Cities 161 (2025) 105854

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

Formalising the urban pattern language: A morphological paradigm towards understanding the multi-scalar spatial structure of cities

Cai Wu [a,b,c,*], Jiong Wang [a], Mingshu Wang [d], Filip Biljecki [c,e], Menno-Jan Kraak [a]

[a] *Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, the Netherlands*
[b] *Thrust of Urban Governance and Design, Society Hub, The Hong Kong University of Science and Technology (Guangzhou), China*
[c] *Department of Architecture, College of Design and Engineering, National University of Singapore, Singapore*
[d] *School of Geographical and Earth Sciences, University of Glasgow, Glasgow, United Kingdom*
[e] *Department of Real Estate, Business School, National University of Singapore, Singapore*

ARTICLE INFO

Keywords:
Urban morphology
Scales
Pattern language
Urban planning
Street pattern
Urban spatial structure

ABSTRACT

The urban form is a foundational element in urban analytics, planning, and design. However, systematic and consistent depiction of urban form is challenging due to the complexity of urban elements and the variety of scales involved. This paper formalizes the concept of 'urban pattern language' as a multi-scalar analytical approach to decode such complexity, drawing on Christopher Alexander's idea that offers solutions for recurrent design problems observed in historic and contemporary urban settings. This analytic approach is applied to two case study cities to explore how urban forms can be decoded and communicated across scales and demonstrate how urban morphological elements can be systematically organised into recognisable patterns that simplify analysis and enhance understanding. The findings show that these patterns are not arbitrary but follow structured, rule-based relationships that vary across scales, revealing an underlying order within the urban form. Finally, the study illustrates that these rules are unique to each city, potentially reflecting specific cultural, historical, and spatial contexts. By identifying city-specific, multi-scalar patterns, this framework offers a powerful framework for urban planning and design, allowing practitioners to develop adaptable and context-sensitive strategies.

1. Introduction

The urban form, is an enduring and fundamental element in urban analytics, planning, and design (Fleischmann, Romice, & Porta, 2021; Moudon, 1997; Stevens & Thai, 2024; Wang, Huang, & Biljecki, 2024). It holds the key to understanding the mutual influence of the built environment and human behaviours (Bielik et al., 2019; Crooks et al., 2015; Elzeni, ELMokadem, & Badawy, 2022; Panerai, Castex, Depaule, & Samuels, 2004; Venerandi, Zanella, Romice, Dibble, & Porta, 2017; Xia, Yeh, & Zhang, 2020). However, depicting the urban form meaningfully and systematically is always challenging, given the myriads of urban elements, such as buildings and streets, and scales, from micro to macro, involved in shaping the physical built environment (Batty, 2008). Hence, a common practice is to use urban patterns, the recurring configurations or arrangements of urban elements (Marshall, 2004), to reduce complexity and summarise the characters of the urban form. This study integrates and extends existing urban morphology and spatial analysis frameworks through a structured, multi-scalar "**Urban Pattern Language**". As Christopher Alexander coined in his seminal work "A Pattern Language" (Alexander, Ishikawa, & Silverstein, 1977), a pattern language represents a set of guidelines or solutions for reoccurring design problems derived from historic and contemporary urban environments. Original pattern language has brought clarity to architectural and neighbourhood design by providing a replicable framework for analysing spatial relationships and human-scale details (Salingaros, 2000). Our urban pattern language further extends this concept, viewing the urban landscape as a series of patterns of different urban elements at varying scales, which offers a lens to scrutinise the fabric of city life, revealing advantages such as enhanced liveability, efficiency, and sustainability. This approach facilitates pattern identification, comparison across cities, and adaptability for diverse urban planning applications. The urban pattern language conceptual framework is built upon two fundamental hypotheses: firstly, that distinct patterns of different urban elements exist at various scales are not arbitrary but follow specific

* Corresponding author at: Thrust of Urban Governance and Design, The Hong Kong University of Science and Technology (Guangzhou), China.
E-mail address: caiwu@hkust-gz.edu.cn (C. Wu).

https://doi.org/10.1016/j.cities.2025.105854
Received 28 March 2024; Received in revised form 26 January 2025; Accepted 24 February 2025

rules, for example, the different street layouts will have different preferred building designs; and secondly, the rule or relationship between the diverse patterns is unique with potential as a reflection to the cities' particular background and needs. Thus, understanding and exploring these pattern relationships can explain historical urban development and provide actionable guidelines for contemporary urban planning and design.

2. The foundation of urban pattern language

Urban design and planning are intricate fields that constantly grapple with the challenge of deciphering and applying enduring principles amidst societal changes, technological advances, and demographic shifts (Batty & Marshall, 2017; Healey, 2006; Young, 2017). This quest for stability and resonance in urban spaces finds a kindred spirit in Christopher Alexander's seminal work, "The Timeless Way of Building" (Alexander, 1979). Alexander posits that truly profound urban spaces exude a "timeless" essence, a harmonious blend of form, function, and human experience that remains steadfast amidst the whirlwind of societal changes, technological advancements, and demographic shifts. This is also echoed in Alexander's "A Pattern Language," which provides a tangible roadmap for urban designers and planners. It suggests that internalising and applying specific design patterns can infuse modern urban settings with the same harmonious resonance that characterises timeless spaces. Initially rooted in architectural principles, this pattern language approach has burgeoned into one of the 20th century's most influential concepts (Dawes & Ostwald, 2017; Iwańczak & Lewicka, 2020). It offers a structured framework, encapsulating realised patterns that address recurring design challenges, streamlining solutions, and fostering effective communication among professionals (Namwanje, Sanz, & Rocco, 2023).

In urban planning and design, the consistency and diversity of physical patterns or forms of cities have been observed and studied at different scales in specific urban contexts (Bobkova, Berghauser Pont, & Marcus, 2021; Macdonald, 2016). For example, using form-based code (Parolek, Parolek, & Crawford, 2008) to facilitate urban design and planning suggests that functionality and consistency can be anchored by strictly stipulated forms/patterns. The Form-based code seeks to use regulated plans, buildings, landscapes, and street patterns to revitalise old communities. Alternatively, the Typomorphology approach links various architectural forms with the cultural and social heritage of the city to inform future design (Leite & Justo, 2017). More examples including Conzen's multi-scale town-plan analysis (Conzen, 1960), which emphasizes the interplay between street networks, building forms, and land use and Stewart and Oke's Local Climate Zones (Stewart & Oke, 2012), which introduces a classification system for climate-responsive urban design. Without intentionally using the pattern language concept, these different patterns from various scales have been combined to create a cohesive urban narrative. In dealing with the planning and design challenges in an urban context, the traditional pattern language concept also shows tremendous potential for an upscaling expansion. It offers us three wise counsels: Patterns, Scales, and Language, which provide a structure to decode the complex urban landscape and apply this knowledge.

2.1. The patterns

The complex urban landscape can be understood through the lens of urban morphology, which the International Seminar on Urban Form (ISUF) (1997) defines as the study of the form of human settlements and their formation and transformation process. This discipline scrutinises the layered structure of urban patterns—quantifiable, discrete entities that emerge from the form of cities. Urban patterns, introduced across various disciplines, are a consistent framework for research, planning, and communication (Gallion & Eisner, 1980; Lynch, 1960; Wentz et al., 2018). They serve as a constant that ensures that the urban form is comprehensible and design intentions are transparently conveyed and uniformly understood, fostering collaborative efforts among urban scholars, planners, designers, and stakeholders.

Urban built environments, with their intricate tapestry of life, memories, and aspirations, are more than just conglomerates of buildings and streets. To decode this complexity, scholars and urban planners have first tried to break down the built environment into a few selectable urban elements, such as Kevin Lynch's "Image of the City" (Lynch, 1960), which dissects the city into five basic urban elements: Path, Edge, Landmark, District, and Node. The second step is to turn these urban elements into patterns, crystallised templates that distil urban forms into discernible, replicable entities. Historically, these patterns captured urban form various urban elements, ranging from street layouts and building typologies to public space arrangements (Bolleter, Hooper, Kleeman, Edwards, & Foster, 2024; Chen, Huang, Liao, Gao, & Biljecki, 2024; Marshall, 2004; Pont, 2010; Wu, Wang, Wang, Smith, & Kraak, 2024). The aim was to identify and replicate patterns fostering community, enhancing liveability, and facilitating urban mobility. For instance, the grid pattern of streets, popularised in ancient civilisations and cities like New York, simplified navigation and land division (Boeing, 2021; Stanislawski, 1946). The pattern of a courtyard house, prevalent in many cultures, emphasizes communal living and climate responsiveness (Abass, 2016). These patterns, rooted in urban geometry and spatial organisation, provided aesthetic appeal and practical tools to decipher urban landscapes.

With advanced tools and infrastructure such as geoinformation systems, artificial intelligence, and data analytics, urban patterns have transitioned into the digital realm, facilitating quantitative analysis (Batty, 2019; Cai, Demuzere, Tang, & Wan, 2022; De Sabbata et al., 2023; Li, Li, Yang, Liu, & Huang, 2023). These digital tools enable the measurement of urban form using morphological indicators and support the identification of urban patterns with a level of accuracy and detail previously unattainable (Biljecki & Ito, 2021; Clifton, Ewing, Knaap, & Song, 2008; Kang, Zhang, Gao, Lin, & Liu, 2020; Wu & Biljecki, 2023; Zhang, Ghosh, & Park, 2023). For example, Space Syntax methodologies (Hillier, Leaman, Stansall, & Bedford, 1976; van Nes & Yamu, 2021; Ye & Van Nes, 2014) offer analytical tools for understanding spatial connectivity and movement patterns. Street patterns, space matrix, urban block, and polycentricity (Anas, Arnott, & Small, 1998; Marshall, 2004; Meijers, 2008; Pont, 2010) are just a few examples of patterns to describe urban form; many more are introduced. This paper considers these patterns as urban that policymakers, designers, and planners are most familiar with and work with on a daily basis. Thus, by anchoring our study in these enduring patterns, we could offer academically rigorous, directly relevant insights and actionable insights for the practitioners shaping our urban futures.

2.2. The scales

The research also acknowledges the importance of scale when applying patterns in an urban context. The urban pattern may manifest differently with various levels of detail when viewed at different scales (Batty, 2008; Schmitt et al., 2023; Zhang et al., 2023). This diversity coincides with the need for different professionals, policymakers, planners, or architects who work on different scales. Hence, it is important to identify the scales of these patterns, whether the focus is on an overarching city blueprint or the intricate design of a specific neighbourhood, pattern with scales provides the tools to address these challenges.

Corresponding to the urban professionals this paper aims to address, the scales can be summarised into three levels: **Macro, Meso and Micro** (Boeing, 2018; Lim, Ignatius, Miguel, Wong, & Juang, 2017; Schirmer & Axhausen, 2016). At a **macro** level, which usually means the entire metropolis or a city agglomeration, policymakers, and urban planners employ overarching strategies, using spatial/master plans to promote development, mobility, sustainability, and resilience. At this scale, the urban patterns generally describe the distribution of the urban elements across the city: density, compactness, sprawl, etc. (Batty, 2008). Concepts and works on patterns at this scale are exemplified by urban spatial structure, compact city, and transit-orientated development (Anas et al., 1998; Malczewski, 2009; Meijers, 2008; Singh, Lukman, Flacke, Zuidgeest, & Van Maarseveen, 2017; Taubenböck, Wurm, Geiß, Dech, & Siedentop, 2019; C. Wu, Smith, & Wang, 2021), etc.

Zooming into the ***meso*** scale, usually contoured by a district or neighbourhoods (Mohamed, Ubarevičienė, & van Ham, 2022; Sharifi, 2019b), urban planners and designers focus on street layout and land parcel relationships (Liu, Shi, Peng, & He, 2023), capturing the essence of vibrant street life and architectural rhythm using urban design schemes. Urban patterns on this specific scale are characterised mainly by the street patterns of general traffic or pedestrian networks, the creation of the city skyline, and the landscape, which are both crucial concepts in urban design practices.

At finer **micro** scales, represented by the block or land parcels, urban designers, architects, and landscape architects craft human-centric architectural experiences, emphasising functionality, aesthetics, and economic considerations. This scale focuses on the shape of individual buildings and their intricate relationship with the surrounding environment. The patterns here typically focus on the shape of the buildings, the design of public space or patterns integrating both aspects, such as the Spacematrix (Pont, 2010).

Of course, patterns may exist on multiple scales and manifest differently, even given the same urban element, such as buildings, streets, and open spaces. They are approached differently by each profession, leading to varied patterns and levels of detail. The urban patterns mentioned earlier more or less fit into the urban scales, forming a multi-scalar expression of urban pattern language that aligns seamlessly with the varied focus of urban professionals. For example, the street pattern at the micro-scale may focus on the pedestrian and show more organic character, while on the meso-scale, focus on the vehicle and efficiency; the macro scale, in contrast, focusing on the arterial road, may adopt a different pattern. As Batty suggests (Batty, 2008, 2020), the scalability in urban studies is like a different lens of resolution through which we view the city. In this light, this study articulates the patterns as consistent urban elements that manifest themselves collectively at different levels of detail in the various scales.

