COMPUTATIONALLY MAPPING SPATIAL PROPERTIES OF CHINESE HISTORIC TOWNS USING SPACE SYNTAX

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Abstract. Due to its geographic size and long cultural history of fluctuating borders, China has a large number of historic settlements; each with their own unique geometric, cultural, social, and spatial characteristics. Despite the various studies that have attempted to qualitatively describe the spatial properties of historic towns, there are limited attempts to understand the spatial qualities of these towns through a quantitative approach, such as space syntax. This paper proposes and demonstrates a computational approach based on space syntax to map spatial properties of these towns. Four spatial features are examined and evaluated to capture the spatial patterns of Chinese historic towns: (1) axiality, (2) curvature, (3) intelligibility, and (4) synergy. The approach has been applied to four typical towns in China: Pingyao, Lijiang, Kulangsu, and Wuzhen. This computational approach provides a new way to complement existing qualitative measures of understanding the urban form and use of historic towns, providing a powerful tool to support the development of policy affecting historic town design/planning, heritage conservation, and heritage tourism.

Keywords. Chinese historic towns; spatial properties; space syntax.

1. Introduction

"[S]pace is not a background to human activity, but intrinsic to it ... space is first and foremost *configurational*." (Hillier, 2014)

Historic towns present a precious legacy for contemporary society that embodies how humans use the spaces enveloped within human settlements. China, due to its extensive history and vast territory, has a large number of historic towns that have each evolved with their own unique geometric, cultural, social, and spatial characteristics and configurations. These different configurations embody recognisable spatial patterns that engender the ideology of previous Chinese dynasties and traditions. For instance, Pingyao, in northern China, was built by the Han people and is often characterised by urban and architectural forms such as walled enclosures, orthogonal spatial layouts, and an ordinal spatial hierarchy (Wu, 1986, Whitehand and Gu, 2006, Gu, 2001). In contrast, while borrowing

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from the architectural heritage of the Han people, some minority ethnic groups designed their towns following a different ideology. The spatial layouts of these towns, such as Lijiang, are, in part, informed by their geography, making use of mountains and rivers, which is incorporated philosophically as organic elements in the resulting spatial layout of Lijiang. These characteristics are generally analysed and discussed qualitatively in the literature on historic Chinese towns such as Pingyao, Lijiang, Kulangsu, and Wuzhen. However, this approach limits the development of a more critical and nuanced understanding of the spatial patterns of urban settlements. A quantitative approach provides focused empirical data on which to identify and understand the connections and patterns of use of a human settlement, and relation information to support the methodological comparison between towns that may assist in developing an understanding of not just what a city looks like, but why it is used the way it is, and how it might be adapted in the future.

Firstly, in this paper spatial properties of Chinese historic towns are reviewed. Based on the review, qualitative spatial properties are identified through the application of space syntax techniques to analyse spatial configuration. Secondly, to map the qualitative measures of these Chinese towns, four spatial features are examined and evaluated to capture the spatial patterns of these historic settlements: (1) axiality, (2) curvature, (3) intelligibility, and (4) synergy. A set of space syntax measures and formulas are then used to interpret the four spatial features. Finally, computational analyses are conducted to analyse the spatial patterns of the four historic town case studies to examine their relationships with each other.

2. Spatial properties of Chinese historic towns

The spatial layouts of Chinese historic towns incorporate spatial patterns that reflect the philosophical and ideological characteristics of previous cultural groups who lived on the site and their cultural traditions. The accord of Heaven and Man (*tianrenheyi*) and the geomantic principles and ideas (*fengshui*) have long influenced the design of traditional urban forms and the organisation of architectural space in China. The first known Chinese urban planning publication *The Craftsmen's Record* (*kaogongji*, ca. 475 - 221 B.C.E), describes the spatial and functional design for an 'ideal city'. The 'ideal city' includes several noticeable features such as a walled enclosure, axiality, orientation, arteries, and hierarchy of the spatial layout (Wu, 1986, Whitehand and Gu, 2006, Gu, 2001). *The Book of Master Guan* (*guanzi*, ca. 500 - 100 B.C.E) extends the principles introduced in *The Craftsmen's Record* by responding to the specificity of a site and determining a city's size based on its unique characteristics (Wu, 1986).

