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A Spacematrix and Clustering Approach to understanding the morphology of Singapore's Housing Development Board (HDB) Estates

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Abstract. Urban morphology profoundly influences city planning and experiences significant transformations as cities evolve. This paper investigates paradigm shifts in block-level planning through a case study of Singapore, a city celebrated for its precision in urban planning and swift transformation. Integrating urban morphology theories with empirical data, we explore Singapore's block-level urban form across various stages of development. Utilising a Spacematrix approach alongside a clustering analysis of urban blocks, we categorise Singapore's towns into four distinct clusters: Suburban, Balanced Mix, Dense Urban, and Vertical Growth, each reflecting unique density patterns and building forms. This clustering reveals how Singapore's planning ideologies have transitioned from maximising space utilisation to prioritising sustainability and quality of living. This signifies a paradigm shift towards a comprehensive and inclusive urban design ethos. The paper contributes to the urban planning discourse by underscoring the technological advancements, especially with merging spatial data and GIS, in shaping modern urban analytics and planning. The insights from the clustering analysis enhance our understanding of Singapore's exceptional urban path and offer valuable perspectives for other metropolises navigating the complexities of urban expansion and sustainability.

Keywords. Urban morphology, urban planning, urban pattern, spacematrix, machine learning

1 Introduction

Urban morphology, as a cornerstone of urban planning and studies, provides critical insights into the physical form of cities and the socio-economic forces that shape them. The detailed analysis of urban form at the block level is particularly revealing, offering a lens through which the finer textures of urban life can be examined. These small-scale changes indicate larger shifts in planning policy and ideology, making them a rich subject for scholarly inquiry (Moudon, 1997; Whitehand & Morton, 2004).

The Spacematrix method has emerged as a valuable tool in urban morphology studies, offering a robust framework for analysing urban blocks. Developed to assess the spatial qualities contributing to urban resilience and adaptability, the Spacematrix categorises urban areas into nine distinct types based on three parameters: Floor Space Index (FSI), Ground Space Index (GSI), and building height (L). This method allows for a nuanced comparison of urban density and its impact on the functionality of spaces. It has been applied in various contexts to study the relationship between urban density, built form, and social space. For example, Berghauser Pont and Haupt (2010) utilised the Spacematrix method to compare European cities, revealing distinct patterns of urban density and its correlation with spatial functionality. Similarly, research in the context of rapidly urbanising Asian cities has employed this method to evaluate the impacts of high-density living on social interactions and the sustainability of urban environments (Ye et al., 2018).

Singapore's urban development provides a distinctive backdrop for applying the Spacematrix method. Since its independence, Singapore has faced the challenge of housing a growing population on limited land. The Housing and Development Board (HDB) was established in 1960 to address this challenge, and it has since been instrumental in shaping the urban landscape. The HDB estates, which house a majority of the population, are not just housing units but comprehensively planned

