



Article

Uncovering Urban Palimpsest through Descriptive and Analytical Approaches to Urban Morphology—Understanding the Ottoman Urban Fabric of Bursa, Türkiye

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Abstract: This study examines the transformation of the urban fabric by analyzing changes in both structural and numerical parameters of spatial organization, with a particular emphasis on the hierarchical relationships between streets, blocks, and buildings. The research utilizes Bursa, the former Ottoman capital in Turkey, as a case study to explore these dynamics. The elements of streets, blocks, and buildings are posited as fundamental components in conceptualizing cities as layered palimpsests, where successive historical layers coexist within the urban fabric. The research establishes a conceptual parallel between the methodologies and analytical tools of urban morphology, particularly through the shared notion of the palimpsest. In the case of Bursa, the architectural remains and urban form of the Early, Classical, and Late Ottoman periods and of the Republican period are superimposed. In particular, the late Ottoman reform era, the Tanzimat period of the 19th century, brought great change. Historical maps from this era serve as primary sources for comprehending the evolving character and spatial configuration of the city. This research presents a novel methodological contribution by extending the analytical framework of urban morphology to integrate both qualitative and quantitative data. It employs Geographic Information Systems (GISs) and statistical methods to quantify changes in the urban fabric, assessing both pre-modernization and post-modernization phases. Historical maps from the 19th century are utilized as primary sources to trace and compare transformations within the urban fabric, with clustering techniques further aiding this analysis. The findings provide a deeper understanding of the dynamic processes that shape the historic structure of cities, offering a dual approach to urban transformation that harmonizes historical continuity with modern development.

Keywords: urban morphology; urban palimpsest; qualitative and quantitative analysis; urban heritage; urban transformation



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1. Introduction

The urban fabric transformations in urban morphology are determined by the evolution or changes in urban form and the relationships between urban fabric elements (streets, plots, squares, open spaces, and green spaces) [1] (p. 537). Patterns in the inherited urban landscape are the past of the urban fabric [2] (p. 8); while some patterns remain constant, and certain aspects are embedded in the urban fabric, new ways of urban development continue to emerge [3] (p. 79). The urban fabric absorbs historical patterns, preserving them as evidence of retrospective value and as a guide for future urban development.

Cities are exposed to different transformation factors such as natural disasters or man-made actions, which create paradoxes in urban organization and complicate the legibility of inherited morphological elements within the contemporary urban fabric. From the morphological perspective, the urban fabric is complex and multi-layered in the contemporary city,

thus acting as palimpsest. In the case of layered/palimpsest cities, the analysis of urban fabric transformations focuses on specific topics: the tendency for changes, derivation, or persistence of features (configuration), the degree of historical stratification between periods (size), the powerful constancy of relationships, and the distinctive residues of past periods (types).

The former Ottoman capital city of Bursa represents a special case for investigating the transformation of the Ottoman urban fabric, due to its rich evolutionary history and the presence of significant Turkish-Islamic urban heritage elements. The traditional Islamic urban fabric, characterized by narrow, steep, and winding dead-end streets from the medieval era, could no longer accommodate the demands of a growing city. Therefore, urban transformation was considered one of the most important tasks during the Ottoman reform era, known as the “Tanzimat” (1839–1876), as well as during the last Ottoman period, and the post-war republic era (1922–1960). These transformations led to the loss of the integrity of the traditional Islamic urban fabric. Moreover, during the Islamic period, major fires and earthquakes wiped out almost the entire historic core of Bursa, especially around the Khan area. This extensive damage led to the reconstruction of buildings and new planning decisions aimed at modernizing the city [4]. Consequently, the urban fabric in the Khan area has become a complex organism where patterns from the past and present coexist (formation and transformation).

The process of urban fabric transformation is inherently complex, and understanding it requires a comprehensive approach in obtaining information about urban forms in the historic environment, as explaining them helps to understand the essential mechanisms of cities. This necessitates tracing, describing, and revealing patterns through different time dimensions within the urban fabric to evaluate the levels of the transformation process. Position, outline, and internal arrangement are key principles used to describe the urban tissue and the evolution of types across different periods [5,6]. Therefore, examining the transformation of the urban fabric only through qualitative evaluation can be deceptive; a more quantitative assessment is needed to establish a rigorous trace and comparison.