However, not all Chinese cities follow the 'ideal city' pattern. Different types of Chinese towns display different spatial patterns reflecting their geometric, cultural, social, and historical characteristics. Wang *et al.* (1999) categorise Chinese cities into seven types: ancient capital, traditional city, scenic spot, local ethnic culture, modern historical spot, special functionality, and general historical spot. For example, the spatial layouts of historic towns in northern China are different from those in the south. The urban planning of the ancient Chinese capital Beijing contains a 7.8 km long axis through the Forbidden City. It describes within

its streets and buildings a strict spatial order that represents its imperial authority as a capital city during the Ming and end of the Qing dynasties (1420 - 1912). While in the south of China, there are numerous waterfront towns which are organised around river delta systems such as in the Pearl River Delta region of Guangzhou. Unlike the Forbidden City, 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 for example can be described as "bridges, rivers and dwellings" (Zhang, 2002). In addition, although some minority ethnic groups follow the building ideology of the northern Han people, their towns have their own unique characteristics, including a number that are also influenced by modern development.

3. Space Syntax measures mapping

Space syntax was initially proposed by Hillier and Hanson in *The social logic of Space* (Hillier and Hanson, 1984). It is based on graph theory which abstracts a unit (for instance, open space) as a node with the connections between these units identified as links where a topological relationship between these units are subsequently built (Jiang and Liu, 2010). Space syntax has developed into a series of measures to computationally analyse and explain patterns and relations in and between spaces. While the term connectivity indexes the number of nodes that a node is connected to, the term depth is calculated by the shortest topological path from one node to another. One of the most important measures in space syntax is integration (*i*). It "is a normalized measure of distance from any a space of origin to all others in a system. In general, it calculates how close the origin space is to all other spaces, and can be seen as the measure of relative asymmetry (or relative depth)" (Hillier and Hanson, 1984). In terms of spatial structure, the *i* value indicates the potential to-movement in a given space, or, what might be termed its closeness. In contrast, the term choice indexes how likely a node is chosen from all the pairwise node-node walk in a connectivity graph. That is to say, choice can be understood as the betweenness in a street network, considered as through-movement. Both integration and choice are justified measures in applying space syntax to index and identify street centrality in an urban setting.

In addition, space syntax has introduced some normalised measures for comparison purposes: for example, integration HH (HH is an acronym for Hillier and Hanson) (Hillier and Hanson, 1984) and Normalised Angular Choice (NACH) (Hillier *et al.*, 2012). Normalised measures make the comparison of spatial configurations among different cities possible.

According to the spatial properties previously identified, four spatial features are examined: axiality, curvature, intelligibility, and synergy. The first two measures, axiality and curvature, are used to summarise the 'ideal city' pattern of Chinese historic towns. The latter two measures, intelligibility and synergy, are derived from space syntax terminology; describing the relationship shared between the parts and the whole, which can also be used for design/planning of urban settlements.

3.1. AXIALITY

Axiality is a typical spatial property in Chinese ancient towns influenced by the Han building ideology. Pingyao, Xi'an, and Beijing possess an orthogonal street pattern with a rectangular shape. Hillier and Hanson (1984) use the term grid axiality to describe this spatial street pattern with the following formula:

$$G_A = \frac{2I^{\frac{1}{2}} + 2}{L} \tag{1}$$

Where L is the number of axial lines and I is the number of islands in the street network A. Axial lines are a set of fewest, longest, straight, and intersecting lines to cover all the spaces of urban grids, ensuring all lines are intersected and rings of circulation completed (Hillier and Hanson, 1984). Different from road centrelines, axial lines are considered as visibility lines representing how far people can move and see (Jiang and Liu, 2010). Islands are defined as voids/blocks in the open street spaces. Note axial lines can be automatically generated by the software UCL depthmapX.