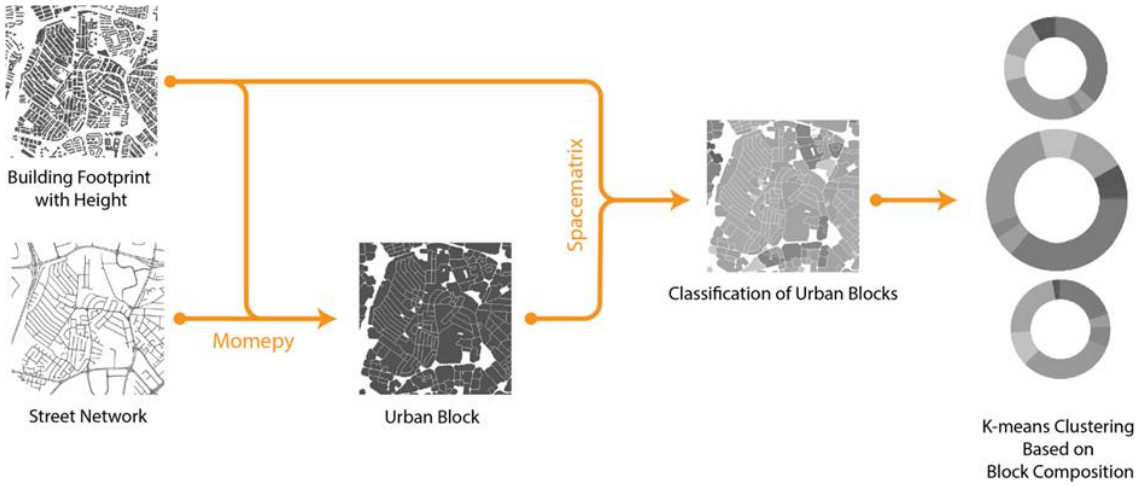

Figure 1. Methodology Flow Chart

townships with amenities, green spaces, and commercial facilities (Wong et al., 2008; Yuen, 2009; Yuen, 1998). In Singapore, the HDB's role has evolved from simply providing mass housing to facilitating community bonding and supporting the nation's sustainability goals. The planning of HDB towns has mirrored the broader shifts in urban planning, from the efficient use of space in the formative years to incorporating green technologies and community spaces in the latest developments. This evolution reflects a transition from a quantitative to a qualitative approach in urban design, underscoring the changing priorities of urban governance.

The planned nature of these HDB estates offers a unique opportunity to study the evolution of urban form through the lens of government policy. From the early utilitarian blocks designed primarily for mass housing to the recent developments incorporating sustainability principles and community-centric design, the transformation of HDB estates encapsulates Singapore's planning paradigm shifts and the different development needs. This study aims to trace these changes by comparing different HDB towns across various development phases and geographic locations, using the Spacematrix method to provide a quantifiable measure of these transformations. The study's findings aim to enrich the discourse on urban morphology and planning, offering valuable insights for cities worldwide that are navigating the challenges of growth, sustainability, and urban quality of life.

2 Method

2.1 Data and Software Availability

This study embraces a case study approach, meticulously analysing Housing and Development Board (HDB) estates in Singapore, chosen to reflect diverse development stages, geographic locations, and community frameworks within the urban tapestry of the city-state. The detailed workflow is illustrated in Figure 1: The data involved in this study is the building footprint with height information and street networks. Building footprint and street network are available on Open Street Map. The height data, however, is not open data but is available by purchase on the OSM Building. The urban blocks were synthesised utilising Momepy (Fleischmann, 2019), an open urban morphology quantitative analysis library in Python. This study harnessed building footprint and street network data from OSM, which were then processed via Momepy to demarcate individual urban blocks within the selected HDB estates. After that, the Spacematrix model is applied to categorise the urban blocks into nine patterns with their height and density information. Lastly, unsupervised clustering is introduced, categorising the HDB estates into different groups based on the composition of the pattern.

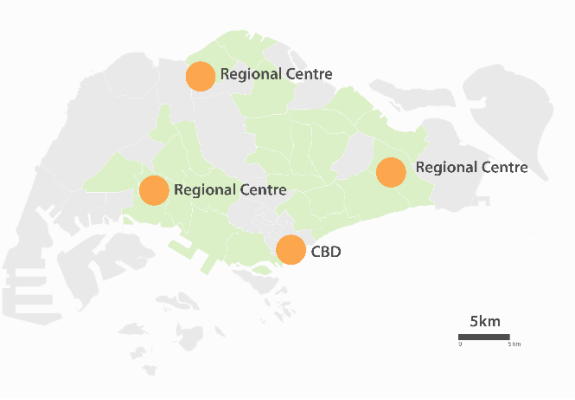

Figure 2. Singapore's CBD and three regional centres.

The case study area of Singapore is shown in Figure 2. Singapore has a prominent Central Business District (CBD) and three other regional centres (URA, 2019). For the study, 25 HDB towns were selected, excluding any that are unbuilt or located within the CBD. This exclusion ensures a focus on established residential areas, allowing

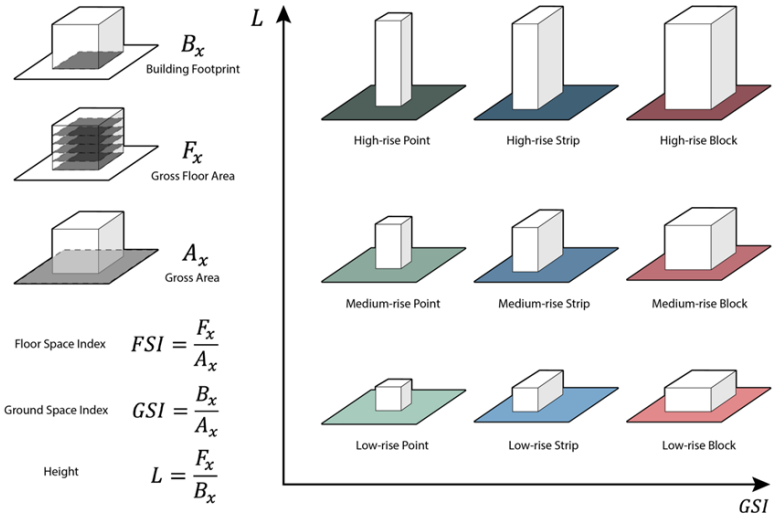

Figure 3. Spacematrix and the Block Typology

for a more accurate analysis of the lived-in urban landscape and community dynamics. The list of HDB towns or estates is presented in Table 1 (Housing Development Board, 2023) and their location is coloured in green in Figure 2. Most of these HDB towns are planned from the 1970s to the 1980s. However, the earlier year of commencement does not necessarily mean it is more "mature" or intensely developed.