2.3. The language

The pattern language as a solution is not a mere collection of patterns. It combines unique patterns involving different elements at varying scales following certain rules. The language could be interpreted as the rule or the relationship between the patterns coming together to form the solution. It provides the urban pattern language with adaptability and diversity: By tweaking and combining patterns, designers can craft solutions that are attuned to local cultures, climates, and histories, ensuring that urban interventions are both globally informed and locally resonant. Hence, as we explore urban patterns, it is not enough to identify and apply patterns in isolation. We must understand how they interact, how the design of a city's street network will impact the choice of the shape of the building and public space, or reversely, how the streets and buildings may facilitate the formation of a broader urban spatial structure.

Understanding urban morphology through pattern language requires not only identifying individual patterns but also understanding their interactions within a multi-scalar framework. Patterns at different scales, such as street networks, building typologies, and open space configurations, dynamically interact to shape the city's spatial structure. For instance, the layout and connectivity of streets influence land use and accessibility, which in turn affect building placement and public space utilisation. Thus, each pattern serves a specific role while also contributing to the larger urban system. This interrelationship is essential, as patterns in isolation lack the contextual foundation needed to influence broader urban structures effectively.

The patterns and the scales provided the foundation to construct the language or unveil the rules between the multi-scalar urban patterns. Building upon Alexander's foundational work, our study introduces a novel approach to formalising and applying urban pattern language, focusing on the dynamic interplay of patterns across different urban scales. Our research has two-fold objectives: **Firstly,** we explore the relationships between these patterns, unearthing the rules that shape our urban landscape. **Secondly,** by employing urban pattern language in different case study cities, we aspire to illuminate the unique diversities and vernacular nuances across cities, postulating its invaluable utility in urban understanding and planning. It is important to distinguish our approach from Christopher Alexander's generative urban design framework. Our study does not investigate how cities evolve through self-organizing generative processes but rather seeks to quantify the spatial relationships inherent in urban morphology using empirical methods.

By building a multi-scalar structure of urban patterns and exploring its underlying rules of composition, our proposed urban pattern language may unlock a novel approach to a comprehensive understanding of the urban landscape. To prove our concept, we have designed a case study identifying urban patterns and revealing their relationships in different cities. As an illustration, we selected one pattern from each scale and carried out the analysis in two cities.

3. Formalising the concept

Here, we introduce a framework to systematically formalize the urban pattern language and elucidate its utility in demystifying cities' layered and intricate structures. Fig. 1 delineates the categorisation of patterns into three discernible scales: macro, *meso*, and micro, a classification resonant with the scholarly discourse and professional practice we mentioned earlier. At the macro scale, we consider the city in its entirety and analyse the city as an interconnected web of neighbourhoods, choosing patterns that exemplify these linkages, such as the relative sizing of neighbourhoods as indicative of a Hierarchical structure. The meso-scale investigates the neighbourhood itself, focusing on plot layouts and necessitating patterns that capture the essence of spatial arrangements, such as the street network's influence on the layout of plots and connectivity (Pafka, 2022). On the micro-scale, we zoom into plot-level details, selecting patterns like Spacematrix that detail building shapes and the configuration of open spaces.

These patterns, namely urban spatial structure, street patterns, and Spacematrix, are not arbitrarily chosen; they are rooted in established urban studies literature, reflecting a consensus on their significance in urban analysis (Anas et al., 1998; Liu & Wang, 2016; Malczewski, 2009; Marshall, 2004; Pont, 2010). They inherently link together to provide a cross-scale perspective on urban form. By focusing on buildings and streets, we avoid unnecessary complexity, ensuring our study remains accessible and actionable. The rationale behind this selection process, aligned with our research objectives, will be expounded upon in the subsequent sections, providing a robust framework for applying urban pattern language in a multi-scalar context.

The urban patterns are identified using two primary units of analysis: Street-based Local Areas (SLAs) and plots, each serving distinct yet interconnected roles in understanding the multi-layered urban form. SLAs are defined by the street network and are crucial for capturing the unique characteristics of different city parts (Law, 2017). SLAs are generated using a network clustering method that identifies neighbourhoods based on the street network (Wu, Wang, Wang, & Kraak, 2024). At the macro scale, SLAs provide the basic analysis unit to gauge the distribution and balance of urban mass and enable the assessment of a city's urban spatial structure. Moreover, SLAs play a critical role at the meso-scale. Here, the detailed analysis of the street patterns within each SLA provides insights into the character and layout of these neighbourhoods, whether they adhere to grid, organic, or hybrid patterns. Plots, the second unit of analysis, are generated using Momepy

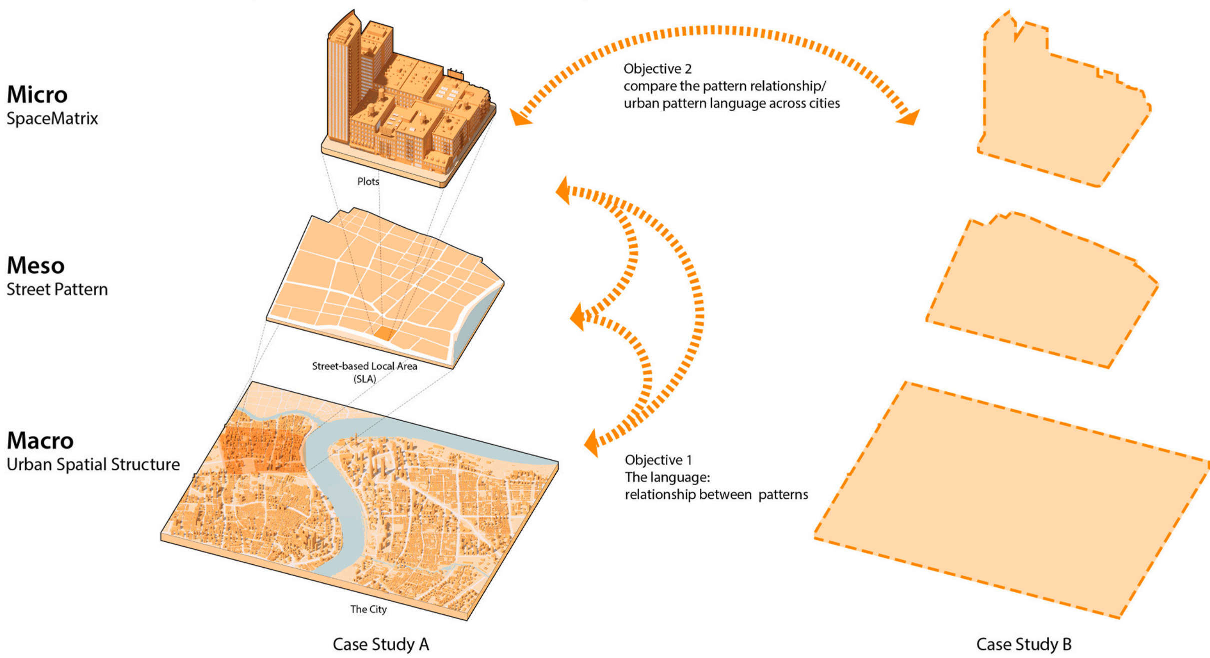


Fig. 1. Conceptual Framework of our approach.

(Fleischmann, 2019), a Python package that utilises building footprints and the street network. These plots are fundamental in the micro-scale analysis, focusing on the shape and arrangement of individual buildings and their relationship with the immediate environment. In summary, SLAs provide a macroscopic view, capturing the overarching urban structure and street layout. In contrast, the plots allow for a microscopic examination of the physical form and spatial composition at a more localized level.

Our methodology involves systematically quantifying urban patterns using digital tools such as machine learning and network analysis. The quantitative methods allow for better consistency, reproducibility, and transferability in today's digital age. More detail on how we quantify these patterns will be introduced in this section. To reveal the pattern language, say the relationship between the patterns as our first objective, we analyse the compositional relationship between these patterns. For example, is there a preferential block typology for a specific street pattern? Alternatively, whether certain street patterns are linked to the high concentration of urban mass in metropolitan areas. The second research objective is achieved by comparing the pattern language in two cities. Did they follow the same pattern language? If not, what are the potential reasons and implications? We aim to demonstrate the versatility and applicability of our multi-scalar urban pattern language approach, offering insights into the unique complexities of urban landscapes.

3.1. Macro scale

The macro scale is the crudest pattern in this study. Here, we are interested in patterns that best represent the general distribution of urban elements across the city: Where and how many are built. Together, they provide an image of the urban spatial structure of the city (Xu et al., 2022). Using the neighbourhood as the unit of analysis, we measure the relationship of urban mass size between the neighbourhoods. This so-called urban spatial structure can be interpreted as the hierarchy of neighbourhood. To determine the hierarchy of the neighbourhoods, we must first determine the relative urban mass (C_i) for each neighbourhood, which is given by formula (1).

$$C_i = 0.5\left(\frac{F_i}{F_{max}} + \frac{S_i}{S_{max}}\right) \tag{1}$$

where:

C_i: Relative urban mass of neighbourhood *i*.

F_i: Total floor space in neighbourhood *i*, which is the aggregated gross floor area of all the plots (Fig. 3).

S_i: Total street length in neighbourhood *i*.

F_{max} : Maximum floor space in the neighbourhoods across the city.

S_{max} : Maximum street length in the neighbourhoods across the city.

The choice of this formula is guided by the need to capture the urban mass in a way that reflects both the building and the streets within each neighbourhood. Equal weights are given to floor space and street length to provide a balanced representation of the neighbourhood's urban mass. By standardizing floor space and street length relative to the city's maximum values, this approach normalizes variations across neighbourhoods, enabling a meaningful comparison of their relative urban mass. This formula helps reveal the hierarchical structure within the urban spatial configuration, a crucial factor for understanding the distribution and balance of urban form across a city.

Neighbourhoods are assigned hierarchies as primary, secondary, and tertiary centres. The three-class classification of neighbourhoods is informed by principles from Zipf's law (Batty, 2006) and the central place theory (Malczewski, 2009), which is widely applied in urban studies to describe the hierarchical organisation of cities and urban centres. Zipf's law and the central place theory suggest that urban areas naturally organize into a hierarchy, with one main centre (such as a central business district or CBD) followed by regional centres and subcentres. The Jenks natural breaks method, a clustering algorithm that minimizes intra-group variance while maximizing inter-group differences, is used to classify neighbourhood hierarchies based on urban mass distribution, producing a clear and objective classification into primary, secondary, and tertiary groups.

We further use the primary centres to calculate the polycentricity. Polycentrcity refers to the balance of the distribution of the urban mass in a city, which provides an indicator of the urban spatial structure.

$$P_{std}(n) = 1 - \frac{\delta_m(n)}{\delta_{max}(n)} \tag{2}$$

where:

$P_{std}(n)$: Polycentricity measure for a system of n primary neighbourhoods.

$\delta_m(n)$:The standard deviation of urban mass C_i across all neighbourhoods in the urban system.

$\delta_{max}(n)$: Theoretical maximum standard deviation when one neighbourhood holds all urban mass and the remaining $n - 1$ neighbourhood has zero mass.

This formula provides a relative measure of polycentricity, capturing the balance in urban mass distribution across neighbourhoods. Hence, the macro-scale pattern in this case study is the identification of the neighbourhoods' hierarchy and the measurement of polycentricity.

3.2. Meso scale

At the mesoscale, which focuses on the morphology of each neighbourhood/SLA, we use street patterns as the key pattern. Street patterns, the planar layout of the street network. It shows how buildings (or plots) are organised within neighbourhoods via the connecting street network. Street patterns reveal essential information about the spatial arrangement and neighbourhood layout, showing how buildings and plots interact with the circulation network. Streets act as boundaries that delineate and organize plots, shaping the meso-level spatial structure of neighbourhoods (Marshall, 2004). This perspective is critical for understanding how spaces are interconnected, accessible, and functionally cohesive. Street patterns, in this case, are determined using thirteen street metrics and classified using a random forest classification algorithm. The street metrics are listed in Appendix 1 and calculated using NetworkX and OSMnx by representing streets as a graph. The street patterns, training dataset, and random forest classifier are adopted from Wu's work (Wu, Wang, & Kraak, 2023; Wu, Wang, Wang and Kraak, 2024).

As shown in Fig. 2, four different types of street patterns are identified: Grid, Organic, Deformed and Cul-de-sac. Each street pattern has unique characters, leading to different urban functions and activities. The character of these patterns is reflected by the metrics we applied to identify street patterns in the random forest classifier.

The Grid, also known as Gridiron, is a typical street pattern with uniform directions, straight streets, and right-angled X-shaped crossroads. It is characterised by a more uniform orientation, leading to a structured urban layout. The organic pattern contradicts the grid, with curly streets in various directions and diverse street junction appearances. It is usually more curvature, which means less straight, and the direction of the street is also more diverse, reflecting its more natural and less structured layout. The Deformed, or Hybrid, falls between the Grid and Organic patterns, showing characteristics of both, with a balanced character like a moderate X-shaped crossroads percentage and Street length. The Cul-de-sac is most recognisable for its dead-ends, having the highest Circuity and Street length, indicating its suburban nature with fewer intersections and longer streets (Wu et al., 2023). This classification provides a straightforward yet effective framework for capturing the diversity of street configurations relevant to our research objectives. Each pattern class is distinguished using quantitative measures, such as circuity, junction type, and orientation entropy, applied to the training data to ensure objective classification. While these four classes sufficiently serve the current study, the typology can indeed be expanded or modified depending on the focus of future studies.

