelligibility value of the “ideal city” in Kaogongji is zero due to the lack of axial lines.

The social life of citizens living in the capitals is more controlled by government officials than those in towns, thereby confirming the influence of a grand Confucian concentric order to a certain degree. In group 1, Kulangsu has the lowest intelligibility value (0.307), followed by Lijiang (0.360) and Wuzhen (0.368); nevertheless, the difference is minor. We can also see that their historical forms are more intelligible, which further proves the hypothesis. The overall results have proven the hypothesis. However, intelligibility cannot be seen as a factor to influence and differentiate urban forms due to the insignificant differences in our analytical results.

4.2.4. Synergy

Axial and angular synergy values have been presented in Fig. 6. The regular grids of the ancient capital cities (group 3) have shown a higher axial synergy value. In the four historic towns, Kulangsu has the smallest axial synergy value that matches the hypothesis. Kulangsu has the highest angular synergy values among the four historic towns, which confirms a stronger angular legibility due to its unique geography. Wuzhen does not have a higher angular synergy value as expected. Therefore, the hypothesis can only be proven in terms of the axial synergy that is a topography measure like intelligibility, which can provide insights into the overall clarity of the system, such as how easily it is for a visitor to understand the whole urban form through an experience of its parts.

The results partially support the hypothesis that the synergy values of the historical spatial layouts of the four towns (group 2) are higher than those of their current spatial layouts (group 1). In group 1, Kulangsu has the lowest synergy value, while Pingyao has the highest synergy value. The selected ancient capital cities (group 3) have the overall highest synergy values. The significance of this finding is that firstly, no clear pattern regards the angular synergy evidenced in ancient capital cities (group 3) because they have lower angular synergy values than the four selected towns’ current (group 1) and historical spatial forms (group 2), although group 3 has the highest axial synergy values that strongly support the other part of the hypothesis. Therefore, the organization of the spatial layout of ancient capital cities is more topology-based than geography-based. Secondly, the axial synergy values of group 2 are higher than those of group 1, which confirms the hypothesis. The angular synergy values of group 2 are also higher than those of group 1. Finally, in group 1, Pingyao has the highest angular synergy value, while Kulangsu has the lowest axial synergy value, which confirms that Kulangsu is a town organized by its geography, and it also
has the highest angular synergy value in group 1. However, Wuzhen does not have a higher synergy value (angular and axial synergy) as expected even though it is a Han-based town.

4.2.5. Organic spatial layout

Only Lijiang, Wuzhen, and Dadu have rivers flowing through their urban fabric. Accordingly, the axial-line distributions of Lijiang, Wuzhen, and Dadu are considered. Table 2 summarizes the statistics of the decisive axial lines in Lijiang, Wuzhen, and Dadu. We found that axial lines flowing through and around rivers are in favor of choice rather than integration, which challenges the original hypothesis.

For example, in Lijiang, the decisive axial lines take up 7% of the total axial lines. Table 2 illustrates that the choice difference is larger than integration (global and R3). The mean integration value of decisive lines is 1.08 (global) and 1.08 (R3) times those of non-decisive lines. By contrast, the mean choice value of decisive lines is 1.85 (global) and 1.48 (R3) times those of non-decisive lines. Therefore, the rivers in HCTC are located in areas with higher choice values.

This notion indicates that rivers are quite easily accessed for tourism purposes in these towns. When one navigates in historic Chinese towns with an organic spatial layout, as long as they find a river, it will be easier to orient themselves relative to the river and optimize their way-finding options through the urban system. Specifically, if they are not far away from a river, then they are not far away from the center of the town. In terms of the spatial design, the decisive axial lines provide a way to facilitate sightline corridors to ensure that the role of rivers can be effectively emphasized. The feng shui practices address that the planning of HCTC should sit in the north and face south (zuobeichaonan) and be surrounded by rivers and mountains to be filled with life breath (qi) (Li et al., 2019). Our analysis has partially examined the role of rivers from a syntactic perspective.

Figure 7 shows the pairwise scatter plots between every two spatial measures. Correlations have not been undertaken due to the small sample size of the case studies. However, some tendencies can be observed from the graphs. Some fit correlations can be found, including axiality-curvature (negative), axiality-synergy_500 (negative), curvature-synergy_500 (positive), intelligibility-synergy_axial (positive), and synergy_500-synergy_750 (positive). The results of angular synergy do not fully support the hypothesis. Hence, we now only consider such relationships: axiality-curvature and intelligibility-synergy_axial. A comprehensive understanding of the general relationships between the measures can be obtained from the pairwise scatter plot graphs.

We also conducted an ANOVA test to check the differences between and within groups (Table 3). Significant differences have been found in four measurements: mean NAIN, max NAIN, axiality, and curvature. The validity of the results might still need further testing due to the small sample size of each group; however, it does show the differences of each group in terms of their spatial pattern. Although the comparison of intelligibility and synergy values cannot be applied to the overall groups, they are useful indicators to reveal the spatial configurations of the selected individual HCTC.

5. Discussion

The two main types of spatial layout of HCTC are as follows: orthogonal and organic. Our analytical results have further revealed these two distinguished urban forms, and mathematical measures are used to understand how they may have been influenced by traditional Chinese ideologies, such as Confucianism and feng shui practices. Accordingly, we propose two spatial patterns based on the results: axiality-oriented and concentric river. The river is not present in all HCTC and can only play a certain role in configuring an organic spatial layout of HCTC, and this is a limitation of the study.