Urban morphometrics, as a modern quantitative approach to urban morphology [7,8], addresses this need by analyzing urban form through the segmentation of its elements. This method involves selecting measurable characteristics and classifying these elements [9,10] to represent various statistical interpretations of urban morphology, enabling a more precise and objective understanding of the urban fabric. By deriving comprehensive metrics from plots, plot series, and building patterns, urban morphometrics enables the clustering of urban areas based on morphometric similarities or differences, facilitating their identification and comparison.

The methodology focuses on discrete variables related to the structures of urban elements, categorizing them as either continuous or abstract (discontinuous). Abstract metrics are based on conceptual or categorical information, such as land use types, building types, or neighborhood and urban tissue types. In contrast, continuous metrics are measurable characteristics derived from these discrete types, quantified through attributes like street length, block size, building height, density, or the compactness of spaces.

To bridge the gap between the structural and statistical perspectives of urban form, this study introduces a simplified model that conceptualizes the similarities and differences between abstract and dynamic (continuous) pattern characteristics. The model identifies clusters based on morphological, qualitative, and quantitative characteristics in the process of urban fabric transformation in the Khan area of Bursa.

We aim to address a main research question: how can urban fabric transformation be described in terms of changes in structural and numerical parameters?

This research aims to address the main research question by recognizing developmental clusters based on descriptive and analytical approaches to urban morphology. It aims to identify changes and persistence in measurable elements of urban form [11] within the urban fabric. The urban fabric transformation in Bursa can be traced through two cartographic maps, which guide the trajectory of development stages to identify similarities

and differences regarding key attributes such as type, configuration, size, and relationships between elements. The expected outcome of this study is to provide additional insights into understanding the historical stratification principle and the possible application of descriptive statistical analysis while quantifying urban form. It also evaluates the implementation of palimpsest methods to trace the qualitative and quantitative changes from the modernization era to the contemporary urban heritage site.

2. Background (Research and Theoretical Framework)

In urban morphological agenda [12–20], the genesis and function of cities are often explored through theories that seek to understand how cities emerge, evolve, and are interpreted. These theories examine cities from various perspectives, often focusing on historical processes, essential elements that constitute growth patterns, forms of transition, change, and recurrence. Urban morphology provides a set of concepts and methods within these theories that lead to the systematic investigation of the phases of change and the development of towns. This investigation, known as traditional qualitative urban morphology, is primarily descriptive. However, it lacks a quantitatively rigorous framework for understanding the geometric properties of urban form.

Similarly, the palimpsest method traces the process of formation by which new forms are constituted, considering existing forms to invite further ones—essentially reusing previous formations. Gérard Genette, a renowned French scholar, pioneered the use of the palimpsest method (layering old documents) in literary research [21] (p. 147). His approach focuses on the objects of the poetic, aiming to understand the hidden and visible aspects of formations, recognize them as continuing “genres/types”, and describe the persistent links between particular modes and themes [22].

The application of these methods is in the analysis of historical layering, the concept of type, and hierarchy in relationships. Within this framework, further concepts such as the principles of persistence and belonging, derivation, and the degree of continuity and discontinuity provide parameters for investigation.

The complex nature of urban morphology can be investigated more comprehensively through strengthening the link between traditional qualitative approaches extended to the potential offered by quantitative assessments [23]. These combined approaches can explain the central concerns of the field with rigor and facilitate comparisons in urban morphology.

2.1. Descriptive (Qualitative) Framework of the Urban Morphology

A central concern of Conzen’s research on towns, particularly his study of Alnwick, *Northumberland: A Study in Town-Plan Analysis* (1960) [15], is the description and understanding of the processes that lead to the physical view of towns. Conzen identifies this as a heterogeneous collection of three form complexes in morphological terms: town plan, built fabric, and the utilization of buildings and space. This ongoing process constitutes the townscape. The town plan itself has three basic complexes of plan elements—street system (streets), plot pattern (plots), and building pattern (block plans of buildings)—that are hierarchically related. Their distinct combinations are identified as plan units by Conzen. These elements are organized in a hierarchy based on their varying degrees of persistence in the temporal response of a town plan: streets are the most stable over time, the plot system has less stability than streets, and the building system is the least stable [24,25]. The building fabric provides the most visually obvious connection to history in a town, with its historical signs written into its structure. His methodology focuses on identifying town plans and maps by analyzing the three fundamental elements of urban form across various historical periods. It involves modeling their development units and mapping the spatial relationships of physical features, considering two key aspects: classification and interaction.