3.3. Micro scale

The micro-scale represents the finest analysis in this research and uses the SpaceMatrix model (Pont, 2010). The Spacematrix model is especially suitable for micro-scale analysis in our research as it is diverse enough to encompass most building forms in the urban landscape but not too complicated, so it only requires relatively simple data. The SpaceMatrix classifies the plots into nine types based on the Floor Space Index (FSI), Ground Space Index (GSI), and Height (L) (Ye, Li, & Liu, 2018), which is shown in Fig. 3.

FSI, also known as the floor area ratio or plot ratio, illuminates the building density of a block. It is deduced by comparing the gross floor area to the building's footprint. Where F_x represents the gross floor area (mˆ2) and A_x indicates the gross area (mˆ2) of individual street blocks, as illustrated in Fig. 3. Pertinent to a building typology, GSI signifies the interrelation between built and unbuilt spaces within blocks. Mathematically, it is expressed in Fig. 3. Here, B_x represents the entire building footprint. L is derived by dividing FSI by GSI. It is worth noting that L does not just represent a straightforward average of the number of floors in buildings but offers a more nuanced understanding, accounting for individual building footprints.

Considering Asia's compact urban density (Chen, Chiu, & Lin, 2020; Chen, Koch, & Reicher, 2023), we have adopted a different threshold of L values to differentiate the urban blocks into low-rise, medium-rise, and high-rise. In our classification, high-rise blocks typically encompass office structures and residential towers. At the same time, those at the lower end of the L value spectrum often comprise single or dual-story residences and educational institutions. On the typological front, GSI values guide the categorisation of blocks as point, strip, or block structures. Blocks with GSI values below 0.2 are tagged as "point", those between 0.2 and 0.36 as "strip", and the remainder as "block". In sum, the SpaceMatrix generates a 3 × 3 grid classification of street blocks, resulting in nine distinct categories, as shown on the right of Fig. 3.

Given the urban patterns at the three scales defined explicitly, we can utilise these patterns to test the core concept of this research, the existence of urban pattern language and its effectiveness in distinguishing a city's morphological urban spatial structure. The expected results of this paper would be that there is a relationship between these three patterns, and the relationship is unique to each case study city. While this study does not explicitly analyse temporal change, it is important to recognize that urban elements evolve at different rates. Some features, such as street networks, tend to remain stable over long periods, while others, like building configurations, may change more rapidly in response to economic, social, and policy-driven factors.

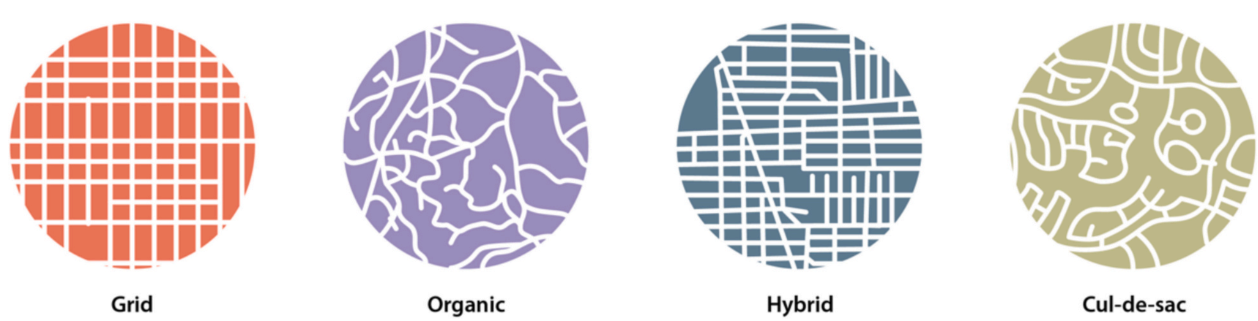


Fig. 2. Street patterns that are in the focus of our work.

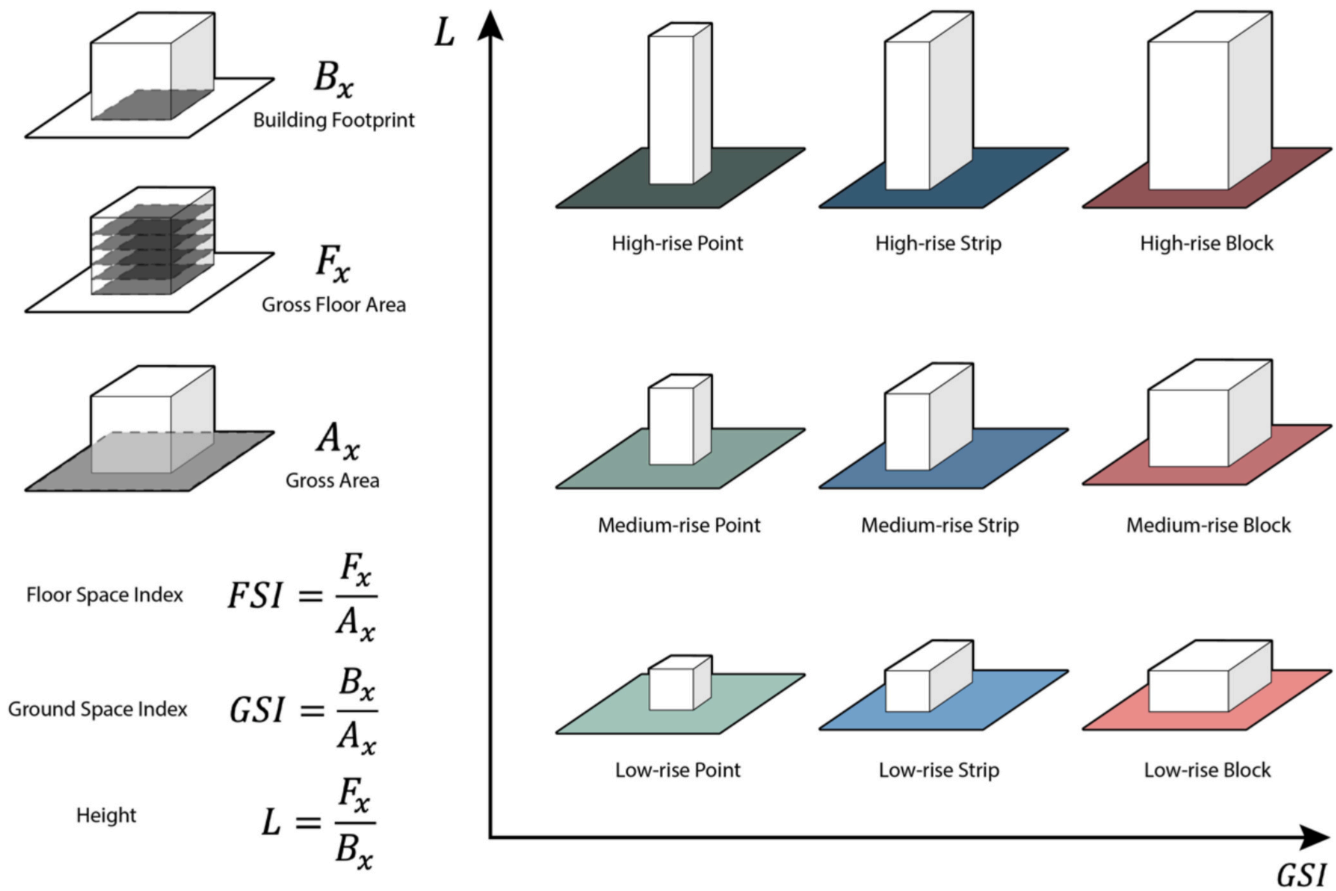


Fig. 3. SpaceMatrix and the Plot Typology.

4. Case study

4.1. Case study area

Beijing and Singapore were selected based on their size and uniqueness to test the concept of the urban pattern language. Both metropolitan cities serve regions beyond their administrative boundaries. Size-wise, the study area in Beijing is confined to the Fifth Ring Road, encompassing approximately 670 km^2 and housing about 10 million people, accounting for half of the city's population. In contrast, the main island of Singapore, covering roughly 710 km^2, has a population of about 5.6 million. Beijing is significantly more densely populated, given similar urban areas. Their large, yet similar size ensured that diverse urban patterns existed within the comparable study area. In contrast, their unique urban contexts ensured that the difference in the potential urban pattern language could be revealed.

The unique background for the two cities is shown in Fig. 4, with major urban centres indicated in orange. For Singapore, the major urban centres are clearly defined by the official master plan (Wu, Wang, Wang, Smith, & Kraak, 2024). In the case of Beijing, major urban centres are identified based on commonly recognized locations and general knowledge of the city's spatial organisation. As China's capital, Beijing

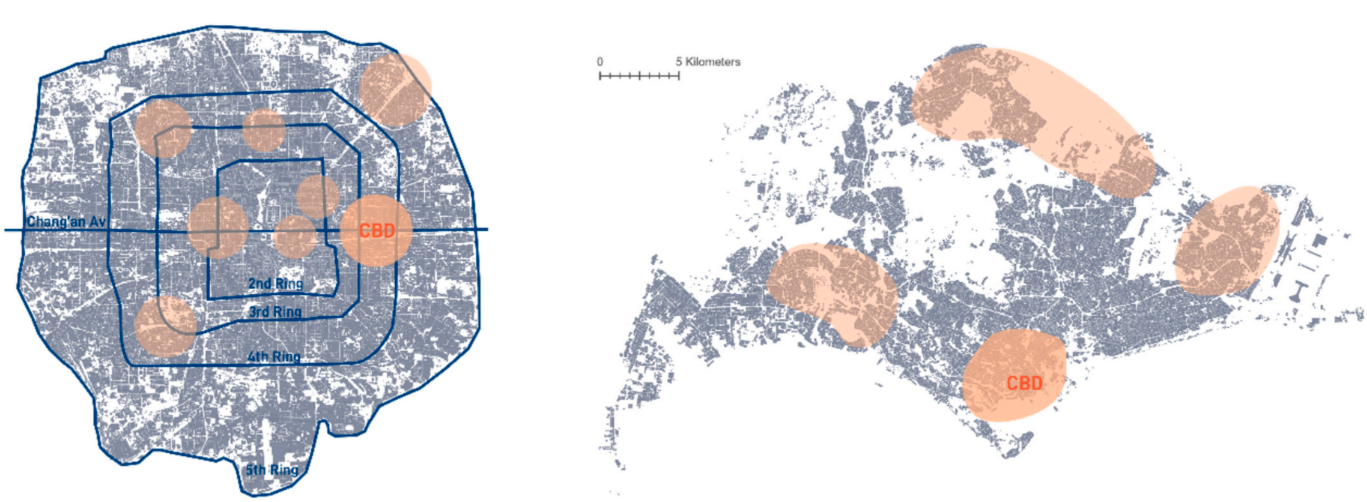


Fig. 4. Case study area of Beijing (left) and Singapore (right). Orange highlights the major urban centres in public notion. Data: OpenStreetMap.

is a vital political, cultural, financial, and business hub in both the regional and global context. Its historical core, located within the Second Ring Road, showcases traditional architectural forms such as courtyard houses and hutongs alongside landmarks like the Forbidden City. Following rapid urban regeneration and expansion, particularly post-2008 Beijing Olympics, the city's landscape has manifested a ring structure extending from the Second to the Sixth Ring Road. This expansion has been marked by a focus on development in the outer ring regions. A notable thoroughfare, Chang'an Avenue separates Beijing's Northern and Southern parts. The city's main commercial and business centres, as perceived by the public, are primarily situated in the Northern part, including the Central Business District (CBD).