Table 1. 25 HDB towns and the year of commencement (information from Housing Development Board, Singapore)

HDB Town/Estate	Year
Ang Mo Kio	1973
Bedok	1973
Bishan	1984
Bukit Batok	1981
Bukit Merah	1960
Bukit Panjang	1984
Bukit Timah	Unknown
Choa Chu Kang	1977
Clementi	1974
Geylang	1963
Hougang	1979
Jurong East	1979
Jurong West	1979
Kallng/Whampoa	1959
Marine Parade	1972
Pasir Ris	1983
Punggol	2010
Queenstown	1952
Sembawang	1996
Sengkang	1994
Serangoon	1983
Tampines	1980
Toa Payoh	1965
Woodlands	1971
Yishun	1976

2.2 Spacematrix

Following the generation of urban blocks, they were assorted into nine distinct typologies per the Spacematrix method. These typologies traverse the continuum from low-density, sprawling urban forms to high-density, consolidated constructs, presenting a gamut of urban morphologies for detailed examination. The Spacematrix classifies the plots into nine types based on the Floor Space Index (FSI), Ground Space Index (GSI) and Height (L), as illustrated in Figure 3.

Considering Singapore's denser urban layout compared to Europe, where the original Spacematrix model was developed, our study has established a unique range of L values to distinguish urban blocks by their height profiles into low-rise, medium-rise, and high-rise categories. In this system, high-rise blocks generally comprise office buildings and residential skyscrapers. At the same time, the lower end of the L value range typically includes structures like single or double-story houses and educational facilities. We use GSI values to classify blocks into point, strip, or block forms for typology. Blocks with a GSI value under 0.2 are identified as the "Point", those with values between 0.2 to 0.36 as the "Strip", and any above that as the "Block". Overall, the Spacematrix method produces a 3x3 grid that categorises street blocks into nine unique types, as illustrated to the right in Figure 3.

This typological classification enabled a comparative discourse across the diverse HDB estates. By scrutinising the Spacematrix typologies within each estate, the

	Cluster 0 Suburban	Cluster 1 Balanced Mix	Cluster 2 Dense Urban	Cluster 3 Vertical Growth
High-rise Block	0.02%	0.48%	1.02%	0.00%
High-rise Strip	0.19%	0.97%	4.69%	1.34%
High-rise Point	0.60%	0.63%	1.23%	8.82%
Medium-rise Block	4.20%	9.21%	13.85%	3.32%
Medium-rise Strip	14.60%	36.31%	21.05%	13.75%
Medium-rise Point	2.46%	3.82%	5.11%	1.63%
Low-rise Block	25.52%	17.09%	13.40%	19.70%
Low-rise Strip	44.77%	26.17%	25.11%	40.54%
Low-rise Point	7.63%	5.31%	14.53%	10.90%

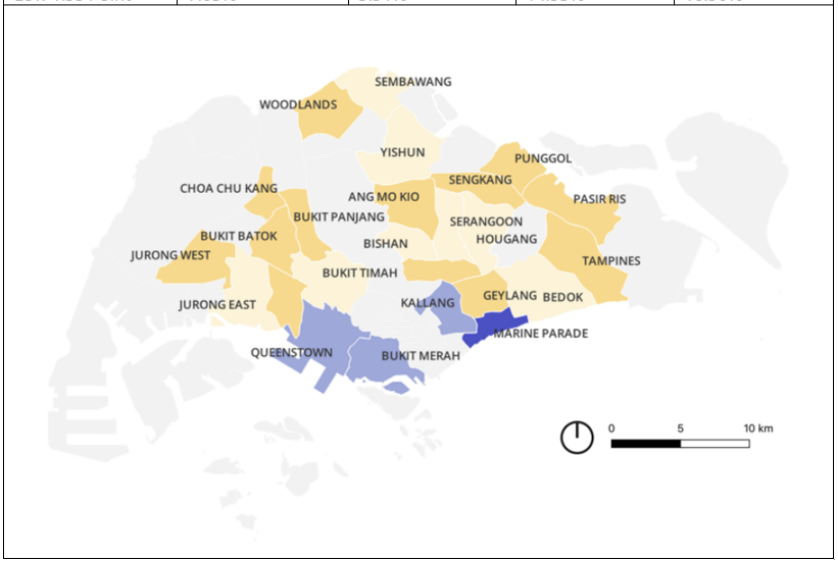

Figure 4. Block typology composition in different clusters.

investigation sought to decode the patterns and trajectories in the evolution of Singapore's urban fabric.