In cities where historical layers overlap, the relationship between time and space is inherently complex, resembling a kind of palimpsest. The residue of the previous periods is distributed over the built-up area, often erasing parts of the past while leaving traces

or things that leave its marks [26] (p. 51). The matter is complicated by the fact that the physical aspect of the process (physical substance and its arrangement) is resistant to change and persistent, since another or one part of a town with other parts are themselves linked in patterns (levels of resolution)—plan unit (urban tissue) types, types of form complexes, patterns of elements—of the past and the present—configurations that repeat within a series of events.

Research by Caniggia G and Maffei GL (1979) [14] on towns is concerned with the interpretation of the historical process of formation and change in town structures over time. The principle of aggregation is the basis of their work on towns [27]. Caniggia and Maffei consider buildings as elements within the towns where the processes are legible, and their aggregation (formation of a building aggregate) is depending on the structures (through routes) whose formation is linked to the notion of the fabric (formation of the urban fabric) of which the urban organisms (towns) are composed [28]. Caniggia seeks to understand the relationship between the time (temporal) and space (spatial) within the built environment by distinguishing two aspects: copresence and derivation. Spatial relations define copresence, while temporal relations are selected to define derivation.

These belonging or coextension principles within the built environment are conceptualized by Karl Kropf as levels of resolution/levels of specificity illustrated by the multi-level diagram to represent a coherent hierarchy of built form [29] (p. 50). The multi-level diagram conceptualizes Conzen's and Caniggia's conception of hierarchy, allowing for overlapping elements and representing relationships analytically. It illustrates the relationships between and within levels in the hierarchy of built form. Using Kropf's multi-level diagram offers guidance to visualize the process of formation and transformation of a settlement over time while qualitatively interpreting the urban fabric as a palimpsest. The diagram can help reveal hidden meanings and rules at different levels of resolution [30] within the generic structure, providing greater detail and identifying specific types of built forms through the element separation in morphological analysis. Kropf follows three principles while investigating the specific types within generic structure via its "position, outline and internal arrangement" [31] (p. 43).

Aldo Rossi [20] defined the concept of permanence as visible/reflected features in the city's physical structures, basic layout (street or simple urban tissue), and monuments. Rossi [20] (p. 60) indicates that cities tend more towards evolution than preservation, and during this evolution, monuments are not only conserved but also consistently exhibited as primary elements to establish a relationship between the past and present, and monuments can persist in different layers of the urban landscape. From this point of view, monuments serve as important representatives of insight and are also key aspects of a place's identity.

In a recent paper, for instance, urban scientist Éva Lovra integrated several qualitative methods of urban morphology to analyze the relationship between urban morphological features and historical events. In her novel research [1,32], she used a spatial-temporal clustering approach based on the historical stratification principle to establish a taxonomy of 70 towns and urban tissue typologies from the period and territory of Austria-Hungary, based on their spatial and temporal similarities.

2.2. Analytical (Quantitative) Framework of the Urban Morphology

The range of quantitative approaches to urban morphology facilitates complex and meaningful comparative studies in morphological contexts. This section presents relevant methods for quantitatively investigating urban form. Michael Batty advances the understanding of cities towards the quantitative side [33] (p. 15), shifting from a top-down to a bottom-up approach [34] to capture the degree of diversity while explaining relationships within the hierarchy [35]. According to his way of thinking, urban form—differentiated from one to another or over time—is defined by the geometry of size and shape, scale, and dimension.

Morpho is a methodology for quantitatively assessing urban form at different scales, using various criteria such as street and block accessibility, building age, dimensions of

street blocks and plot series, building alignment, the ratio of building height to street width, and building usage. This methodology focuses on both synchronic (current) and diachronic (historical) analysis, allowing for the monitoring of the evolution of urban form over time [36].

Urban morphology addresses different aspects, different scales, and different elements of urban form, providing a consistent descriptive language for understanding the spatial structures and processes of urban development and transformation [31]. Morphometrics involves the quantitative investigation and description of urban morphology by quantifying and classifying urban elements based on characteristics such as size and shape, using multivariate statistical analysis [37]. Quantitative urban morphological analysis [37,38] is used to systematically characterize urban form elements based on their attributes, measurements, and metrics at different scales of the built environment.

