A Comparative Analysis of Urban Morphology in Cairo and Makkah Using Open-Source Spatial Data

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Abstract

Urban morphology, the study of a city's physical form, provides critical insights into societal forces and spatial organization. Computational tools and geospatial data have revolutionized this field, enabling quantitative, comparative analysis. This study leverages these advancements to compare two seminal Islamic cities: Cairo, Egypt, and Makkah, Saudi Arabia—representing divergent urban evolution shaped by historical layering versus large-scale pilgrimage. Using the Momepy library for Python, we analyzed OpenStreetMap data, calculating morphological indicators at both building and street network levels. Key metrics included tessellation for urban grain, convexity and Equivalent Rectangular Index (ERI) for shape complexity, elongation for building typology, and Edge Betweenness Centrality (EBC) for street network structure. The results reveal a fundamental morphological divergence. Cairo's organic, millennial growth has produced a heterogeneous, polycentric fabric with wide variation in tessellation areas, greater shape irregularity, and a distributed street network where traffic flow is balanced across an extensive grid. In contrast, Makkah's pilgrimage-driven development has yielded a more monocentric, consolidated form, evidenced by larger median building areas, more standardized geometries, and a highly channeled network where movement funnels along hierarchical corridors toward the central Haram area. Despite data limitations, the quantitative evidence consistently demonstrates that distinct historical trajectories and urban functions produce uniquely identifiable spatial signatures. This research underscores the efficacy of computational morphometrics for decoding urban form and provides a replicable analytical framework for understanding how different developmental drivers manifest spatially in complex urban environments.

1. Introduction

Urban morphology, the study of the physical form and structure of cities, examines how urban spaces evolve through the complex interplay of social, economic, and political dynamics. This field decodes the urban fabric to understand how societal forces become materially embedded in a city's layout and architecture, with particular relevance for fostering adaptable, resilient urban environments that support economic prosperity and social cohesion. As a branch of urban studies, urban morphology systematically investigates the spatial form of cities, their historical development, and the various agents—from planners to economic actors—responsible for their transformation (Kropf, 2017).

The methodological approaches in urban morphology have evolved significantly. While traditional methodology relied heavily on qualitative analysis through direct observation and classification of fundamental elements like buildings, plots, and streets (Moudon, 1997). The digital age has fundamentally transformed the discipline of urban morphology, catalyzing a shift toward quantitative science (Dibble et al., 2015).

This transformation is driven by the proliferation of big data-including open-source geospatial datasets-coupled with immense modern computational power. The emerging field of Urban Morphometrics now employs sophisticated computational constructs, such as axial maps and proximity bands (Araldi and Fusco, 2019; Ariza-Villaverde et al., 2013), to objectively analyze the patterns and processes shaping the built environment.

Space syntax theory complements this by quantitatively analyzing how spatial layout shapes urban life. It uses axial maps to model movement and spatial relationships (Hillier and Hanson, 1984). Integrated with GIS, space syntax becomes a powerful computational tool which enables the automated creation of spatial models and calculation of configurational measures, allowing morphologists to systematically analyze urban form across entire cities and correlate spatial structure with socioeconomic data (Jiang and Claramunt, 2002; Jiang and Liu, 2010). Fleischmann (2019) developed the momepy package, a Python toolkit, whose development is particularly timely in this age of urbanization. In this context, measurable characters are vital for recognizing form-based patterns and establishing analytical frameworks. The morphometric characters implemented in momepy enable cross-scale analysis of urban form.

This digital transformation is fundamentally propelled by the advanced capabilities of Geographic Information Systems (GIS). These systems merge vast geospatial data with socio-economic information, enabling quantitative analysis of urban form across entire metropolitan regions. This capability bridges a fundamental gap, allowing researchers to directly correlate physical structures with the social and economic forces that shape them. Consequently, GIS shifts morphological analysis from its traditional focus on small historic towns to a comprehensive, data-driven, and systematic understanding of urban form, providing an empirical foundation for the study of contemporary urban development and for planning and policy. This systematic understanding of urban form provides critical insights for addressing contemporary challenges including rapid population growth,

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urban sprawl, climate change, and sustainable development (e.g., (Güller and Toy, 2024)).