2.3 K-means Clustering

A clustering algorithm was applied to the dataset to enrich the analysis, segmenting the urban blocks into four clusters based on morphological characteristics. More specifically, K-means clustering is a robust partitioning method that segments data into K distinct, non-overlapping subgroups or 'clusters' without any cluster-internal hierarchical structure. It is an unsupervised learning algorithm that solves the well-known clustering problem efficiently. The core objective of K-means is to minimise the total intra-cluster variance or the squared Euclidean distance between the points and the centroid of their respective clusters.

In the context of our study, the choice of K-means clustering for this study was motivated by its simplicity, efficiency, and widespread acceptance in data analysis. K-means is particularly suited for identifying inherent groupings within data based on specified characteristics, in this case, the morphological attributes of urban blocks. By leveraging this algorithm, we could distil the essence of each cluster, revealing the planning paradigms underlying Singapore's urban development. The clusters were interpreted to understand their morphological composition, which corresponded with specific urban planning strategies and phases of development. For instance, clusters with higher proportions of high-rise developments suggested planning approaches that emphasise vertical growth in response to urban density and land constraints. A preliminary examination of the dataset and silhouette score determined k = 4, revealing four distinct urban development patterns in Singapore's HDB estates.

3 Results

The K-means clustering gives us four groups of HDB towns with distinct characters in block pattern composition, as illustrated in Figure 4. We named the clusters for ease of understanding and differentiation. These groups are also mapped to reveal their geographic location.

Cluster 0, the "Suburban", is characterised by a dominance of low-rise developments in blocks and strips at 25.52% and 44.77%, along with a moderate presence of medium-rise blocks and strips at 4.2% and 14.6%. The limited high-rise development suggests a suburban or peri-urban setting. Areas in this cluster likely have more open spaces and emphasise community-style living, away from the hustle and bustle of highly urbanised areas.

These estates are distributed across the island, typically in transitional areas between the urban centres like Bukit Timah, Yishun, and Bedok. They are planned in various stages of urban expansion from the 1970s to 1990s. This indicates regions with less dense development, possibly focusing on residential areas or those with more available land for future developments.

Cluster 1, the "Balanced Mix", shows a mix of urban and suburban characteristics. There is a higher presence of medium-rise and low-rise developments, especially in strips (36.31% and 26.17%), and a moderate level of high-rise development. This suggests a diverse urban landscape that accommodates various functional needs. The location of these groups of HDB estates falls into the region decimated for regional centres of Singapore, like Woodlands, Jurong, and Tampines. The commencement period is similar to cluster 0 from the 1970s to the 1980s. This suggests a clear division of urban function. Hence, they include areas with a balance of residential, commercial, and recreational spaces, providing a well-rounded living experience.

Cluster 2, "Dense Urban," indicates highly urbanised areas with dense housing. The high values in high-rise and medium-rise categories, both in blocks and strips, point to areas where vertical living is prominent. The presence of all forms of housing (high-rise, medium-rise, and low-rise) suggests that these might be older urban areas that have undergone various phases of development. These regions are centrally located, with proximity to the CBD and easy access to amenities and public transport like Queenstown and Bukit Merah. They are also some of the earliest HDB towns planned. Some of them even date back to the pre-independence era in the 1950s. This suggests that these estates serve as the extension of the dense urban core and carry functions not just for residential but also for those overspilled from the CBD.

Cluster 3, the "Vertical Growth", is defined by its high values in high-rise points with 8.82%, indicating a concentration of tall residential buildings, with moderate to high values in low-rise strips and points, and low values in medium-rise developments. This group seems less common and has only one HDB estate, Marine Parade. It is an area that has seen recent development with modern high-rise residential and commercial buildings with immediate access to coastal lines and CBD. It is probably due to the unique geographic location and scenery resources that make the Marine Parade unique as an area with modern urban planning focused on maximising land use through tall residential towers.