Dibble et al. [10] proposed urban morphometric methods following the analogy with biological morphometrics for the systematic investigation of the evolution of urban form. These methods quantify the size, shape composition, density, usage, and arrangement of urban form elements using multivariate statistics for rigorous description and classification. In a subsequent study, A. Venerandi et al. [39] applied this urban morphometrics approach to characterize city forms and their changes over time. By measuring and comparing key morphological features, this method identifies similar and recognizable patterns, which are defined by statistical recurrence. Schirmer and Axhausen [9] employed a morphometric method to define a set of attributes related to urban morphology at various scales, including objects, compositions, neighborhoods, and municipalities. This approach allows for the identification of typologies at these scales and classifies the built environment into distinct typological classes.

Space syntax, a quantitative assessment of the urban morphology developed by Bill Hillier and Julienne Hanson in (1984) [40], employs a syntactic analysis of street networks and configurational assessment to explore various forms and configurations. This method focuses on the geometric and topological attributes and measurements of the built environment. The configurational approach in urban morphology involves understanding the relationship between voids and solid spaces [31], where their spatial configuration is the result of a generative process.

The notion of configuration itself represents the relationships between different levels of urban forms, which can adapt and evolve over time due to changes or variations, leading to the creation of different types [31]. To effectively distinguish the similarities and differences in configuration, it is necessary to establish a clear definition of various street patterns, enabling comparison and the recognition of distinctive types [41]. This helps generate meaningful types and establish an effective typology by offering choices among them. Stephen Marshall [42] characterized street and pattern types, as well as network structures, to better understand the evolution of cities by examining their past and present.

Vialard [41] proposed typological atlases of blocks and block faces based on their internal and external load relationship with streets and buildings, using an analytical and quantitative approach to urban and building morphology. The method focuses on the geometric representation of blocks and building footprints, considering their size, relationships, and configurations. This approach assesses the potential of the existing city profile and provides tools and urban design parameters for evaluating alternative scenarios for future development of built form and architecture.

3. Methodology

The proposed methodological approach is based on the research and theoretical framework of this study, by utilizing morphological, qualitative, and quantitative analysis to investigate the evolving interactions of urban form elements over time. This approach views cities as layered palimpsests, where past and present elements of the urban fabric overlap or change. The main layering principle of this methodology follows the methods of Conzen [15], Caniggia and Maffei [14], Aldo Rossi [20], and Éva Lovra [1].

In the case of Bursa, the urban fabric is a continuous entity, reflecting the accumulation of historical layers and the aggregation of urban elements that have transformed in various ways over time. Given this complexity, a simplified methodological approach is necessary for this study. Therefore, the proposed approach comprises four successive steps as presented in Figure 1.