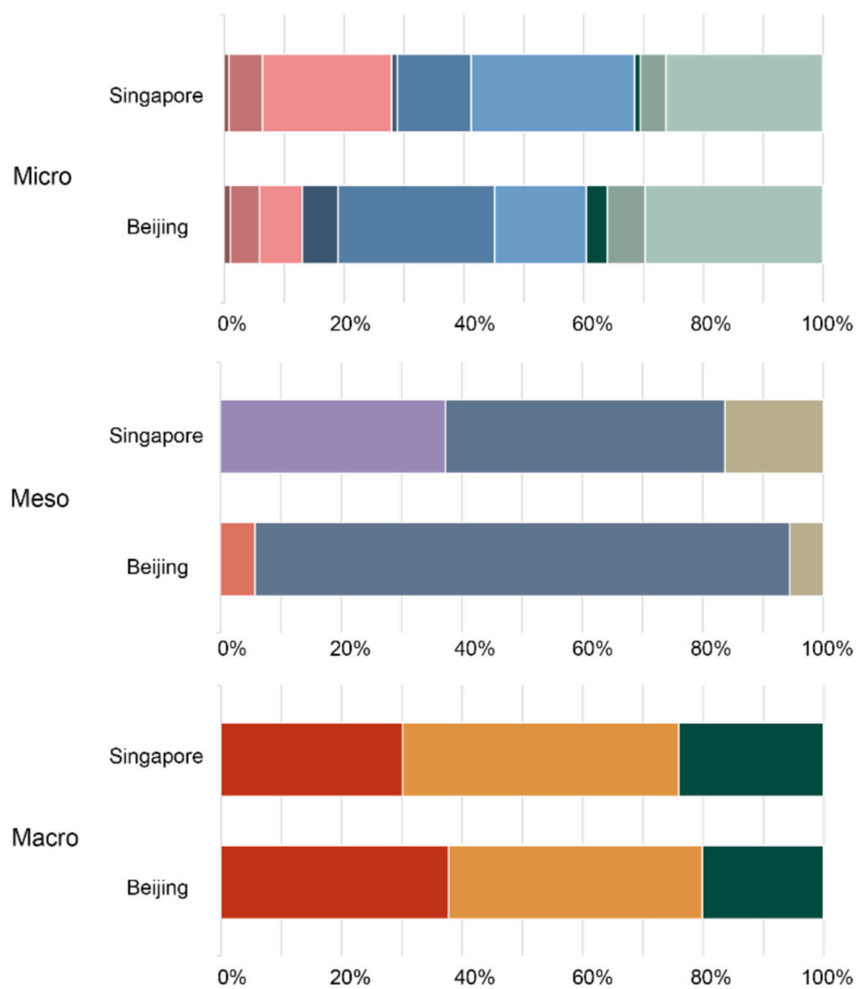
In contrast, Singapore, an island city-state located at the southern tip of the Malay Peninsula, embodies a different urban landscape. Known for its strategic geographical location, Singapore has evolved into a global financial hub and a cosmopolitan city. Since its independence in 1965, the city-state has become renowned for its efficient and visionary urban planning. Characterised by a modern skyline, the form of Singapore is delineated by well-planned satellite towns, a central business district in the South, and industrial estates. This layout reflects a systematic approach to urban development, emphasising green spaces and sustainability. The urban plan of modern Singapore features four major frontiers strategically positioned at the South, North, East, and West of the island. The Southern part houses the predominant historical CBD, serving as the city's business heart. Meanwhile, the other three regions function as regional centres, each with unique strategic roles, facilitating a more balanced development across the country. This decentralised urban planning approach aims to mitigate congestion in the CBD and promote regional growth, ensuring harmonious and sustainable urban development across the island (Wong, Yuen, & Goldblum, 2008; C. Wu et al., 2021; Yuen, 2009).

The two urban elements leveraged in our study are the buildings and streets. We collect data on the street network from OpenStreetMap and obtain building footprints and the floorspace area for each building. With the help of the proposed framework, we expect to reveal the multi-scalar structure of urban patterns for both cities through their unique urban pattern language.

4.2. The multi-scalar relationship between morphological patterns

This section shows the statistical results of the three patterns mentioned in Section 3 for our case study area. Fig. 5 shows the percentage of each type of urban centre, street pattern, and plot in Beijing and Singapore, respectively. At the same time, Table 1 reveals the compositional relationship between the patterns at different scales. By showing the composition and its difference across cities, we hope to reveal the potential existence of urban pattern language, i.e., the relationship between patterns, and demonstrate its ability to inform the difference between cities.

Generally, Singapore and Beijing have distinct pattern compositions across scales, with Singapore appearing to be more diverse, according to Fig. 5. In terms of the hierarchy of urban centres, Beijing shows a greater percentage in primary centres, while Singapore has a higher percentage in secondary centres. With a polycentricity of 0.9832 and more



	Beijing	Singapore
High-rise Block	1.06%	0.73%
Medium-rise Block	4.79%	5.66%
Low-rise Block	7.16%	21.58%
High-rise Strip	6.03%	0.98%
Medium-rise Strip	26.06%	12.24%
Low-rise Strip	15.33%	27.33%
High-rise Point	3.49%	0.94%
Medium-rise Point	6.30%	4.33%
Low-rise Point	29.79%	26.22%

a. Plot Composition

	Beijing	Singapore
Grid	6%	0%
Organic	0.00%	37.33%
Hybrid	88.65%	46.37%
Cul-de-sac	5.59%	16.30%

b. Street Pattern Composition

	Beijing	Singapore
Primary	37.77%	30.19%
Secondary	42.12%	45.74%
Tertiary	20.11%	24.07%
Polycentricity	0.9832	0.8571

c. Urban Centres Composition

Fig. 5. City-wide composition of multi-scalar patterns.

Table 1
Compositional relationship between different patterns and the percentage of difference from the city-wide composition.

a. Compositional relationship and its variation in Macro-Micro scale patterns.

	Beijing						Singapore					
	Primary		Secondary		Tertiary		Primary		Secondary		Tertiary	
High-rise block	1.07 %	0.94 %	0.91 %	−14.15 %	1.35 %	27.36 %	1.65 %	126.03 %	0.48 %	−34.25 %	0.07 %	−90.41 %
Medium-rise block	4.83 %	0.84 %	4.85 %	1.25 %	4.61 %	−3.76 %	9.43 %	66.61 %	4.90 %	−13.43 %	2.34 %	−58.66 %
Low-rise block	6.34 %	−11.45 %	6.67 %	−6.84 %	9.74 %	36.03 %	22.97 %	6.44 %	19.04 %	−11.77 %	24.62 %	14.09 %
High-rise strip	6.10 %	1.16 %	5.71 %	−5.31 %	6.55 %	8.62 %	1.20 %	22.45 %	1.22 %	24.49 %	0.27 %	−72.45 %
Medium-rise strip	23.90 %	−8.29 %	28.75 %	10.32 %	24.46 %	−6.14 %	17.16 %	40.20 %	12.85 %	4.98 %	4.88 %	−60.13 %
Low-rise strip	14.64 %	−4.50 %	14.84 %	−3.20 %	17.64 %	15.07 %	21.46 %	−21.48 %	27.47 %	0.51 %	34.43 %	25.98 %
High-rise point	3.02 %	−13.47 %	4.25 %	21.78 %	2.77 %	−20.63 %	0.69 %	−26.60 %	1.34 %	42.55 %	0.50 %	−46.81 %
Medium-rise point	7.32 %	16.19 %	5.64 %	−10.48 %	5.75 %	−8.73 %	4.77 %	10.16 %	5.38 %	24.25 %	1.77 %	−59.12 %
Low-rise point	32.76 %	9.97 %	28.40 %	−4.67 %	27.13 %	−8.93 %	20.66 %	−21.21 %	27.31 %	4.16 %	31.11 %	18.65 %

b. Compositional relationship and its variation in Macro-Meso scale patterns.

	Beijing						Singapore					
	Primary		Secondary		Tertiary		Primary		Secondary		Tertiary	
Grid	3.43 %	−40.35 %	8.40 %	46.09 %	4.57 %	−20.52 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
Organic	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	32.71 %	−12.38 %	50.86 %	36.24 %	17.41 %	−53.36 %
Hybrid	96.57 %	8.93 %	85.81 %	−3.20 %	79.73 %	−10.06 %	52.61 %	13.46 %	32.97 %	−28.90 %	64.01 %	38.04 %
Cul-de-sac	0.00 %	−100.00 %	5.79 %	3.58 %	15.70 %	180.86 %	14.68 %	−9.94 %	16.17 %	−0.80 %	18.58 %	13.99 %

c. Compositional relationship and its variation in Meso-Micro scale patterns.

	Beijing						Singapore					
	Grid		Hybrid		Cul-de-sac		Organic		Hybrid		Cul-de-sac	
high-rise block	1.69 %	59.43 %	1.07 %	0.94 %	0.25 %	−76.42 %	0.48 %	−34.25 %	1.18 %	61.64 %	0.05 %	−93.15 %
medium-rise block	2.42 %	−49.48 %	5.14 %	7.31 %	1.74 %	−63.67 %	5.52 %	−2.47 %	6.84 %	20.85 %	2.57 %	−54.59 %
low-rise block	4.36 %	−39.11 %	7.18 %	0.28 %	9.71 %	35.61 %	12.50 %	−42.08 %	28.42 %	31.70 %	22.77 %	5.51 %
high-rise strip	11.02 %	82.75 %	6.04 %	0.17 %	0.75 %	−87.56 %	1.65 %	68.37 %	0.75 %	−23.47 %	0.15 %	−84.69 %
medium-rise strip	28.57 %	9.63 %	26.99 %	3.57 %	8.59 %	−67.04 %	17.48 %	42.81 %	9.22 %	−24.67 %	2.86 %	−76.63 %
low-rise strip	15.01 %	−2.09 %	15.03 %	−1.96 %	20.42 %	33.20 %	25.06 %	−8.31 %	29.67 %	8.56 %	25.83 %	−5.49 %
high-rise point	5.08 %	45.56 %	3.54 %	1.43 %	1.12 %	−67.91 %	1.30 %	38.30 %	0.85 %	−9.57 %	0.40 %	−57.45 %
medium-rise point	7.63 %	21.11 %	6.29 %	−0.16 %	5.11 %	−18.89 %	6.43 %	48.50 %	3.15 %	−27.25 %	8.89 %	105.31 %
low-rise point	24.21 %	−18.73 %	28.73 %	−3.56 %	52.30 %	75.56 %	29.57 %	12.78 %	19.93 %	−23.99 %	36.49 %	39.17 %

significant primary centres present, Beijing appears more morphologically polycentric than Singapore's 0.8571. When examining the total street pattern, Beijing exhibits a significantly higher percentage of hybrid street patterns than Singapore, which has a larger proportion of organic patterns, indicating that Singapore's urban layout is more varied, with multiple street patterns, while Beijing's is more unified. For the plot typology, both cities have a majority of point-shaped plots, but Singapore has a higher diversity with substantial percentages of block and strip forms present. Moreover, Beijing has a higher percentage of Highrise to Medium-rise plots compared to Singapore, suggesting a higher development intensity.

We further summarised the compositional relationship of patterns according to their hierarchy and displayed them in Table 1. This table illustrates the cross-scale compositional relationship between the Macro-Micro, Macro-Meso, and Meso-Micro patterns. A second column is added on the right to show the percentage deviation from the overall city-wide distribution of each pattern. Here, the 'overall city-wide distribution' refers to the aggregate distribution of urban elements across the entire study area, serving as a baseline for comparison to identify localized variations and deviations. The green colour marks an increment in the percentage, while the red colour marks a decrease in the percentage. This compositional method allows us to visually and quantitatively compare shifts in urban form and structure across scales, making it particularly suited for identifying unique urban characteristics within each city's pattern language. While no control variables or statistical models were applied here, future research may involve advanced models to explore these relationships further and to test for potential causal patterns. This decision aligns with our study's current focus on pattern identification and cross-scale composition rather than in-depth causative analysis.

Two general trends can be concluded from the results: First, a relation exists between the composition of the lower and higher-scale patterns; this association can be reflected from the large cross-scale composition changes across different patterns when examining an individual city which implies the existence of pattern language in a city. Second, the relation exists in both case studies, but in a different manner; the different relationship could be reflected by the distinct cross-scale composition and its changes in the two cities. This indicates the pattern language's ability to reflect the unique urban morphology.

We start by comparing macro-scale patterns to micro-scale patterns shown in Table 1a. The linkage is inherent because the neighbourhood hierarchy is determined partially using the building floor space. Across primary, secondary, and tertiary centres, the distribution of plot types remains very distinct for both two cities, and this is evident by the change in the percentage of the composition visualised in the right column. The primary centres typically exhibit a higher proportion of high-rise and medium-rise plots, indicative of denser urban mass. Concurrently, there is a notable increase in low-rise plots within tertiary centres. This pattern is particularly evident in Singapore, where there is a consistent decline in high-rise and medium-rise plots from primary to tertiary centres, from 1.65 % and 9.43 % to 0.07 % and 2.34 %. In contrast, the prevalence of low-rise plots, especially strips and points, escalates markedly from 21.46 % and 20.66 % to 34.43 % and 31.11 %. The trend in Beijing presents a more complex scenario. Contrary to expectations, primary centres have the highest percentage of low-rise point plots with 32,76 %, which diminishes the tertiary centre of

27.13. Additionally, the proportion of high-rise blocks escalates to 1.35 % in tertiary centres. Notably, tertiary centres in Beijing exhibit more high-rise plots than secondary centres, with figures approaching those of primary centres. This suggests that Beijing's tertiary centres are experiencing intensive urban development characterised by high building densities and a significant amount of undeveloped land.