This paper employs the Momepy package to analyze the urban morphology of two Islamic cities: Cairo and Makkah. These cities represent compelling case studies for morphological analysis within the Middle East region. The application of this computational approach facilitates a nuanced comparison, revealing both the formative forces that have shaped each urban environment and the potential commonalities in their spatial structures. Cairo and Makkah, though sharing Islamic cultural foundations, evolved under different formative pressures. Cairo developed as a multi-functional administrative and commercial hub through layered historical growth. Makkah was fundamentally shaped by its pilgrimage function, oriented toward accommodating millions of visitors to the Holy Mosque.

We hypothesize these divergent logics produced distinct morphological signatures: Cairo should exhibit greater heterogeneity and network complexity from organic evolution; Makkah should display polarized structure—extreme densification and standardization near the Haram versus different patterns peripherally.

Using Momepy and OpenStreetMap data, we address two questions: (1) How do building morphology metrics differ between cities, revealing developmental processes? (2) Do street network patterns confirm Cairo’s hypothesized polycentricity versus Makkah’s pilgrimage-oriented monocentricity?

By addressing these questions, this study makes two key contributions. First, it provides the first systematic quantitative comparison of these two iconic Islamic cities, filling a gap in morphological research on the Middle East. Second, it demonstrates how existing morphometric tools can be deployed not merely descriptively, but as instruments for testing specific hypotheses about how differing urban functions shape built form over time—offering a replicable template for similar comparative studies across the region.

The structure of the remainder of this paper is organized around the core components of empirical research. It proceeds with an examination of case studies and the methods of data collection, followed by a delineation of the overall methodology. The findings are then presented and critically discussed in the subsequent sections.

2. Case Studies in Historical Urban Growth and Data Collection

This research employs a comparative case study methodology, focusing on Cairo, Egypt, and Makkah, Saudi Arabia. These cities were selected as paradigmatic examples of distinct urban paradigms within the Middle East region. Cairo represents the historically layered administrative-commercial city, shaped by successive processes of addition, adaptation and reuse (Michieletto, 2025). Makkah exemplifies the pilgrimage-centered holy city, where urban form has been fundamentally oriented toward accommodating visitors to the Holy Mosque (Maroufi and Rosina, 2017). A systematic computational analysis of their urban form will illuminate the spatial manifestations of these two developmental forces.

2.1 Cairo, Egypt

Cairo’s growth is a narrative of layered urban palimpsest, where each era physically inscribes itself upon the landscape (Abu-Lughod, 2018). Its foundational layer began with early Islamic Al-Fustat (641 AD) and the Fatimid dynasty’s walled city of Al-Qahira (969 AD), whose core street plan remains the spine of historic Cairo. The Mamluk period (1250–1517) catalyzed expansion beyond the Fatimid walls, densifying the urban fabric and cementing Cairo’s role as a preeminent Islamic capital. A major morphological shift occurred in the 19th century under Khedive Ismail, who created Downtown Cairo—a modern district of gridded boulevards and European-style architecture linking the historic core to the Nile. The 20th and 21st centuries are defined by explosive, multi-nodal growth. Post-war population pressure spawned vast informal settlements, while state-led projects produced planned satellite cities in the desert, such as New Cairo and the new administrative capital. This latest layer has created a polycentric metropolitan region. Thus, Cairo’s form results from sequential layering: from early Islamic nuclei, through medieval consolidation and 19th-century modernization, to its contemporary explosion into the desert—a physical manifestation of political, economic, and demographic forces.

2.2 Makkah, Saudi Arabia

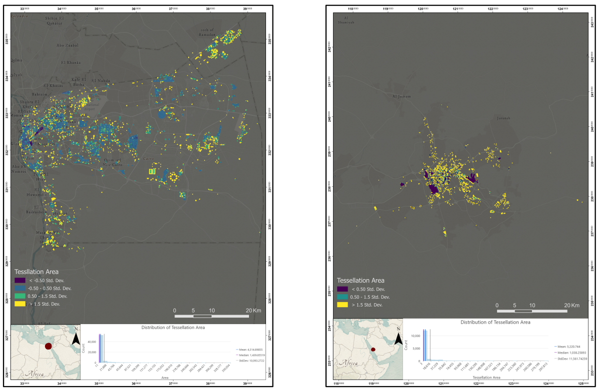
Makkah’s historical growth reflects a unique urban evolution shaped entirely by its religious significance (Nabhan et al., 2023). It has transformed from a compact settlement, constrained by topography, into a modern metropolis. The mid-20th century marked a turning point with the expansion of the Grand Mosque, followed by major infrastructure projects that pushed the city beyond its natural confines. The contemporary era is defined by mega-projects involving extensive mountain levelling and vertical construction. This evolution demonstrates how pilgrimage requirements and state-led development have rapidly reshaped Makkah’s landscape, prioritizing capacity and accessibility over organic growth.