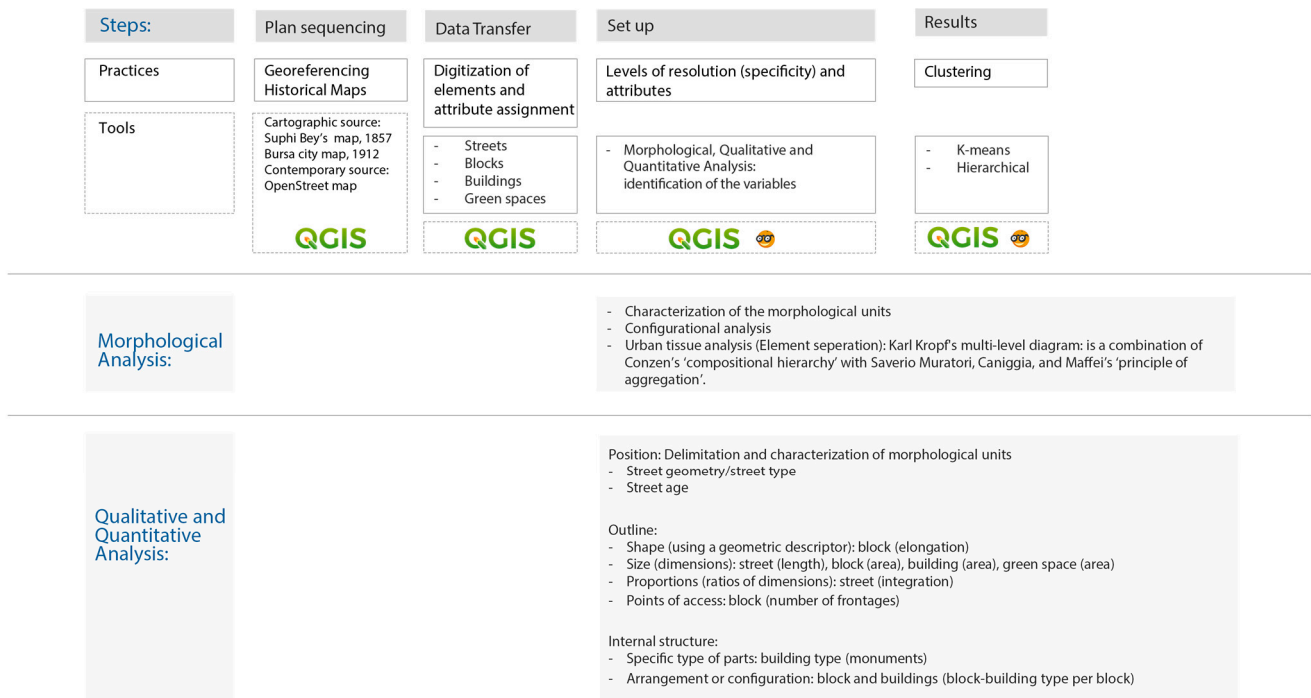


Figure 1. The four-step research framework for investigating the qualitative and quantitative changes in layered/palimpsest cities.

The first step in the method involves planning the sequencing process, which includes georeferencing two historical maps (from 1857 and 1912) and layering them with contemporary data. QGIS [43] is used for both the georeferencing and the transfer of map elements into the GIS. Once the maps have been georeferenced, the second step is to digitize the elements and assign attributes to them in QGIS. These elements are identified based on features observed in both historical and contemporary maps, such as streets, blocks, buildings, and green spaces.

In the subsequent setup section, the focus shifts to elaborating on the descriptive and analytical framework of urban morphology. This involves integrating methods [34–36] and techniques within GIS and using statistical analysis to evaluate the variables of change and persistence across different levels of the generic structure. This step is designed according to the approaches of Micheal Batty [35] and Karl Kropf [29] to underline the logic of the analysis, which begins with determining the appropriate resolution level. The basic principle is to start by identifying broader patterns that resist change, followed by progressively increasing the resolution to detect more detailed variations. Once the relevant features have been digitized and the resolution level determined, morphological, qualitative, and quantitative variables are identified. Morphological analysis is applied to identify structured spaces, with the characterization of the morphological units or regions, configurational analysis, and element separation analysis at other levels, aiming to provide a descriptive approach in a qualitative way that enhances understanding of the transformation process. Qualitative analysis is based on three key principles—position, outline, and internal arrangement—which are used to define specific types across different periods. To identify changes and persistence (specific types of elements) in measurable components of urban form within the urban fabric, seven primary character categories are determined: morphological unit, shape, size, proportions, points of

access, specific types of parts, and arrangement or configuration. A descriptive statistical analysis is then conducted within GIS and tested using Orange data mining software (3.35) [44], focusing on qualitative and quantitative character parameters. This analysis considers their statistical distributions over time to describe the spread (ranges) and variance of values.

The final step is to perform statistical cluster analysis in GIS to determine whether the clusters exhibit continuity or change over time in relation to the historical development of the cities. Using Orange data mining software, we further refine the clustering results in GIS by applying K-means and hierarchical clustering methods.