Moving on to the relationship between macro-scale and *meso*-scale urban patterns in Table 1b, the composition of street patterns within the various neighbourhoods of Beijing and Singapore reveals distinct trends that underscore the divergent approaches to urban planning and development in the two cities. In general, Beijing, with a more polycentric urban spatial structure at the macro level, has a more monotonous street pattern. In Beijing, the dominant street pattern in the Primary centres is the Hybrid type, which accounts for a significant majority of 96.57 %. This Hybrid preference decreases in Secondary centres and further still in Tertiary centres to 79.73 %. Interestingly, the Secondary centres exhibit a substantial proportion of Grid streets of 8.4 %, 46.09 % above the city-wide level, indicative of a structured and perhaps newer urban planning approach in these less central areas. Singapore's neighbourhoods exhibit a distinct preference for Organic and Hybrid Street patterns. In Primary centres, Hybrid streets are the most dominant, with 52.61 %, which suggests a deliberate blend of planning strategies combining elements of both grid-like and organic layouts. This might reflect Singapore's approach to creating functional spaces that also preserve the natural and historical context of the city. In Secondary centres, there is a significant presence of Organic streets with 50.86 %, indicating a preference for street layouts that evolve naturally, possibly respecting the existing environmental features and cultural heritage. In both cities, the rise in the proportion of Cul-de-sacs from primary to tertiary centres could suggest a move towards creating more secluded spaces, perhaps for residential developments, prioritising privacy and lower traffic flow in the lower development intensity part of the city.

The relationship between the meso and micro-scale pattern, shown in Table 1c, street pattern and plot types, is also significant. Firstly, the cul-de-sacs street pattern favours low-intensity development with a significant composition of low-rise point, strip, and block types in both cities. This trend is especially evident in Beijing, with a 35.61 %, 33.2 % and 75.56 % increment for city-wide value for low-rise Block, Strip, and Point plots. The favour for low and medium rise point plots in Singapore is more significant, with a 105.31 % and 39.17 % increment, respectively. The Hybrid Street pattern is also observed in both cities, and we observe a stark contrast between Beijing and Singapore. In Beijing, the hybrid street pattern has the most balanced distribution with minimum change in the percentage of the city-wide composition. It is slightly more Medium-rise Block and Strip and less Low-rise point plots. In Singapore, the hybrid street patterns have a much higher percentage of block plots and fewer point forms than in Beijing. The Grid and Organic Street patterns have the largest high-rise block and point plots in Beijing and Singapore, respectively, indicating they handled an immense development intensity.

To conclude, the statistical analysis presented in this section, referencing the patterns detailed in Section 3, clearly depicts urban form and structure within our case study cities. Fig. 5 delineates the distribution of urban centres, street patterns, and plot types in Beijing and Singapore, revealing fundamental differences in their urban compositions. In parallel, Table 1 uncovers the intricate compositional relationship between these patterns at varying urban scales. First, the contrasting composition and changes in percentage of difference from the city-wide composition to cross-scale composition suggest the presence of an identifiable urban pattern language. Second, the urban pattern language is very distinct between cities, marked by the offering insights into the multi-scalar urban structure of each city.

4.3. The urban pattern language for Beijing and Singapore

The pattern identification and multi-scalar urban structure are mapped in Fig. 6, from the bottom macro scale polycentricity to the micro-scale Spacematrix on the top. Analysing urban patterns at various scales systematically revealed the structural differences between Beijing and Singapore.

Macro scale distribution reveals a distinct hierarchy of neighbourhoods based on street density and building mass. Major centres in red are characterised by larger building mass and street length, while secondary and tertiary centres are in yellow and green and might have less density and mass, respectively. The primary centres in Singapore align precisely with the defined business and commercial centres located in the South, West, and East parts of the island, corresponding to the plans illustrated in Fig. 4. In Beijing, the situation is more complicated. More neighbourhoods are categorised as the primary centres, and their distribution does not have a clear pattern. Traditionally, the major business centres are primarily located in Northern Beijing and are clearly defined. However, we also observed several primary centres in Southern Beijing that are less perceived by the public than in Fig. 4.

The meso-scale analysis reveals the distribution of street patterns within Beijing and Singapore, as classified by the random forest classification algorithm. It presents a clear urban design and planning differentiation between the two cities. Beijing's urban form predominantly features a Hybrid pattern and segments of Grid and Cul-de-sac patterns. The Hybrid streets, with their blend of structured and organic characteristics, likely accommodate a variety of urban functions, suggesting a city in transition, possibly integrating modern grid-like development while retaining elements of traditional urban form. Grid patterns may be attributed to the city's historical periods of rapid development, aiming for efficient urban layouts (Boeing, 2021; Rowe, van den Berg, & Wang, 2019). Although less frequent, cul-de-sacs are primarily present in the urban fringe and indicate limited accessibility by planned or undeveloped areas. In contrast, Singapore's layout is notably absent of Grid patterns. The dominance of Hybrid and Organic patterns in Singapore may point to a city that has developed with a strong consideration for existing landscapes.

The distribution of urban plot types within Beijing and Singapore also displays distinct morphological patterns in the two cities landscapes. Beijing, shown at the top of the image, is rich in blue tones, representing strip-shaped plots. The varying brightness of blue indicates a mix of high-rise, medium-rise, and low-rise strip-shaped buildings. Other than the urban fringe, the low-rise strip plots are mostly observed in the core of Beijing which may indicate its strong association with the historical building form in the preserved area. The darker blue areas signal a higher density of high-rise structures within these strip formations, potentially indicating major avenues or boulevards lined with tall buildings, like the Second Ring Road and Chang'an Avenue. In contrast to the abundant blue, the red and orange hues representing block and point-shaped buildings are less prominent which could imply that Beijing's urban design and planning have favoured strip-shaped developments over the block or point-shaped ones. In particular, the High-rise point plots, mostly indicating skyscrapers, are clustered in several areas in Beijing, Including the Southwest and Northeast. They are indicating multiple commercial centres present. Moving to the Singapore plot at the bottom, the urban landscape is diverse, with all nine types represented. In general, the composition of the different plot types is more balanced in Singapore compared to Beijing. The red and orange areas, representing block and point-shaped buildings, appear more frequently than in the Beijing plot. This would suggest a more balanced mix of building forms in Singapore, with a notable presence of high-rise blocks and point-shaped buildings alongside the strip-shaped ones. The presence of lighter shades in the Singapore plot, particularly in the blue strip, possibly reflects a lower urban development intensity. Considering that Singapore island only hosts about half of the population of the study area in Beijing, these might correspond to residential

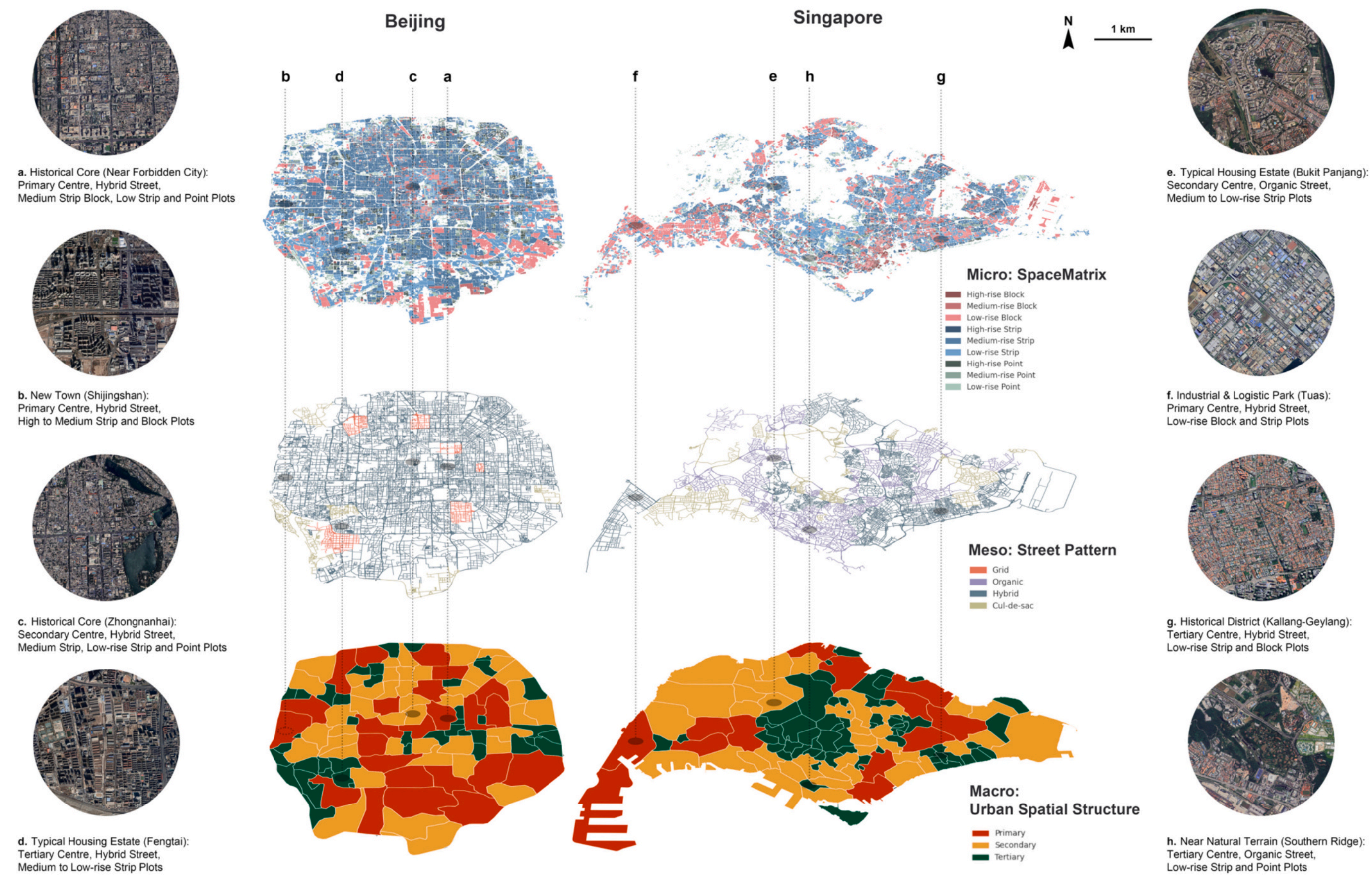


Fig. 6. Patterns identified at different scales and their typical combination presented in satellite images (Source: Google Earth).

neighbourhoods or commercial areas less densely built up. Another point of note is that the highrise plots are mostly concentrated in the southern part of Singapore, where the central building district is located, indicating that Singapore has a prominent urban centre. Lastly, although point plots have a large presence in numbers in both cities, they are not visually significant in the mapping due to their relatively smaller size.

With the help of the multi-scalar urban patterns identified, we can now begin to construct the urban pattern language in our case study cities. In this study, the three types of urban centres identified by their hierarchy of urban mass, the four street patterns, and the nine Spacematrix block typologies give us 108 unique combinations. These combinations' frequency and spatial distribution defined the cites' morphological character and summarised the urban pattern language. In Beijing and Singapore, the top ten combinations account for approximately 65.63 % and 50.35 % of the morphological patterns refer to Appendix 2a & 2b. To uncover the urban pattern language for Beijing and Singapore, we displayed a few areas in Beijing and Singapore where the most frequent combinations are clustered, as shown in Figs. 6a to 6h. These combinations, when viewing their spatial distribution in conjunction with the satellite imagery, provide a more vivid description of the morphological aspect of the cities' urban landscape.

The difference in urban pattern language between Beijing and Singapore is compelling. The most common combinations for both cities are observed in historical districts and housing estates. The typical housing estate for Beijing is illustrated in Fig. 6b and d. They are either Primary centres with Hybrid Street patterns, High to Medium-rise Strip and Block plots featuring high development intensity or Tertiary centres with Hybrid Street patterns, Medium to low-rise Strip plots focusing on housing needs. In Singapore, the housing estates are largely dominated by the HDB (Housing and Development Board) developments shown in Fig. 6e, featuring a secondary centre with an organic street pattern and Medium to low-rise trip plots. The historical district is also very different for both cities, where Beijing shows a primary or secondary centre with a hybrid street pattern and higher density in Fig. 6a and c. Singapore's historical district features a Tertiary Hybrid Low-rise strip and block combination in Fig. 6g. More distinctions could be informed using the urban pattern language; for example, the Industrial & Logistic Park shown in Fig. 6f, is also an important part of the case study area in Singapore, while this type of urban layout did not make a significant presence in the case study area of Beijing. In both cities, the point-type plots, although marked a significant presence by count, are mostly service buildings in housing estates and parks, which only occupy a smaller land. Thus, they are not apparent in the satellite image.

The different choice of urban patterns and their distinct combination preference suggest a deep-rooted connection between cities' context and the resulting urban pattern language. This context could be about the urban planning strategies tailored to the unique socioeconomic characteristics of each city, or it could be about the cultural and aesthetic preferences of the residents that collectively shaped the unique pattern languages. Given this paper's research scope and focus on introducing a new concept, we do not further investigate the reason behind all the discoveries depicted in this case study but hint at it as an opportunity for future work and follow-up studies. Nevertheless, this case study reveals the intricate interplay between various urban patterns. Moreover, distinct urban pattern languages represented by the different compositional relationships between the multi-scalar patterns of Beijing and Singapore are also uncovered. Our case study fulfilled our research objectives by aligning closely with its initial objective: to develop a comprehensive understanding of urban morphology through a multi-scalar lens. The results illustrate how the chosen patterns of polycentricity, street pattern, and spacematrix are effective tools for decoding the complexities of the urban environment.