2.3 Data Collection

The primary data source for both street networks and building footprints in this study is OpenStreetMap (OSM). As a collaborative, open-source geographic database—often described as the ”Wikipedia for maps”—OSM relies on a global community of volunteers for data contributions. The relevant data for Cairo and Makkah was programmatically retrieved using the OSMnx library for Python. Initial analysis, however, revealed that the collected building data was less comprehensive than anticipated. This discrepancy in data completeness is a recognized challenge in OSM-based urban studies, often attributed to a comparative lack of consistent volunteer mapping efforts in some Arab cities. The density and activity of the OSM contributor community are generally lower in these regions than in many North American and European cities, resulting in uneven spatial data coverage.

3. Methodology: Quantitative Urban Morphological Analysis

Following data acquisition, this study employed a computational approach to quantitatively analyze and compare the urban forms of Cairo and Makkah. The primary tool for this analysis was **Momepy**, a specialized Python library designed for urban morphological analysis, which facilitates the computation of a



(a) Cairo, Egypt (b) Makkah, KSA

Figure 1. Tessellation analysis for (a) Cairo, Egypt and (b) Makkah, KSA.

wide array of metrics describing physical characteristics and spatial configurations.

The analysis was conducted at two levels: the **building footprint** level and the **street network** level. A suite of key morphological indicators was selected to capture dimensions of form, shape, and network structure. The definition, urban significance, and mathematical computation for each metric are detailed below.

3.1 Building-Based Morphological Metrics

3.1.1 Tessellation

- **Expression:** Tessellation creates a continuous spatial fabric, known as a Voronoi diagram, from building footprints. Each cell in this diagram represents the “sphere of influence” of a single building.
- **Urban Significance:** This transforms discrete buildings into a continuous surface, enabling the analysis of urban density, land use intensity, and the underlying structural grain of the city without the gaps between structures.
- **Mathematical Model:** Given a set of generator points (building centroids) P_i, the tessellation generates a polygon V_i for each point, defined as:

$$V_i = \{X \mid d(X, P_i) \le d(X, P_j) \, \forall \, j \neq i\} \tag{1}$$

where:
d is the Euclidean distance
P_i is the centroid of building i
X ia an arbitrary point in the plane
V_i is the voronoi cell (polygon) associated with building i

3.1.2 Convexity (Convex Fill Ratio)

- **Expression:** This metric assesses the compactness and complexity of a building’s shape by comparing its area to the area of its convex hull (the smallest convex polygon that can contain it).
- **Urban Significance:** It measures architectural complexity. Lower values indicate more intricate, concave footprints (e.g., with courtyards or recesses), often found in traditional or specialized structures, while values near 1 indicate simple, convex shapes common in modern buildings.
- **Mathematical Model:**

$$\text{Convexity} = \frac{\text{Area}_{\text{Footprint}}}{\text{Area}_{\text{Convex Hull}}} \tag{2}$$

Range: $0 < \textit{Convexity} \le 1$

3.1.3 Elongation

- **Expression:** Elongation quantifies the linearity of a building footprint by relating its area to its perimeter through the minimum bounding rectangle.
- **Urban Significance:** This metric helps classify building typologies. High elongation (values approaching 0) is characteristic of linear structures like row houses, warehouses, or certain administrative buildings, whereas low elongation (values approaching 1) indicates more compact, nearly square forms.
- **Mathematical Model:** Following the implementation in momepy, elongation is derived from the area and perimeter of the building footprint:

$$\text{Elongation} = \frac{p - \sqrt{p^2 - 16a}}{p + \sqrt{p^2 - 16a}} \tag{3}$$

where:
a is the area of the building footprint, and
p is the perimeter of the building footprint.

This formulation, based on (Gil et al., 2012), calculates elongation through the relationship between area and perimeter rather than directly extracting the side lengths of the minimum bounding rectangle. This approach ensures orientation-invariant measurements while remaining computationally efficient.
Range: $0 < \textit{Elongation} < 1$