3.1. Plan Sequencing

The decision to focus on the 19th century for this study was driven by the availability of cartographic material and the relatively stable nature of urban structural changes within the existing Ottoman urban fabric. This enabled the documentation of enduring patterns for reference in the analysis. The most comprehensive representation of Bursa is the cadastral plan created in 1857 by Suphi Bey [45], which acts as the primary research reference, supplemented by the Bursa city map from 1912 [46]. These historical maps have been georeferenced in QGIS [43] to align with the OpenStreetMap [47] data accurately. Three components of the townscape—town plan, building type, and land use pattern [15,48]—and landmarks (monuments) can be identified and traced from Suphi Bey’s Maps. However, for the period of 1912, only street structure (simple tissue) and landmarks are available. Therefore, we were able to use the landmarks as common reference points on both historical maps and the contemporary map. Khans Area (Orhan Gazi complex and its surroundings) was chosen due to its centrality as the Old Town, typically serving market aggregation in Ottoman urban settings, thereby encompassing intense historical layering or the largest number of morphological periods. Notably, this site hosts numerous monumental buildings, demonstrating a rich history of construction and maintenance over time [49], despite the substantial loss of structural integrity caused by historical fires and earthquakes [50]. The delineation of site boundaries follows the guidelines outlined in the Bursa Management Plan of 2013–2018 [50,51], which delineates both core and buffer zones. Figure 2 illustrates the geographical positioning and layout of the selected site.

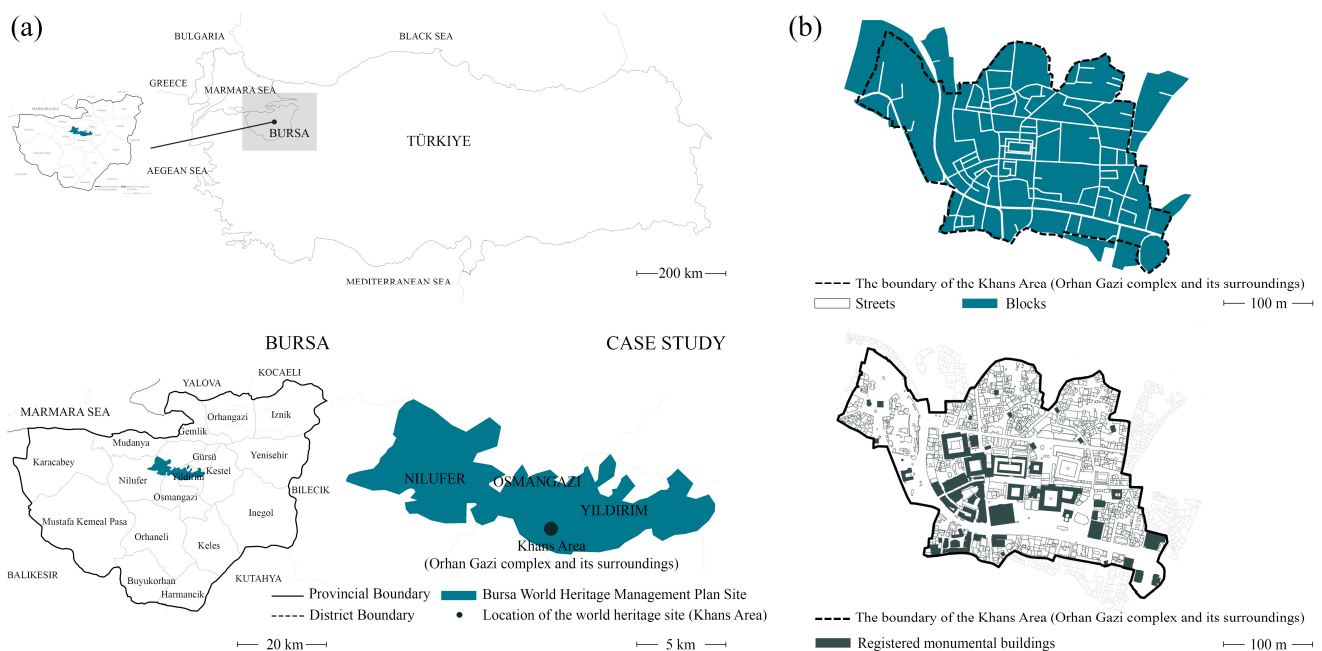


Figure 2. Representation of the geographical position of the city of Bursa within Türkiye, the location of the Bursa World Heritage Management Plan Site within the Bursa Municipality (a), and the location of the Khans area (a), and the site boundary of the Khans Area and its surroundings (b).

3.2. Data Transfer

During the cartographic map digitization process, the three main urban form complexes depicted in the 1857 map—streets, blocks, buildings, and land use—were subjected to the extraction of relevant information layers and attribute assignment procedures. These physical elements were then transformed into shapefiles. The 1912 plan included the layout of streets and solid representations of several protected official buildings. The shapefiles of the current maps, which depict streets, blocks, buildings, building utilizations, green spaces, and site coverage of the selected heritage site originate from the Bursa Municipality.