5. Discussion

The preliminary case study confirmed the premises of our proposed urban pattern language approach in urban analytics, design, and planning: the relationship exists between various patterns. It is distinct enough to reflect the different urban contexts. Here, we define the relationship between the patterns and the language. Hence, as urban researchers and planners, we must consider the interplay between urban elements and patterns at different scales. It also provides new research directions to investigate the relationship in detail. Some of these relationships could be top-down, where the street pattern defines the plot size and building form, or bottom-up, where the block typology collectively defines a city centre. Given the current information and research scope, this paper cannot conclude the causal relationship. Furthermore, differences in the compositional relationships between urban patterns are revealed, highlighting variations in how multi-scale spatial structures interact across different cities. Thus reflecting each city's unique historical, cultural, and socioeconomic context. They are theoretical and practical, guiding urban analysis, planning, and design. Identifying and understanding urban pattern language also offers several potential benefits for policy. By systematically decoding the structure of urban form, policymakers can gain insights into the functional and cultural rationale behind city layouts. This understanding could inform targeted urban interventions that align with a city's unique morphological characteristics, promoting policies that respect existing spatial patterns and enhance their functionality. Additionally, a well-defined urban pattern language could support data-driven decision-making, enabling cities to tailor zoning laws, transportation networks, and public space planning to better suit their specific spatial configurations. Building on this rationale, we discuss further completing this urban pattern language framework and what it could mean for urban professionals.

5.1. Function and performance of urban pattern language

First, the urban pattern language is still far from complete, given the current premise that relationships between patterns exist. Tracing back to the very definition of a pattern language, which inherently incorporates the consideration of function and performance by definition: a set of patterns to solve reoccurring design problems. The design problem is missing in our current framework: what is the function behind the urban patterns and their combination? How do we assess their performance in fulfilling their functions? These are crucial application aspects that directly address urban professionals' needs. It is crucial to understand the function behind each pattern, why it exists, and its purpose.

Other than the Form-Based Code mentioned earlier, the Sponge City Initiative is a significant example of the function of formulating the urban pattern language across different urban elements and scales. Sponge City uses ecological design to slow down rainwater drainage through urban infrastructures to prevent flooding and promote sustainability (Chan et al., 2018). The Sponge City design exemplifies how urban pattern language can extend beyond morphological descriptions to encompass performance-driven urban design strategies. By integrating multi-scalar patterns, such as permeable surfaces, green infrastructure networks, and hydrological corridors, Sponge City interventions can be systematically decoded into a pattern language. This framework can potentially be applied to more urban policy, planning, and design topics that contribute to sustainability (Dastjerdi & Lak, 2023).

Incorporating performance metrics into the pattern language framework offers a way to evaluate the effectiveness of urban designs. Performance can be measured regarding urban vitality, bikeability, access to amenities, environmental sustainability, and social inclusiveness (Ghavampour & Vale, 2019; Sharifi, 2019a; Talen, 2012; Wang, 2021; Ye et al., 2018). By integrating these aspects, the pattern language approach can evolve from a purely morphological analysis to one that considers the lived experience of city inhabitants. Urban scholars and planners are no strangers to the myriad studies on how urban forms interplay with various emergent urban performance indicators in today's dynamic landscape. The quest to correlate urban form with emergent dynamic data has taken centre stage over the past decade. Be it environmental indicators such as energy consumption (Bielik et al., 2019), urban heat island effects (Liu et al., 2021), pollution (McCarty & Kaza, 2015), and disease transmission (Venerandi, Aiello, & Porta, 2023); economic patterns examining facets like income distribution (Liu et al., 2021) and property values (Webster, 2010); or sociocultural patterns exploring crime rates(Mao, Yin, Zeng, Ding, & Song, 2021), urban vitality (Wang & Vermeulen, 2021), and social segregation (Salazar Miranda, 2020) – there has been a burgeoning interest in deciphering these interrelationships. The rationale behind this surge is clear: understanding these associations can provide invaluable insights that guide urban development strategies, ensuring cities are sustainable but also equitable and vibrant (Alves, van Opstal, Keijzer, Sutton, & Chen, 2024). While scholars are trying to establish such relationships, in this expanded framework, pattern language becomes a tool for describing the urban form and predicting and optimising urban function and performance. By a comprehensive understanding of function, form, and performance, urban pattern language can guide future urban planning and design decisions towards creating cities that are not only aesthetically pleasing and culturally resonant but also efficient, sustainable, and conducive to the well-being of their residents.

5.2. An extendable framework

We must emphasise that pattern language is an adaptive framework capable of incorporating a wide array of patterns that extend far beyond those examined in our case study. This study represents merely an initial foray into the potential applications of pattern language in urban landscapes. The flexibility of this approach allows for the inclusion of additional critical patterns in urban planning that may emerge from future technological and societal developments. Incorporating such patterns is not merely an academic exercise; it holds practical importance in addressing the growing challenges of urban environments. As cities become more dynamic and their demography changes, the range of relevant urban patterns will undoubtedly expand. Such as the digital infrastructure layouts and new urban mobility networks in the smart city initiatives (Fakhimi, Khani, & Sardroud, 2021; Richter, Hagenmaier, Bandte, Parida, & Wincent, 2022). These elements are vital to a city's functionality, sustainability, and resilience. Future research could also explore how urban pattern language accounts for the temporal evolution of different urban elements. This would involve analysing historical datasets to assess how spatial patterns change over time, potentially enhancing the framework's applicability in dynamic urban environments. As societal change and technological advancement pose new requirements, the urban pattern language framework is structured to evolve by incorporating the latest research findings and emerging urban trends. It has the potential to integrate interdisciplinary studies, encompassing sociological, environmental, and technological perspectives. This integration ensures that urban planning and design are responsive to current and future needs, facilitating the development of efficient and adaptable cities that are liveable and responsive to their inhabitants' needs.

In short, as we advance this framework with more relevant patterns, functions, and performance evaluations, we envision an urban pattern language that is not static but grows with the city it describes. It will be capable of accommodating the complexities of urban ecosystems, reflecting changes over time, and providing a living document of urban evolution. This extendable nature empowers urban professionals to plan for the present and lay a foundation for future generations to build upon, adapt, and improve. It can guide the development of smart cities where the interconnectivity of systems can be planned with precision (Lv, Hu, & Lv, 2020). It can also inform the preservation of historical urban forms

(Gong, Li, Tong, Que, & Peng, 2023; Wang & Gu, 2020; Whitehand & Gu, 2007), ensuring that new developments respect and enhance the city's existing character. In essence, the urban pattern language is a tool for continuity and change, providing a structured yet flexible approach to urban development that is sensitive to the needs of both the city and its residents.

5.3. The vernacular pattern language

The case study vividly illustrates that Beijing and Singapore possess distinct urban pattern languages, potentially reflecting their unique historical, cultural, and socioeconomic contexts. This distinctiveness is not merely an academic observation but holds profound implications for vernacular and contextual urban analysis, planning, and design. In Beijing, the pattern language is associated with the city where traditional and modern elements are interwoven, reflecting its long history and rapid contemporary development. The city's morphology, characterised by a mix of street patterns and a preference for strip-shaped developments, mirrors its complex socio-political landscape and urban growth strategies. Conversely, Singapore's pattern language speaks to its strategic urban planning tradition (Yuen, 2009), which prioritises adaptability, environmental consciousness, and community-centric development (Cho & Križnik, 2017; Ooi, 1992; Wong et al., 2008). The prevalence of hybrid and organic street patterns and a balanced mix of building forms in Singapore underscores a deliberate effort to harmonise urban growth with quality of life and sustainability. The distinctive pattern language is a potent indicator of a city's underlying socio-political, economic, and cultural fabric. The observation that the same street pattern prompts a diverse composition of block typologies in Singapore and Beijing is telling. It reflects not merely the higher population density of Beijing but also hints at differing urban planning strategies.

The divergent pattern languages potentially shed light on broader societal structures and values. While the patterns themselves might be universal, like the types of street networks and the shape of the building, the choice of pattern and their multi-scale combination will be deeply local, rooted in the specificities of a particular urban environment (Wang & Gu, 2020). Thus, the vernacular pattern language is enabled in two ways. First, it results from the different combinations of universal patterns from the various scales. Second, it lies in the different choices of patterns and their combination by different cities. Each city's unique history, culture, and geography will have its own preferential set of patterns. Just as in architecture, the vernacular is reflected in the multi-scale patterns from the arrangement of space to finer patterns about the roof structure (Habibi, 2019; Rapoport, 2003); the vernacular in a larger urban context could be potentially reflected in the multi-scalar urban patterns. Together, they provide enough diversity of urban morphology within and between cities to create a dynamic and vibrant built environment. Applying a pattern language approach strongly resonates with the typo morphology mentioned earlier (Samuels, 2008). Evgeniya and her colleague have exemplified some groundwork, where she uses a combination of patterns from various urban elements to reveal the different plot systems in five European cities (2021). They offer invaluable insights for urban planners and designers, emphasising the need for context-sensitive approaches that respect and leverage each city's inherent character and needs. The distinct urban pattern languages of Beijing and Singapore underscore the importance of recognising and preserving the vernacular identity of cities in the face of global urbanisation trends.

Nevertheless, it is imperative to acknowledge the study's limitations and the need for a critical self-appraisal. While the Urban Pattern Language has shown potential, its application is in its nascent stages, and its adaptability across a broader spectrum of global urban settings remains to be thoroughly tested. Furthermore, this preliminary study establishes the foundational relationships between different urban patterns but does not exhaustively account for the socio-political and economic variables that also shape urban landscapes. Looking ahead, there exists an opportunity for future research to extend the Urban Pattern Language, incorporating a wider array of urban elements and patterns. This expansion would enable a more holistic urban planning and design strategy that seamlessly blends functionality with sustainability. For urban professionals, the insights gleaned from this study are a step towards a deeper understanding of urban morphology. Yet, continuous refinement and critical examination of the Urban Pattern Language will be essential for its evolution into a robust tool for creating vibrant, sustainable, and resilient urban spaces.

6. Conclusion

This work formalizes Urban Pattern Language, an extendable framework for understanding urban form through pattern language, offering a structured approach that integrates existing methodologies and enables future refinements for diverse urban applications. It presents a comprehensive methodological framework that can adapt to diverse urban contexts, as demonstrated through our comparative case study of Beijing and Singapore. Through the analysis of macro, *meso*, and micro scales, the research demonstrates how urban patterns serve as a lens through which the intricate tapestry of urban form can be understood and navigated. Our current study is an initial attempt to discover and quantify these urban patterns as they manifest in diverse scales, aligning with Alexander's framework but focusing primarily on identifying patterns and exploring their spatial arrangements. This foundational analysis is the first step in applying Alexander's theory in urban studies and planning.

The preliminary study reveals that urban patterns follow consistent, hierarchical relationships within each city yet vary significantly between cities, highlighting distinctive urban identities shaped by local context. This confirms the existence of a structured relationship among patterns at different scales and underscores the value of the Urban Pattern Language in capturing and interpreting the specific urban morphology of each city. These findings offer a replicable framework for urban planners and researchers, enabling them to navigate and apply multi-scalar spatial insights in diverse urban settings.

CRediT authorship contribution statement

Cai Wu: Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft. **Jiong Wang:** Supervision, Methodology, Conceptualization, Writing – review & editing. **Mingshu Wang:** Supervision, Writing – review & editing. **Filip Biljecki:** Supervision, Writing – review & editing. **Menno-Jan Kraak:** Supervision, Writing – review & editing.

Declaration of competing interest

None.

Acknowledgments

We appreciate Guosheng Yang's help with the visualization and Wen Zhou's assistance in obtaining data. We thank the members of the HKUST(GZ) Urban Morphology Studio and the NUS Urban Analytics Lab for their discussions.

Appendix

Appendix 1
List of Street Metrics to identify street pattern.

	Metric	Definition	Value remark
Composition	Street Length	Calculate the graph's average edge length.	In meters
	Diameter	It is the shortest distance between the two most distant nodes in the network.	In meters higher value implies slower movement through the network.
	Circuity	Circuity is the sum of edge lengths divided by the sum of straight-line distances between edge endpoints.	**1 to ½π** higher value implies the street is more circular
	Orientation Entropy	Orientation entropy is the entropy of its edges' bidirectional bearings across evenly spaced bins.	**1.386 to 3.584** higher value implies the streets are more ordered.
Configuration	k_avg	graph's average node degree (in-degree and out-degree)	higher value implies better connectivity with more route choices.
	Self-loop	Calculate the percentage of edges that are self-loops in a graph.	**0 to 1**
	L-junction	The proportion of nodes with two streets connected	**0 to 1**
	T-junction	The proportion of nodes with three streets connected	**0 to 1**
	X-junction	The proportion of nodes with four streets connected	**0 to 1**
Explanatory	Degree Pearson	Compute the degree assortativity, which is the similarity of connections in the graph concerning the node degree, which means the number of streets connected to a street junction.	**−1 to 1** higher value implies the streets are more ordered.
	Transitivity	The ratio between the observed number of triangles and the number of closed triplets in the graph	**0 to 1** Higher value implies the network contains internal communities.
	Global reaching centrality	The global reaching centrality of a weighted directed graph is the average over all nodes of the difference between the local reaching centrality of the node and the greatest local reaching centrality of any node in the graph.	**0 to 1** A higher value means the network shows a more hierarchical structure.
	Global Efficiency	The average efficiency of all pairs of nodes in a graph is the average multiplicative inverse of the shortest path distance between the nodes.	**0 to 1** A higher value means the network shows better accessibility.