3.1.4 Equivalent Rectangular Index (ERI)

- **Expression:** The Equivalent Rectangular Index evaluates how closely a building’s shape resembles a perfect rectangle, considering both area and perimeter characteristics.
- **Urban Significance:** It indicates the efficiency and regularity of the building form. Modern, formal developments typically have high ERI values (close to 1), while informal or historic organic buildings often have lower values due to their irregular, adaptive shapes.
- **Mathematical Model:** Based on Basaraner and Cetinkaya (2017) and implemented in momepy, the ERI is calculated using the minimum rotated rectangle to ensure orientation-invariant measurements:

$$\text{ERI} = \sqrt{\frac{\text{A}_\text{f}}{\text{A}_\text{m}}} \times \frac{\text{P}_\text{m}}{\text{P}_\text{f}} \tag{4}$$

where:
A_f is the footprint area
A_m is the area of minimum rotated rectangle
P_f is the footprint perimeter
P_m is the perimeter of minimum rotated rectangle

Using the minimum rotated rectangle (oriented bounding box) via the rotating calipers algorithm ensures that the metric is invariant to building rotation—a perfect rectangle rotated at any angle will consistently yield an

ERI value of 1.
Range: $ERI > 0$ *(typically* ≤ 1*, though minor numerical variations may occur)*

3.2 Street Network-Based Morphological Metrics

3.2.1 Edge Betweenness Centrality

- **Expression:** Network centrality measures a node's importance within a graph, with different metrics like betweenness centrality—which identifies nodes on the shortest paths between others—serving specific purposes. This is useful for comparing network representations, such as in (Senousi et al., 2022), where betweenness was applied to both station-based and line-based models to reveal different facets of transit system centrality.
- **Urban Significance:** Segments with high betweenness centrality act as critical thoroughfares and key connectors for city-wide movement. This metric highlights the primary structural skeleton of the urban network and predicts potential corridors for high traffic flow.
- **Mathematical Model:**

$$CB(e) = \sum_{s \neq t \in V} \frac{\sigma_{st}(e)}{\sigma_{st}} \tag{5}$$

where:
V is the set of nodes (intersections)
σ_{st} is the total number of shortest paths from node s to node t
$\sigma_{st}(e)$ is the number of those shortest paths that pass through edge e

This study specifically employs **Edge Betweenness Centrality**. This is a critical metric of network centrality that identifies the importance of a street segment (edge) as a connector by calculating the fraction of all shortest paths between pairs of nodes that pass through it.

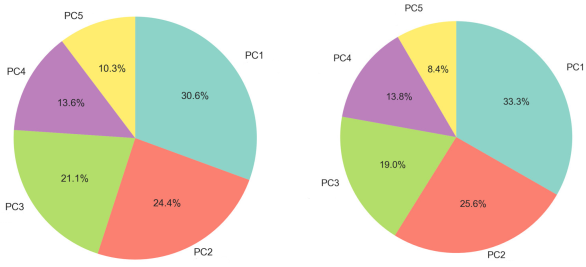
This multi-dimensional suite of metrics provides a robust quantitative profile for a comparative analysis of the distinct urban morphologies of Cairo and Makkah, linking their spatial forms to their unique historical and functional contexts.

4. Results and Discussion

This section presents and discusses the results of the quantitative analysis of urban indicators and characteristics in Cairo and Makkah. The findings are visualized through spatial distribution maps, with corresponding statistical distributions and key descriptive statistics provided for each indicator.

Before interpreting these results, we must establish the methodological boundaries of this study. As a comparative analysis based on openly available data and descriptive statistics, our aim is to identify morphological patterns that warrant further investigation, not to claim definitive causal relationships. The following discussion should be read as an exploratory hypothesis-generating exercise rather than a confirmatory analysis.

The analysis reveals a clear morphological divergence between the two cities, though these findings must be considered alongside significant data limitations. but this interpretation requires careful qualification due to data limitations that may bias the comparison.



(a) Cairo, Egypt (b) Makkah, KSA

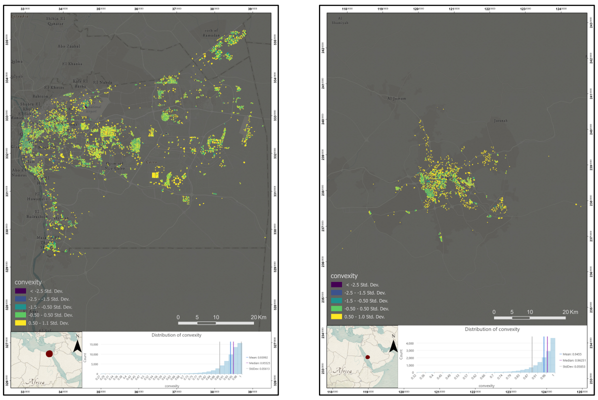
Figure 2. PCA variance distribution for (a) Cairo, Egypt and (b) Makkah, KSA.