The result of grid axiality is a value between 0 and 1 with which closer to 1 indicates a stronger grid axiality (Asami *et al.*, 2001). Figure 1a is a street network with four islands. Six axial lines pass through the open space ensuring all the islands have been thoroughly covered. According to formula (1), the grid axiality of Figure 1a can be calculated as 1. This indicates that this street network has a perfect orthogonal shape and strong axiality. On the contrary, with the same number of islands in Figure 1b, nine axial lines are required to cover that street network. The value of its grid axiality is 0.67. Although there are some curved streets in Figure 1b, it still shows a strong axiality. The value of grid axiality is directly associated with the number of islands and axial lines regardless of the scale of that grid, thus providing the opportunity to compare the degree of grid axiality in different cases with different shapes and scales. Generally, a grid axiality value around 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).

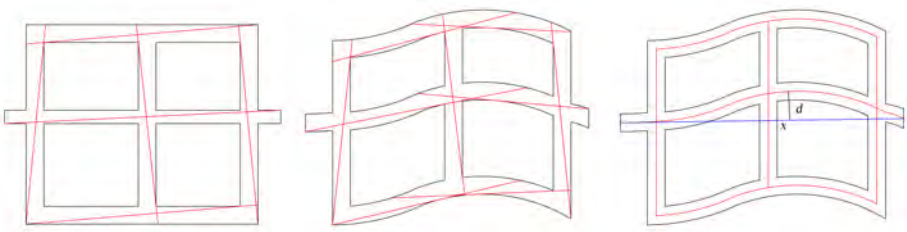

Figure 1. 1a: (left) Axial lines covering the street network with axiality. Figure 1b: (middle) Axial lines covering the street network with axial deformation. Figure 1c: (right) Curved streets transformation illustration.

3.2. CURVATURE

Curvature describes the form of streets through their degree of curvature where 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 Chinese town possesses. Unlike the measure of grid axiality, which 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 Zafrir-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. The formula is as follows:

$$Cur_A = \frac{L}{S} \tag{2}$$

Where L is the number of axial lines in a given street network, and S is the number of streets in the network A. While Omer and Zafrir-Reuven (2015) did not demonstrate how they count the number of streets, this paper follows a method of transforming curved streets into street segments adopted by Liu and Jiang (2012) to calculate the number of streets in the network. As shown in Figure 1c, road centrelines are generated through CAD software. By linking the two endpoints of a curved road centreline, a baseline is created with its length x and the distance d between it and the farthest vertex on the curved centreline. The curved centreline will be chopped by two from the farthest vertex when the ratio d/x is greater than 1.5% ($x > 30$ metres) or greater than 15% ($x \leq 30$ metres) (Liu and Jiang, 2012). In this way, the number of streets is determined by how many street segments have thus been generated. Note that roads that do not exhibit axial lines are not counted. Returning to Figure 1a, the degree of its curvature is calculated as 1, wherein Figure 1b it is 1.5. Importantly, the curvature degree is calculated based on the assumption that the street network is flat. Thus, the vertical curvature associated with a settlement's topography and its impact on its urban form is not considered in this paper.

3.3. INTELLIGIBILITY

Intelligibility indexes the degree to which the number of immediate connections a line has to other lines. It is a reliable guide to the importance of that line in the system as a whole - it is a correlation between axial connectivity and global axial integration (Hillier *et al.*, 1987). Stronger intelligibility implies that it is easier for a visitor unfamiliar to the system (for example, a tourist) to navigate the whole system. In other words, one can read the whole system from the part within the system that the visitor is located at. Intelligibility has been widely used in space syntax research over the years, and it is a potential indicator as to how visually intelligible a settlement like a Chinese historic town is. In addition, it provides further insights into the detailed spatial design of historic towns.

Note: in order to compare the correlation values across different cases with different nodes, a further z-test is needed to normalise the value.

3.4. SYNERGY

Synergy is defined as the correlation between radius-3 and radius-*n* integration. It measures the degree to which the internal structure of an area relates to the larger-scale system in which it is embedded (Hillier, 1996). It is also called axial synergy while this paper uses angular synergy instead. For the differences between axial integration/synergy and angular integration/synergy, readers need to refer to (Hillier and Iida, 2005). In space syntax research, the local metric radius is often set from 500m (Hillier *et al.*, 2012) to represent local topological radius (step 3) approximately. This paper uses the correlation of angular integration (radius *n*) and local integration (radius 500m) to interpret synergy due to a smaller size of historic Chinese towns. The co-presence of high global angular integration and local angular integration means a visitor has easier access to a local site without the spatial interference of visual congestion (Li *et al.*, 2016). As heritage tourism develops, the vehicle is strictly limited in the tourist spots of historic towns where the visual navigation of tourists needs to be carefully designed. Therefore, synergy can be used as a potential indicator as to how to plan urban spaces so that they make buildings and places of significant heritage value more visually present.