Appendix 2a
Top 10 pattern combinations by count in Beijing.

1	Secondary Hybrid Low-rise Point	13.44 %
2	Secondary Hybrid Medium-rise Strip	12.73 %
3	Primary Hybrid Low-rise Point	7.20 %
4	Secondary Hybrid Low-rise Strip	6.82 %
5	Primary Hybrid Medium-rise Strip	5.89 %
6	Tertiary Hybrid Medium-rise Strip	5.22 %
7	Tertiary Hybrid Low-rise Point	4.73 %
8	Primary Hybrid Low-rise Strip	3.40 %
9	Secondary Hybrid Low-rise Block	3.15 %
10	Tertiary Hybrid Low-rise Strip	3.05 %

Appendix 2b
Top 10 pattern combinations by count in Singapore.

1	Tertiary Hybrid Low-rise Strip	6.79 %
2	Secondary Hybrid Low-rise Strip	6.07 %
3	Tertiary Hybrid Low-rise Block	6.06 %
4	Tertiary Organic Low-rise Point	6.01 %
5	Secondary Hybrid Low-rise Block	5.02 %
6	Secondary Hybrid Low-rise Point	4.33 %
7	Tertiary Organic Low-rise Strip	4.18 %
8	Secondary Organic Low-rise Strip	4.01 %
9	Tertiary Cul-de-sac Low-rise Point	3.95 %
10	Secondary Organic Low-rise Point	3.94 %

Data availability

Data will be available at the university's open data platform.

References

Abass, F. (2016). A review of courtyard house: History evolution forms, and functions Mohmed Solla MICROCORP SDN BHD. www.arpnjournals.com.
Alexander, C. (1979). *The timeless way of building* (p. 552). New York Oxford University Press.

Alexander, C., Ishikawa, S., & Silverstein, M. (1977). A pattern language: towns, buildings, construction. In *A pattern language*. OXFORD UNIVERSITY PRESS.

Alves, A., van Opstal, C., Keijzer, N., Sutton, N., & Chen, W. S. (2024). Planning the multi-functionality of nature-based solutions in urban spaces. *Cities, 146*, Article 104751. https://doi.org/10.1016/J.CITIES.2023.104751

Anas, A., Arnott, R., & Small, K. A. (1998). Urban Spatial Structure. *Journal of Economic Literature, 36*(3), 1426–1464. https://doi.org/10.1007/978-1-349-04537-2_6

Batty, M. (2006). Rank clocks. *Nature 2006 444: 7119, 444*(7119), 592–596. https://doi.org/10.1038/nature05302

Batty, M. (2008). The size, scale, and shape of cities. In *, Vol. 319, Issue 5864*. *Science* (pp. 769–771). UNAIDS. https://doi.org/10.1126/science.1151419.

Batty, M. (2019). Urban analytics defined *Doi:*https://doi.org/10.1177/2399808319839494, *46*(3), 403–405. doi:https://doi.org/10.1177/2399808319839494.

Batty, M. (2020). *Defining complexity in cities (pp. 13–26)*. https://doi.org/10.1007/978-3-030-36656-8_2

Batty, M., & Marshall, S. (2017). Thinking organic, acting civic: The paradox of planning for cities in evolution. *Landscape and Urban Planning, 166*, 4–14. https://doi.org/10.1016/J.LANDURBPLAN.2016.06.002

Bielik, M., Schneider, S., Kuliga, S., Griego, D., Ojha, V., König, R., … Donath, D. (2019). Examining trade-offs between social, psychological, and energy potential of urban form. *ISPRS International Journal of Geo-Information, 8*(2), 52. https://doi.org/10.3390/ijgi8020052

Biljecki, F., & Ito, K. (2021). Street view imagery in urban analytics and GIS: A review. *Landscape and Urban Planning, 215*, Article 104217. https://doi.org/10.1016/J.LANDURBPLAN.2021.104217

Bobkova, E., Berghauser Pont, M., & Marcus, L. (2021). Towards analytical typologies of plot systems: Quantitative profile of five European cities. *Environment and Planning B: Urban Analytics and City Science, 48*(4), 604–620. https://doi.org/10.1177/2399808319880902/SUPPL_FILE/EPB880902_SUPPLEMENTAL_MATERIAL.PDF

Boeing, G. (2018). *A multi-scale analysis of 27,000 urban street networks: Every US city, town, urbanized area, and Zillow neighborhood*. Environment and Planning B: Urban Analytics and City Science. https://doi.org/10.1177/2399808318784595

Boeing, G. (2021). Off the grid…and Back again?: The recent evolution of American street network planning and design. *Journal of the American Planning Association, 87* (1), 123–137. https://doi.org/10.1080/01944363.2020.1819382/SUPPL_FILE/RJPA_A_1819382_SM4089.PDF

Bolleter, J., Hooper, P., Kleeman, A., Edwards, N., & Foster, S. (2024). A typological study of the provision and use of communal outdoor space in Australian apartment developments. *Landscape and Urban Planning, 246*, Article 105040. https://doi.org/10.1016/J.LANDURBPLAN.2024.105040

Cai, Z., Demuzere, M., Tang, Y., & Wan, Y. (2022). The characteristic and transformation of 3D urban morphology in three Chinese mega-cities. *Cities, 131*, Article 103988. https://doi.org/10.1016/J.CITIES.2022.103988

Chan, F. K. S., Griffiths, J. A., Higgitt, D., Xu, S., Zhu, F., Tang, Y. T., … Thorne, C. R. (2018). "Sponge City" in China—A breakthrough of planning and flood risk management in the urban context. *Land Use Policy, 76*, 772–778. https://doi.org/10.1016/J.LANDUSEPOL.2018.03.005

Chen, C.-Y., Koch, F., & Reicher, C. (2023). *Developing a two-level machine-learning approach for classifying urban form for an East Asian mega-city.*. https://doi.org/10.1177/23998083231204606

Chen, T.-L., Chiu, H.-W., & Lin, Y.-F. (2020). How do east and southeast Asian cities differ from Western cities? *A Systematic Review of the Urban Form Characteristics.*. https://doi.org/10.3390/su12062423

Chen, W., Huang, H., Liao, S., Gao, F., & Biljecki, F. (2024). Global urban road network patterns: Unveiling multiscale planning paradigms of 144 cities with a novel deep learning approach. *Landscape and Urban Planning, 241*, Article 104901. https://doi.org/10.1016/j.landurbplan.2023.104901

Cho, I. S., & Križnik, B. (2017). *Community-based urban development : Evolving urban paradigms in Singapore and Seoul*. Springer Singapore.

Clifton, K., Ewing, R., Knaap, G. J., & Song, Y. (2008). Quantitative analysis of urban form: A multidisciplinary review. In. *Journal of Urbanism, 1*(1), 17–45. https://doi.org/10.1080/17549170801903496

Conzen, M. R. G. (1960). Alnwick, Northumberland: A study in town-plan analysis. *Transactions and Papers (Institute of British Geographers), 27*, iii. https://doi.org/10.2307/621094

Crooks, A., Pfoser, D., Jenkins, A., Croitoru, A., Stefanidis, A., Smith, D., Karagiorgou, S., Efentakis, A., & Lamprianidis, G. (2015). Crowdsourcing urban form and function. *International Journal of Geographical Information Science, 29*(5), 720–741. https://doi.org/10.1080/13658816.2014.977905

Dastjerdi, M. S., & Lak, A. (2023). Towards resilient place emphasizing urban form: An assessment framework in urban design. *Sustainable Cities and Society, 96*, Article 104646. https://doi.org/10.1016/J.SCS.2023.104646

Dawes, M. J., & Ostwald, M. J. (2017). Christopher Alexander's a pattern language: Analysing, mapping and classifying the critical response. *City, Territory and Architecture, 4*(1), 1–14. https://doi.org/10.1186/S40410-017-0073-1/TABLES/3

De Sabbata, S., Ballatore, A., Miller, H. J., Sieber, R., Tyukin, I., & Yeboah, G. (2023). GeoAI in urban analytics. *International Journal of Geographical Information Science*. https://doi.org/10.1080/13658816.2023.2279978

Elzeni, M. M., ELMokadem, A. A., & Badawy, N. M. (2022). Impact of urban morphology on pedestrians: A review of urban approaches. *Cities, 129*, Article 103840. https://doi.org/10.1016/J.CITIES.2022.103840

Fakhimi, A. H., Khani, A. H., & Sardroud, J. M. (2021). Smart-city infrastructure components. *Solving Urban Infrastructure Problems Using Smart City Technologies: Handbook on Planning, Design, Development, and Regulation, 17–54*. https://doi.org/10.1016/B978-0-12-816816-5.00002-4

Fleischmann, M. (2019). Momepy: Urban morphology measuring toolkit. *Journal of Open Source Software, 4*(43), 1807. https://doi.org/10.21105/JOSS.01807

Fleischmann, M., Romice, O., & Porta, S. (2021). Measuring urban form: Overcoming terminological inconsistencies for a quantitative and comprehensive morphologic analysis of cities. *Environment and Planning B: Urban Analytics and City Science, 48*(8), 2133–2150. https://doi.org/10.1177/2399808320910444/ASSET/IMAGES/LARGE/10.1177_2399808320910444-FIG 4.JPEG

Gallion, A. B., & Eisner, S. (1980). *The Urban Pattern: City Planning and Design*, 451. https://books.google.com/books/about/The_Urban_Pattern.html?id=SZs7UfhTdZgC.

Ghavampour, E., & Vale, B. (2019). Revisiting the "model of place": A comparative study of placemaking and sustainability. *Urban planning, 4*(2 public space in the new urban agenda: Research into implementation), 196–206. Doi:10.17645/up.v4i2.2015.

Gong, Y., Li, B., Tong, D., Que, J., & Peng, H. (2023). Planner-led collaborative governance and the urban form of urban villages in redevelopment: The case of Yangji Village in Guangzhou. *China. Cities, 142*, Article 104521. https://doi.org/10.1016/j.cities.2023.104521

Habibi, S. (2019). Design concepts for the integration of bamboo in contemporary vernacular architecture. *Architectural Engineering and Design Management, 15*(6), 475–489. https://doi.org/10.1080/17452007.2019.1656596

Healey, P. (2006). *Urban complexity and spatial strategies towards a relational planning for our times*. Routledge.

Hillier, B., Leaman, A., Stansall, P., & Bedford, M. (1976). Space syntax. *Environment and Planning. B, Planning & Design, 3*(2), 147–185. https://doi.org/10.1068/b030147

Iwańczak, B., & Lewicka, M. (2020). Affective map of Warsaw: Testing Alexander's pattern language theory in an urban landscape. *Landscape and Urban Planning, 204*, Article 103910. https://doi.org/10.1016/J.LANDURBPLAN.2020.103910

Kang, Y., Zhang, F., Gao, S., Lin, H., & Liu, Y. (2020). A review of urban physical environment sensing using street view imagery in public health studies *Doi:*https://doi.org/10.1080/19475683.2020.1791954, *26*(3), 261–275. doi:https://doi.org/10.1080/19475683.2020.1791954.

Law, S. (2017). Defining street-based local area and measuring its effect on house price using a hedonic price approach: The case study of metropolitan London. *Cities, 60*, 166–179. https://doi.org/10.1016/j.cities.2016.08.008

Leite, J. S., & Justo, R. (2017). *Typo-morphology: From research to architectural education*. https://doi.org/10.1201/9781315226255-180

Li, K., Li, Y., Yang, X., Liu, X., & Huang, Q. (2023). Comparing the three-dimensional morphologies of urban buildings along the urban-rural gradients of 91 cities in China. *Cities, 133*, Article 104123. https://doi.org/10.1016/J.CITIES.2022.104123

Lim, T. K., Ignatius, M., Miguel, M., Wong, N. H., & Juang, H. M. H. (2017). Multi-scale urban system modeling for sustainable planning and design. *Energy and Buildings, 157*, 78–91. https://doi.org/10.1016/J.ENBUILD.2017.02.024

Liu, H., Huang, B., Zhan, Q., Gao, S., Li, R., & Fan, Z. (2021). The influence of urban form on surface urban heat island and its planning implications: Evidence from 1288 urban clusters in China. *Sustainable Cities and Society, 71*, Article 102987. https://doi.org/10.1016/J.SCS.2021.102987

Liu, X., Shi, X. Q., Peng, Z. R., & He, H. D. (2023). Quantifying the effects of urban fabric and vegetation combination pattern to mitigate particle pollution in near-road areas using machine learning. *Sustainable Cities and Society, 93*, Article 104524. https://doi.org/10.1016/J.SCS.2023.104524

Liu, X., & Wang, M. (2016). How polycentric is urban China and why? A case study of 318 cities. *Landscape and Urban Planning, 151*, 10–20. https://doi.org/10.1016/j.landurbplan.2016.03.007

Lv, Z., Hu, B., & Lv, H. (2020). Infrastructure monitoring and operation for smart cities based on IoT system. *IEEE Transactions on Industrial Informatics, 16*(3), 1957–1962. https://doi.org/10.1109/TII.2019.2913535

Lynch, K. (1960). *The image of the city*. MIT Press.