To enhance the analytical rigor of the study, multivariate statistical analysis was conducted using Principal Component Analysis (PCA). Five urban morphology indicators were included in the analysis: tessellation area, convexity, elongation, ERI, and neighbor distance. These variables represent key spatial characteristics describing urban density, geometric regularity, and building morphology.

Prior to analysis, the variables were standardized to eliminate scale differences. PCA was applied separately to the Cairo and Makkah buildings datasets to identify dominant spatial structure patterns and enable cross-city comparison. The PCA results (as shown in Figure 2) indicate that the first three principal components explain approximately 76.1% of the variance in Cairo and 77.9% in Makkah, suggesting that the selected indicators effectively capture the dominant morphological characteristics of the urban fabric. Both cities show very similar morphological dimensionality (approximately 77%), which indicates that the selected indicators robustly describe urban morphology in both contexts.

The building footprint data for Makkah (13,881) is substantially less comprehensive than for Cairo (57,106), falling below expected levels of coverage. This discrepancy reflects a known challenge with OpenStreetMap in the region, where lower volunteer mapping activity frequently leads to incomplete datasets. Consequently, Makkah's results may be slightly skewed by the under-representation of smaller structures.

Despite these data constraints, the analysis indicates fundamental morphological differences. Acknowledging these data limitations, we proceed with cautious interpretation of the observed patterns. Makkah demonstrates a descriptively higher median building area (366 m² versus Cairo's 277 m²), suggesting an urban fabric dominated by larger-scale structures that align with its modern, pilgrimage-driven redevelopment. In contrast, Cairo's lower median values reflect a more heterogeneous urban fabric, consistent with its historical layering patterns and the prevalence of smaller-scale buildings in its organic and informal neighborhoods. The comparative analysis of tessellation areas reveals distinct urban morphologies for Cairo (Figure 1a) and Makkah (Figure 1b). Cairo exhibits a highly heterogeneous fabric, evidenced by its extreme standard deviation and fragmented spatial distribution, indicative of layered, organic growth. In contrast, Makkah demonstrates a more consolidated structure with a clear core-periphery gradient. Its statistical variation stems from this planned differentiation rather than internal



(a) Cairo, Egypt (b) Makkah, KSA

Figure 3. Convexity maps for (a) Cairo, Egypt and (b) Makkah, KSA.

fragmentation. This reflects Cairo’s historical, unplanned evolution against Makkah’s topographically influenced, centralized development.

Based on the comparative analysis of convexity, both Cairo (Figure 3a) and Makkah (Figure 3b) exhibit tessellations with generally regular, near-rectangular shapes, as indicated by their high average convexity values close to 1. However, a key distinction emerges in the lower quartile: Cairo demonstrates a wider range of shape irregularity, with a minimum convexity of 0.27 and a first quartile of 0.92, compared to Makkah’s minimum of 0.32 and Q1 of 0.92. This suggests that while both cities are predominantly composed of regular plots, Cairo’s urban fabric contains complex shapes, reflecting a more heterogeneous and organically evolved morphology.

The ERI analysis reveals distinct morphological patterns between the two cities. While both exhibit high rectangularity in building forms (median ERI 1.0), as shown in Tables 1 and 2. Cairo demonstrates a wider dispersion of ERI values (Table 2), particularly at the lower quartile (0.94), revealing greater morphological diversity. This heterogeneity, coupled with a lower median building area (277 m²), aligns with its complex urban history, incorporating both planned developments and organic growth patterns across different historical layers. In contrast, Makkah’s urban fabric, as evident in Table 1, is characterized by greater uniformity. It shows a lower standard deviation in ERI (0.07 vs Cairo’s 0.11) and a higher first quartile (0.97), indicating more standardized building geometries. This is combined with a larger median building area (366 m²), reflecting its systematic, large-scale redevelopment for pilgrimage infrastructure.

The analysis of building elongation reveals distinct urban forms, with Cairo (Table 2) exhibiting a fabric of more uniformly elongated, rectangular footprints, as indicated by its higher median and quartile values. This pattern reflects a planned regularity, consistent with orthogonal grid planning on the flat Nile Valley terrain. In contrast, Makkah (Table 1) displays a more heterogeneous morphology. Its lower median elongation, higher standard deviation, and significant proportion of compact buildings (low Q1) point to an adaptive irregularity. This is driven by mountainous terrain, which creates irregular plots, and a dense urban core of large-scale towers with compact footprints optimized for the constrained area around the Holy Mosque.