Also, in order to compare the correlation value across different cases with different nodes, a further *z*-test is needed to normalise the value.

4. Computational analysis and results

In this paper, the proposed computational approach was applied to four typical spatial arrangements present in Chinese historic towns: Pingyao, Lijiang, Kulangsu, and Wuzhen. As illustrated in Figure 2, Pingyao (top left) is a typical town built by the Han people, the primary ethnic group of China in ca. 800 B.C.E, and has possessed a clear axiality in its network grid. Lijiang (top right), on the other hand, was built by a minority ethnic group called the Naxi in the 1300s, while Kulangsu (bottom left) was constructed under the influence of modern development in the 1900s where a curved street pattern is visible in its network grid. Finally, Wuzhen (bottom right) is a representative of waterfront towns since the 800s in China in which organic elements are incorporated into the planning of the town's network grid. The grid axiality, curvature degree, intelligibility, and synergy values of the four cases are shown in Table 1.

4.1. AXIALITY

In Table 1, it is clear that none of these cases has a greater grid axiality value than 0.25 that indicates a grid-like pattern system. The grid axiality value of Pingyao is the largest one, followed by Wuzhen, Lijiang, and Kulangsu. Pingyao is a typical town that follows the building traditions of walled enclosures and north-south and east-west axis orientations of buildings and streets. The reason the axiality value of Pingyao is not large enough (less than 0.25) might be because of the irregular walls in the southern parts of the city. However, the axiality degree is still greater than the other three case studies, which is almost three times that of Kulangsu. Wuzhen has the second largest axiality value. As the urban planning of Pingyao and Wuzhen were developed under the influence of the Han people, it

is expected that they would present results that express higher degrees of axiality that are typical spatial properties common in Han-based Chinese historic towns. Finally, Kulangsu, a historic international settlement, presents an axiality that is ambiguous and that cannot be definitively categorised.



Figure 2. The maps of the four cases: Pingyao (top left); Lijiang (top right); Kulangsu (bottom left); Wuzhen (bottom right).

Table 1. The statistics of the four cases.

Cases	Grid axiality	Curvature	Intelligibility	Synergy
Pingyao	0.0690	2.0914	0.4650	0.7030
Lijiang	0.0360	2.1201	0.3890	0.6280
Kulangsu	0.0285	2.3676	0.3710	0.8740
Wuzhen	0.0479	2.1183	0.3860	0.8970

4.2. CURVATURE

In Table 1, Pingyao has the smallest curvature degree, which supports the supposition that in towns built by the Han people, curved street patterns are generally not present. Wuzhen Town, also built by the Han people, is the second least curved urban site of the four case studies. In addition, while Wuzhen is slightly geographically smaller than Lijiang in terms of the geographical area, the curvature degree of Wuzhen and Lijiang are almost the same. The town with the most curved street network is Kulangsu. What makes the curvature degree in Kulangsu special is an outcome of its physical geography. Kulangsu is located on an island surrounded by several mountains which have influenced how the town was planned and has evolved. Contrastingly, towns planned in China with modern development (post-war) principles, are less likely to follow the Han people building tradition, and Kulangsu is one of such examples. If considering the grid axiality and curvature together, a higher axiality value is often accompanied by a less curvature degree. It may provide a clear relationship between curvature and axiality that may be applied in the ongoing planning of Chinese historic towns to ensure that any new development does not destroy these valuable spatial patterns.