The axiality-oriented pattern can be applied to the selected historic towns and cities, except Kulangsu. The study has four hypotheses and measures that are related to such a pattern: axiality, curvature, intelligibility, and synergy. A city/town built by the Han people has a higher axiality value due to the regular spatial layout. Given that ancient capital cities have a strict grid-like pattern, they possess a lower curvature value. Moreover, the axiality value is negatively related to curvature. Meanwhile, intelligibility is possibly related to axial synergy. Han-based towns/cities tend to have a higher intelligibility value. Hence, we suggest axiality value as a key indicator to connect the rest of the measures. Kulangsu, once influenced by the modernist movement, is a town that does not appear to possess an axiality pattern due to the geographic influences of its topography. The statistics from the star
model analysis in phase 1 have shown a shifting of spatial forms in these selected historic towns/cities from regular to deform and from background networks to foreground networks. Overall, the results have suggested the first spatial pattern that Han-based towns/cities are axially-oriented.

The concentric river pattern can be applied to river cities/towns that are considered organic: Lijiang, Wuzhen, and Dadu. The feng shui practices address that the selection of a city/town should consider the location of actual mountains and rivers, sitting in the north (mountain) and facing south (river), called zuobeichaonan. Rivers are important in configuring the spatial layout of a city/town because they provided not only water sources but also essential transportation to support economic growth in ancient times. The study has found that rivers tend to intersect streets with higher choice values rather than integration values in Lijiang, Wuzhen, and Dadu. Hence, we use the term "concentric" to elaborate the syntactic role of rivers in river-based historic towns/cities.

This study has unavoidable limitations. Firstly, this study selected 13 cases for analysis. These 13 cases were...
categorized into three groups, which resulted in four to five cases in each group. This constraint limits the statistical significance of the study. However, the cases were carefully selected to represent the typical types of historic towns/cities within the scope of this study. The analysis using four to five cases is typical in space syntax studies. For example, Omer and Zafir-Reuven (2015) analyzed the street pattern of Israeli cities in which three groups of cases are defined from pre-modern period, modern period, and late modern period, with five cases included in each group. Hence, the number of cases in this study is sufficient to provide valid results. A further constraint of the study is that the level of detail of the historical maps is limited, which can impact the analyses. Some limitations of space syntax as a method should also be noted: space syntax uses graphical analysis that focuses on revealing spatial properties purely based on typology, whereas other aspects of the spatial quality of urban places are not considered, such as the appearance of buildings and functional importance of the space. The planar analysis applied through space syntax does not consider the impacts of 3D geography on axiality, curvature, connectedness, intelligibility, and synergy.

Nevertheless, space syntax being an important approach to spatial analysis has been proven effective and reliable over 4 decades of studies and applications and widely accepted by the international research communities. Despite some limitations, the methodological approach presented in this study has revealed notable advantages in defining and understanding the spatial pattern of historic towns/cities in the Chinese context and can be further expanded to broader cases and purposes.

6. Conclusion

This research conducted a two-phase quantitative analysis to explore the spatial pattern of HCTC using space syntax. We selected four typical historic Chinese towns and compared them with their historical maps. Selected ancient capital cities were used for benchmarking as ancient capitals arguably better inherited the layout of the ideological “ideal city” concept. To present our findings, this study first utilized the star model to analyze the spatial structure of selected towns and cities. The star model results have indicated a decrease in mean NACH value and an increase in max NACH value from group 3 to groups 1 and 2. This notion identifies the shifting of the urban forms in these historic Chinese towns/cities from regular to deformed and from background to foreground networks. The selected Han-based towns are more structural (due to the higher max NACH values) than towns under the influence of ethnic minority groups and their culture, such as Lijiang or those influenced by Western culture, such as Kulangsu. The ancient capital cities do not have a higher max NACH value (below 1.4) due to their strict grid-like patterns. The aforementioned cities and the historical maps of the four towns tend to be more integrated than the current spatial layouts of the four towns.
We have gained a clearer picture of the spatial structure of the selected towns and cities through the application of the star model and can better understand as an urban system. Therefore, the visualized star model can be a useful reference for understanding the spatial pattern of HCTC.

This study discussed five spatial measures that are used to map the spatial characteristics of the selected historic towns/cities. The trace of the "ideal city" pattern can be found in all the above-mentioned capital cities from various perspectives. The hypotheses regarding axiality, curvature, and intelligibility can be fully supported by the results via quantitative measures. Specifically, ancient capital cities (group 3) are more axial, more intelligible, and less curved than groups 1 and 2. The hypothesis regarding synergy is partially supported by the results only in terms of the axial synergy. Meanwhile, the measure of axiality is negatively related to curvature, whereas intelligibility is possibly related to axial synergy. The hypothesis regarding organic spatial layout stating that rivers in Wuzhen, Lijiang, and Dadu are located in a higher integrated area is rejected. Nevertheless, we have found that choice values do differ more explicitly than integration values.

Based on the results, two spatial patterns of HCTC were finally presented and discussed: axiality-oriented and concentric river. This study has demonstrated a syntactical approach based on space syntax theories and methods to quantitatively analyze the spatial pattern of HCTC. The findings have been used to interpret traditional Chinese ideologies, such as Confucianism (a grand concentric order) and feng shui (e.g., the syntactic role of rivers in towns) and their influences on the spatial pattern of HCTC. In the future, these measures will be tested and refined by applying to broader historic town/city cases in the Chinese context to enrich the understanding about these significant historic and cultural treasures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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All the authors have made substantial contributions to this paper. The first author Pan Liao drafted the work, while the rest authors revised it critically. The detailed author contributions are shown below:

Conceptualisation: Pan Liao and Ning Gu; Methodology: Pan Liao, Ning Gu, and Chris Brisbin; Formal analysis: Pan Liao and Rongrong Yu; Writing - original draft preparation: Pan Liao; Writing - review and editing: Ning Gu, Chris Brisbin, and Rongrong Yu; Supervision: Ning Gu, Chris Brisbin, and Rongrong Yu.

Appendix A. Supplementary data

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References