The analysis of neighbour distance reveals a clear contrast in urban spatial structure between the two cities. As stated in Table 2, Cairo exhibits a pattern of moderate and relatively uniform building spacing, with a higher median distance (18.37) indicating that the typical building is significantly farther from its neighbours. This reflects a more planned urban fabric, likely characterized by standardized plot sizes and broader streets on the flat Nile terrain. In stark contrast, Makkah’s spatial organization, described in Table 1, is defined by adaptive density and extremes. Its much lower median distance (11.51) reveals that the typical building is packed far more tightly, a direct result of topographical constraints and immense development pressure near the Holy Mosque. However, its very high standard deviation shows this intense co-location coexists with areas of substantial spacing, creating a polarized urban landscape of dense clusters and isolated structures.

(a) Cairo, Egypt (b) Makkah, KSA

Figure 4. Edge Betweenness Centrality analysis for (a) Cairo, Egypt and (b) Makkah, KSA.

Based on the analysis of 320,937 street segments in Cairo and 115,743 in Makkah, the Edge Betweenness Centrality (EBC) reveals fundamentally different urban network structures. Cairo’s spatial distribution (4a) demonstrates a polycentric model compared to Makkah, where key corridors like bridges and the Ring Road channel regional flows while maintaining generally distributed connectivity across its extensive grid. In contrast, Makkah’s network ((4b)) exhibits a strongly monocentric pattern, with clear channeling of flows along primary arteries converging toward the central Haram area. This structural difference reflects Cairo’s organic evolution as a distributed metropolis versus Makkah’s purpose-driven planning as a pilgrimage-centered city, highlighting how distinct urban functions and growth patterns manifest in street network topology.

4.1 Limitations and Methodological Considerations

This study has several limitations. First, OSM data lacks systematic validation; the disparity in building counts between Cairo and Makkah raises concerns about differential completeness. Future studies should validate using satellite imagery or local mapping agencies.

Second, our analysis relies on descriptive statistics without inferential testing. Future research should apply statistical tests to establish significance.

Despite these limitations, this study demonstrates how open data and morphometric tools can generate hypotheses about Islamic urbanism. The patterns identified provide clear proposi-

Descriptive statistics	Tessellation	Convexity	ERI	Elongation	neighbor_distance
Mean	5220.744	0.945	0.970	0.635	22.812
Std	11561.743	0.059	0.070	0.227	30.695
Min	2.741	0.319	0.219	0.040	0.000
Q1 (25%)	564.498	0.924	0.975	0.470	5.133
Median(50%)	1038.259	0.963	1.000	0.652	11.508
Q3 (75%)	3168.671	0.987	1.000	0.831	25.834
Max	297812.565	1.000	1.126	1.000	197.976

Table 1. Descriptive statistics of the selected morphological properties for Mekkah City (total counts = 13881).

Descriptive statistics	Tessellation	Convexity	ERI	Elongation	neighbor_distance
Mean	4314.699	0.940	0.942	0.671	25.514
Std	10093.272	0.056	0.114	0.202	24.255
Min	10.535	0.267	0.180	0.045	0.000
Q1 (25%)	547.281	0.918	0.940	0.533	9.324
Median(50%)	1439.855	0.955	1.000	0.678	18.370
Q3 (75%)	3435.119	0.979	1.000	0.833	33.001
Max	350054.385	1.000	1.127	1.000	199.843

Table 2. Descriptive statistics of the selected morphological properties for Cairo City (total counts = 57106).

tions for future research with more complete data and rigorous methods.

5. Conclusion

This comparative study substantiates the hypothesized morphological divergence between Cairo and Makkah. Cairo exhibits the predicted signature of organic evolution: heterogeneous fabric, irregular plots, diverse building forms, and a polycentric street network. Makkah confirms the hypothesized pilgrimage-centered structure: monocentric consolidation, standardized geometries, larger buildings with adaptive spacing, and hierarchical networks channeling movement toward the Haram.

Quantitative metrics—tessellation area, convexity, elongation, neighbor distance, and betweenness centrality—consistently capture these divergent logics. Despite data limitations from OpenStreetMap coverage, PCA confirms that the selected indicators robustly describe both urban fabrics (approximately 77% variance explained).

This study contributes the first systematic quantitative comparison of these iconic Islamic cities and demonstrates how morphometric tools can test hypotheses about how urban functions shape built form, offering a replicable template for comparative research across the Middle East.

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