Each cluster represents a unique urban fabric within Singapore, reflecting different phases of development, planning strategies, and lifestyle preferences. "Suburban" is ideal for those seeking a quieter, more spread-out living environment with less development density; "Balanced Mix" offers a harmonious blend of urban and suburban elements, providing residential, employment and various urban functional needs; "Dense Urban" attracts those who thrive in bustling city centres, and "Vertical Growth" caters to modern urban dwellers who prefer living in high-rise apartments with comprehensive amenities and incomparable scenic and geographic locations.

The geographic distribution of these clusters can reflect various factors, including historical development patterns, land availability, and the evolution of urban planning policies in Singapore. The clusters indicate a gradient of development from the central parts of the city outwards, with more dense urban cores in the centre, transitioning to mixed-use areas and then to more suburban-style developments further from the centre. This distribution aligns with common urban development patterns where city centres are more densely developed due to older, historical growth and land scarcity. At the same time, the outskirts are less dense, allowing for more open, spread-out communities.

Another observation is the temporal factor that may influence the morphology of the HDB estates at the block level. Earlier development tends to lead to higher development intensity, for example, cluster 2 HDB Towns. Later-stage development has a more apparent functional division between mixed-used medium-intensity and residential low-intensity HDB towns. However, it is hard to reach a clear conclusion on how these morphological differences may reflect temporal aspects of urban planning as the development of HDB towns is still an ongoing process.

The application of the Spacematrix method and subsequent clustering analysis of Singapore's HDB estates offers valuable insights into the evolution of urban planning strategies. By identifying four distinct clusters of urban development, ranging from Suburban to Vertical Growth, this research highlights how different planning paradigms respond to challenges such as land scarcity, population growth, and sustainability goals. These findings can guide future urban planning efforts by demonstrating the benefits of diverse, mixed-use developments that support community engagement, environmental sustainability, and high-quality urban living. Planners can leverage this knowledge to design cities that are resilient, inclusive, and adaptable to changing urban needs.

4 Discussion and Conclusion

The clustering analysis presented in this study provides a detailed morphological differentiation of Singapore's

HDB towns, revealing a clear correlation between urban form and planning function. The proximity to the CBD and other urban centres appears to significantly influence the morphological characteristics of HDB estates, as seen in the clustering spatial distribution. This functional differentiation, well captured by the Spacematrix typologies, demonstrates a clear spatial hierarchy within the urban planning framework.

While this study has provided valuable insights into the urban morphology of Singapore's HDB estates by applying the Spacematrix method and K-means clustering, several limitations should be acknowledged. First, the study's focus on block-level morphology, while detailed, does not account for other influential factors in urban planning, such as the broader patterns like the distribution of urban mass represented by urban spatial structure (Wu et al., 2021) and the street layouts (Pont et al., 2019; Wu et al., 2024), which greatly influence the arrangements of the buildings and blocks. These factors could provide a more comprehensive understanding of the dynamics that shape urban form. Also, the study is limited by its static nature, which captures the morphology at a single point in time. Urban morphology is dynamic, with continuous changes due to ongoing development and planning interventions. We would also like to acknowledge that the study area encompasses more than just housing estates developed by HDB; it also includes industrial and commercial land use parcels. Nevertheless, by incorporating the proximate urban functions of these HDB estates, we think it can better reflect the strategic role of the different towns.

Future studies could explore multi-temporal datasets to capture urban morphology's evolution and incorporate urban patterns involving other urban elements, such as streets, at various scales. This approach would offer a more comprehensive view of the urban structure and its dynamics. In addition, cross-comparative studies across different cities could provide a global perspective on urban development patterns, revealing universal principles as well as localised adaptations. Such studies would enhance our understanding of urban morphology as a reflection of societal needs, environmental constraints, and technological advancements, ultimately guiding the creation of more resilient and sustainable urban environments.

In conclusion, this study's integration of Spacematrix typologies with clustering analysis has offered a nuanced view of Singapore's urban morphology evolution at the block level. The four identified clusters—Suburban, Balanced Mix, Dense Urban, and Vertical Growth—each narrate a part of Singapore's urban story, reflecting the city-state's strategic responses to its growth challenges and land scarcity. The findings emphasise the shift in planning paradigms from purely utilitarian space-maximization to a comprehensive approach that considers sustainability, quality of life, and community engagement. The transition to lower-density, mixed-use, and transit-oriented developments in strategic urban locations marks a significant shift toward a sustainable urban future. As cities worldwide confront similar challenges, the insights from Singapore's experience can inform and inspire global urban planning practices, offering a valuable model for creating liveable, resilient, and inclusive urban spaces.

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