Macdonald, E. (2016). The planning dimension of sustainable urban design. *Journal of Urban Design, 21*(1), 43–45. https://doi.org/10.1080/13574809.2016.1114378

Malczewski, J. (2009). *Central Place Theory. In International Encyclopedia of Human Geography (pp. 26–30)*. https://doi.org/10.1016/B978-008044910-4.01042-7

Mao, Y., Yin, L., Zeng, M., Ding, J., & Song, Y. (2021). Review of empirical studies on relationship between street environment and crime. *Journal of Planning Literature, 36* (2), 187–202. https://doi.org/10.1177/0885412221992280/ASSET/IMAGES/LARGE/10.1177_0885412221992280-FIG 2.JPEG

Marshall, S. (2004). Streets and patterns. *In Streets and Patterns*. https://doi.org/10.4324/9780203589397

McCarty, J., & Kaza, N. (2015). Urban form and air quality in the United States. *Landscape and Urban Planning, 139*, 168–179. https://doi.org/10.1016/J.LANDURBPLAN.2015.03.008

Meijers, E. (2008). Measuring Polycentricity and its promises. *European Planning Studies, 16*(9), 1313–1323. https://doi.org/10.1080/09654310802401805

Mohamed, A. A., Ubarevičienė, R., & van Ham, M. (2022). Morphological evaluation and regeneration of informal settlements: An experience-based urban design approach. *Cities, 128*, Article 103798. https://doi.org/10.1016/J.CITIES.2022.103798

Moudon, A. V. (1997). Urban morphology as an emerging interdisciplinary field. *Urban Morphology, 1*(1), 3–10.

Namwanje, P., Sanz, V. M., & Rocco, R. (2023). The pattern language approach as a bridge connecting formal and informal urban planning practices in Africa. *Urban Planning, 8*(3), 212–223. https://doi.org/10.17645/UP.V8I3.6799

Ooi, G. L. (1992). Managing change and continuity in the public housing process in Singapore. *Residence and Community, 59*(354), 170–179.

Pafka, E. (2022). Multi-scalar urban densities: From the metropolitan to the street level. *Urban Design International, 27*(1), 53–63. https://doi.org/10.1057/S41289-020-00112-Y

Panerai, P., Castex, J., Depaule, J.-C., & Samuels, I. (2004). *Urban forms : Death and life of the urban block*. Architectural Press.

Parolek, D. G., Parolek, K., & Crawford, P. C. (2008). *Form-based codes : A guide for planners, urban designers, municipalities, and developers.*, 332. https://books.google.com/books/about/Form_Based_Codes.html?id=vI91tHXYJ1YC.

Pont, M. B. (2010). Spacematrix. In *, Vol. Issue 185. Space, density and urban form*. NAi Uitgevers / Publishers Stichting.

Rapoport, A. (2003). *Vernacular architecture and the cultural determinants of form. Buildings and Society: Essays on the Social Development of the Built Environment* (pp. 158–169). https://doi.org/10.4324/9780203480755-20/VERNACULAR-ARCHITECTURE-CULTURAL-DETERMINANTS-FORM-AMOS-RAPOPORT.

Richter, M. A., Hagenmaier, M., Bandte, O., Parida, V., & Wincent, J. (2022). Smart cities, urban mobility and autonomous vehicles: How different cities needs different sustainable investment strategies. *Technological Forecasting and Social Change, 184*, Article 121857. https://doi.org/10.1016/J.TECHFORE.2022.121857

Rowe, P. G., van den Berg, H. J., & Wang, L. (2019). *Urban blocks and grids: History, technical features, and outcomes*. Scholars: Press.

Salazar Miranda, A. (2020). The shape of segregation: The role of urban form in immigrant assimilation. *Cities, 106*, Article 102852. https://doi.org/10.1016/J.CITIES.2020.102852

Salingaros, N. A. (2000). The structure of pattern languages. *Architectural Research Quarterly, 4*(2), 149–162. https://doi.org/10.1017/S1359135500002591

Samuels, I. (2008). Typomorphology and urban design practice I. *Samuels. Urban Morphology, 12*(1), 58–62. https://doi.org/10.51347/JUM.V12I1.4502

Schirmer, P. M., & Axhausen, K. W. (2016). A multiscale classification of urban morphology. *Source: Journal of Transport and Land Use, 9*(1), 101–130. https://doi.org/10.5198/jtlu.2015.667

Schmitt, A., Uth, P., Standfuß, I., Heider, B., Siedentop, S., & Taubenböck, H. (2023). Quantitative assessment and comparison of urban patterns in Germany and the United States. *Computers, Environment and Urban Systems, 100*, Article 101920. https://doi.org/10.1016/J.COMPENVURBSYS.2022.101920

Sharifi, A. (2019a). Resilient urban forms: A macro-scale analysis. *Cities, 85*, 1–14. https://doi.org/10.1016/J.CITIES.2018.11.023

Sharifi, A. (2019b). *Urban form resilience: A meso-scale analysis.*. https://doi.org/10.1016/j.cities.2019.05.010

Singh, Y. J., Lukman, A., Flacke, J., Zuidgeest, M., & Van Maarseveen, M. F. A. M. (2017). Measuring TOD around transit nodes - towards TOD policy. *Transport Policy, 56*, 96–111. https://doi.org/10.1016/j.tranpol.2017.03.013

Stanislawski, D. (1946). The origin and spread of the grid-pattern town. *Geographical Review, 36*(1), 105. https://doi.org/10.2307/211076

Stevens, Q., & Thai, H. M. H. (2024). Mapping the character of urban districts: The morphology, land use and visual character of Chinatowns. *Cities, 148*, Article 104853. https://doi.org/10.1016/J.CITIES.2024.104853

Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society, 93*(12), 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1

Talen, E. (2012). *Design for diversity: Exploring socially mixed neighborhoods*. In *Design for Diversity*: Exploring Socially Mixed Neighborhoods. https://doi.org/10.4324/9780080557601

Taubenböck, H., Wurm, M., Geiß, C., Dech, S., & Siedentop, S. (2019). Urbanization between compactness and dispersion: Designing a spatial model for measuring 2D binary settlement landscape configurations. *International Journal of Digital Earth, 12*(6), 679–698. https://doi.org/10.1080/17538947.2018.1474957

van Nes, A., & Yamu, C. (2021). Introduction to space syntax in urban studies. In *Introduction to space syntax in urban studies*. Springer International Publishing. https://doi.org/10.1007/978-3-030-59140-3.

Venerandi, A., Aiello, L. M., & Porta, S. (2023). Urban form and COVID-19 cases and deaths in greater London: An urban morphometric approach. *Environment and Planning B: Urban Analytics and City Science, 50*(5), 1228–1243. https://doi.org/10.1177/23998083221133397/ASSET/IMAGES/LARGE/10.1177_23998083221133397-FIG 2.JPEG

Venerandi, A., Zanella, M., Romice, O., Dibble, J., & Porta, S. (2017). Form and urban change - an urban morphometric study of five gentrified neighbourhoods in London. *Environment and Planning B: Urban Analytics and City Science, 44*(6), 1056–1076. https://doi.org/10.1177/0265813516658031

Wang, J., Huang, W., & Biljecki, F. (2024). Learning visual features from figure-ground maps for urban morphology discovery. *Computers, Environment and Urban Systems, 109*, Article 102076. https://doi.org/10.1016/J.COMPENVURBSYS.2024.102076

Wang, M. (2021). Polycentric urban development and urban amenities: Evidence from Chinese cities. *Environment and Planning B: Urban Analytics and City Science, 48*(3), 400–416. https://doi.org/10.1177/2399808320951205

Wang, M., & Vermeulen, F. (2021). Life between buildings from a street view image: What do big data analytics reveal about neighbourhood organisational vitality? *Urban Studies, 58*(15), 3118–3139. https://doi.org/10.1177/0042098020957198

Wang, S., & Gu, K. (2020). Pingyao: The historic urban landscape and planning for heritage-led urban changes. *Cities, 97*, Article 102489. https://doi.org/10.1016/J.CITIES.2019.102489

Webster, C. (2010). Pricing accessibility: Urban morphology, design and missing markets. *Progress in Planning, 73*(2), 77–111. https://doi.org/10.1016/J.PROGRESS.2010.01.001

Wentz, E. A., York, A. M., Alberti, M., Conrow, L., Fischer, H., Inostroza, L., … Taubenböck, H. (2018). Six fundamental aspects for conceptualizing multidimensional urban form: A spatial mapping perspective. *Landscape and Urban Planning, 179*, 55–62. https://doi.org/10.1016/J.LANDURBPLAN.2018.07.007

Whitehand, J., & Gu, K. (2007). Urban conservation in China: Historical development, current practice and morphological approach. *Town Planning Review, 78*, 615–642. https://research.birmingham.ac.uk/en/publications/urban-conservation-in-china-historical-development-current-practi.

Wong, T. C., Yuen, B., & Goldblum, C. (2008). Spatial planning for a sustainable Singapore. *In Spatial Planning for a Sustainable Singapore.*. https://doi.org/10.1007/978-1-4020-6542-2

Wu, A. N., & Biljecki, F. (2023). InstantCITY: Synthesising morphologically accurate geospatial data for urban form analysis, transfer, and quality control. *ISPRS Journal of Photogrammetry and Remote Sensing, 195*, 90–104. https://doi.org/10.1016/J.ISPRSJPRS.2022.11.005

Wu, C., Smith, D., & Wang, M. (2021). Simulating the urban spatial structure with spatial interaction: A case study of urban polycentricity under different scenarios. *Computers, Environment and Urban Systems, 89*, Article 101677. https://doi.org/10.1016/j.compenvurbsys.2021.101677

Wu, C., Wang, J., & Kraak, M. J. (2023). *Urban spatial structure from a street network perspective: Mapping street patterns with random forest classification* (S. Sangiambut, Ed.). 18th international conference on computational urban planning and Urban Management, CUPUM 2023. https://research.utwente.nl/en/publications/urban-spatial-structure-from-a-street-network-perspective-mapping.

Wu, C., Wang, J., Wang, M., & Kraak, M.-J. (2024). Machine learning-based characterisation of urban morphology with the street pattern. *Computers, Environment and Urban Systems, 109*, Article 102078. https://doi.org/10.1016/J.COMPENVURBSYS.2024.102078

Wu, C., Wang, M., Wang, J., Smith, D., & Kraak, M. J. (2024). *'Local hubs and global gateways': Understanding the impact of Singapore's master plan on urban polycentricity*. Environment and Planning B: Urban Analytics and City Science. https://doi.org/10.1177/23998083241267070

Xia, C., Yeh, A. G. O., & Zhang, A. (2020). Analyzing spatial relationships between urban land use intensity and urban vitality at street block level: A case study of five Chinese megacities. *Landscape and Urban Planning, 193*, Article 103669. https://doi.org/10.1016/J.LANDURBPLAN.2019.103669

Xu, R., Yue, W., Wei, F., Yang, G., He, T., & Pan, K. (2022). Density pattern of functional facilities and its responses to urban development, especially in polycentric cities. *Sustainable Cities and Society, 76*, Article 103526. https://doi.org/10.1016/j.scs.2021.103526

Ye, Y., Li, D., & Liu, X. (2018). How block density and typology affect urban vitality: An exploratory analysis in Shenzhen. *China. Urban Geography, 39*(4), 631–652. https://doi.org/10.1080/02723638.2017.1381536

Ye, Y., & Van Nes, A. (2014). Quantitative tools in urban morphology: Combining space syntax, spacematrix and mixed-use index in a GIS framework. *Urban Morphology, 18*(2), 97–118. https://doi.org/10.51347/jum.v18i2.3997

Young, R. F. (2017). "Free cities and regions"—Patrick Geddes's theory of planning. *Landscape and Urban Planning, 166*, 27–36. https://doi.org/10.1016/J.LANDURBPLAN.2017.03.007

Yuen, B. (2009). Guiding spatial changes: Singapore urban planning. In *Urban land markets: Improving land Management for Successful Urbanization* (pp. 363–384). Netherlands: Springer. https://doi.org/10.1007/978-1-4020-8862-9_14.

Zhang, P., Ghosh, D., & Park, S. (2023). Spatial measures and methods in sustainable urban morphology: A systematic review. *Landscape and Urban Planning, 237*, Article 104776. https://doi.org/10.1016/J.LANDURBPLAN.2023.104776