4.3. INTELLIGIBILITY

In terms of the intelligibility of the four cases, all resulting values show a moderate coefficient size (as indicated in Table 1), ranging from 0.3 to 0.5. Pingyao has the most significant intelligibility value, followed by Lijiang, Wuzhen, and Kulangsu. The intelligibility value of Lijiang is similar to that of Wuzhen, while Kulangsu seems to be the least visually intelligible historic town. A further pairwise correlation *z*-test is conducted to compare the correlation across the case study towns. It is only significant when it comes to Pingyao and Kulangsu. Pingyao, a traditional Han city, is more intelligible than Kulangsu, a historic international settlement. While less evidence shows that an ancient town is more intelligible than a town influenced by modern development, it does act as a good indicator in terms of tourists' potential visual way-finding through a street network. If further considering axiality and intelligibility together, it seems in Pingyao and Kulangsu they have the same trend. That is to say, a higher grid axiality value is accompanied by a higher intelligibility value. As discussed above, axiality is a typical property distinguished from the Han people and other ethnic minorities. Therefore, axiality may also be a predicting indicator of intelligibility.

4.4. SYNERGY

The synergy comparison of the four case studies indicates some different trends. As per previous results - although not at a significant level - the order of the intelligibility values of the four cases from high to low is: Pingyao, Lijiang, Wuzhen, and Kulangsu. Regarding synergy, the order is Wuzhen, Kulangsu, Pingyao and Lijiang at a radius of 500 metres (all pairwise correlation *z*-tests are significant this time). It is evident that the synergy values in Kulangsu and Wuzhen are quite high. This means their areas with a high local angular integration value are more likely to have a high global angular integration value. The results may,

therefore, provide some useful insights. For instance, local tourist attractions in Pingyao and Lijiang should be addressed to adjust their synergy values. If their local attractions have a high local angular integration value, they are less likely to become global attractors than Wuzhen and Kulangsu whom both possess high global angular integration values. Thus, the spatial design of streets and public space nodes between streets should be targeted in this area to facilitate effective pedestrian flow so that tourists can more easily visually navigate and get easier access to those local attractions.

5. Discussions and conclusion

With the proposed four measures, this paper provides a computational approach to mapping the spatial properties of Chinese historic towns using space syntax. In this paper, syntactic measures of grids axiality, streets curviness, and the relationships between the parts and the whole are used to interpret spatial patterns of Chinese towns. Additional measures can be considered to further explore spatial patterns of Chinese historic towns in a mathematical manner, for instance, integration HH and Normalised Angular Choice (NACH). Moreover, some Chinese towns are organised in response to rivers flowing through or around them (e.g. Wuzhen Waterfront Town) where the syntactic measures of organic elements could also be considered. If rivers are dominant in configuring the spatial layout, the location of rivers and bridges could have configurational meanings. Finally, this paper only compares the four case studies at the overall scale of the entire town, not at the urban granular level of the streets themselves. Due to the limited number of cases, correlation analysis and regression model has not been built. Towns at a smaller scale are considered, and further results will be published in a forthcoming paper.

Some limitations still need to be addressed though. Firstly, flaws may occur due to some manual procedures. This includes manual maps digitalisation and street segments generation. Secondly, our analyses are primarily based on axial line maps. However, automatically generating axial lines has been a long debate in Space Syntax studies (Liu and Jiang, 2012). In this paper, UCL depthmapX is used to automatically generate axial lines which are somewhat problematic. We have to manually check and delete redundant lines to yield the final technically correct axial line maps. Thirdly, all the analyses are based on the assumption that the street networks are flat which are not possible in the real-world topography. Finally, this paper only considers geometrical measures and does not consider subjective evaluation that may be useful regarding how residents and tourists perceive a spatial layout of a historic town (Zawidzki, 2016). Even though with these limitations, the proposed approach is still a powerful tool to understand the spatial properties of Chinese historic towns.

In terms of the case studies that are analysed to demonstrate and evaluate our computational approach, we suggest axiality as a core indicator to link other related measures together, such as curvature and intelligibility. If there is a significant correlation, it requires an additional regression model to be built between axiality and other measures. Intelligibility and synergy can be used for design/planning regarding heritage tourism development. Improving the intelligibility values thus helps tourists easily visually navigate the system network of streets in a historic

town. While improving the synergy values, it helps tourists easily access local tourist attractions without suffering too much visual pedestrian congestion on their way to them. In summary, the overall compactional approach is potentially helpful for case comparison, heritage conservation, and heritage design/planning of the ongoing development of historic towns in China so as to not lose the unique urban character that has made them so important to Chinese identify, culture and history.

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