For the purpose of the study, the process of digitalization involves simplifying graphic representations and information into attributes (layers), which include the following: street network (street age, street geometry, street length, integration, and road segments); blocks (area, elongation, perimeter, block faces, and number of frontages); buildings (areas of building footprints, number of buildings, and building types); and green spaces (area).

3.3. Setup

The core principle of integrating morphological analysis with quantitative measures involves moving up and down the hierarchy. This process includes identifying broader patterns, characterizing morphological regions, enhancing resolution, investigating details of identified elements, and then re-evaluating the wider patterns based on these details. Morphological analysis typically focuses on understanding the historical characteristics and significance of places, as well as identifying and classifying specific features and their differences within different parts of the built environment. This understanding should extend to higher levels of specificity and resolution.

To conduct both qualitative and quantitative analysis, morphological analysis is essential. The research follows two processes: first, the characterization of the morphological unit and configurational analysis to identify these units; second, urban tissue analysis (element separation analysis) combined with Karl Kropf's multi-level diagram [29,31] and Conzen's [15] 'compositional hierarchy', along with Saverio Muratori [19], Caniggia, and Maffei's [14] 'principle of aggregation'. Therefore, we propose using qualitative and quantitative characteristics to distinguish specific types of elements, thereby clarifying changes at different scales.

As detailed in Section 2.1 element separation analysis is divided into three main principles according to Kropf's guidelines [31] (p. 27): position, outline (including points of access), and internal structure. These principles are defined by seven primary character categories, as outlined in Kropf's guidelines [31] (pp. 43–45), which are used for morphological, quantitative, and qualitative analysis: morphological unit, shape, size, proportions, points of access, specific types of parts, and arrangement or configuration.

The five resolution levels for identifying morphological elements are determined: morphological regions (1), streets (2), blocks (3), buildings (aggregation within the block) (4), and green spaces (5). The three key principles used to define elements at each hierarchical level, corresponding to their qualitative and quantitative metrics, are summarized in (Table 1).

Table 1. Categories of character and metrics used for the element separation analysis.

Principles	Category of Character	Levels	Character Variables (Qualitative and Quantitative)	Unit of Measure
Position	Morphological unit	(1) (2) (1) (2)	Street type Street age	
Outline	Shape	(3)	Block elongation	[31,50]
		(1)	Coverage	[n], [m ²]
	Size	(2)	Street segment length	[m]
		(3)	Block area	[m ²]
		(5)	Green area	[m ²]
	Proportions	(2)	Street integration	[n]
Points of access	(3)	Number of block frontages	[n]	
Internal structure	Specific type of parts	(4)	Building type (monuments)	
	Arrangement or configuration	(3) (4)	Block-Building type per block	

3.4. Clustering

The identification of developmental changes in the urban fabric is primarily based on statistical clustering analysis, utilizing results from unsupervised learning on quantitative variables. This method focuses on similarities and differences in overlapping attributes across various time periods, aiding in determining whether clusters have evolved or remained consistent over time. The K-means clustering algorithm is the most widely used technique, representing a dataset based on a predefined number of clusters. It partitions data points into clusters by associating them with the nearest mean [52] (cluster centroid), minimizing variances within clusters through the use of Euclidean distances.

Another approach, hierarchical clustering, generates clusters by progressively grouping similar variables based on their distances until a cluster tree (dendrogram) is formed. The desired number of clusters can then be obtained by cutting the dendrogram at the appropriate level.

The methodology behind the clustering analysis covers these two clustering methods: K-means and hierarchical clustering. The levels of clustering resolution are determined by Conzen's [15] classification method, which examines the ongoing processes in towns based on three basic complexes of plan elements: streets (which define the morphological unit), blocks, and buildings. The investigation is of a quantitative statistical, focusing on K-means clustering within the morphological unit, blocks, and building-level character variables that share homogeneous characteristics. The types of buildings within the clusters are grouped using the hierarchical clustering method to establish typological similarities at the highest levels of specificity. The aim is to validate the clusters, determining whether clusters show continuity or change over time in correlation with the previous formation of the cities. The clustering results in GIS are reviewed using a classification algorithm within the Orange data mining software [44] for simple data visualization.

4. Results of Qualitative and Quantitative (Morphological) Analysis

4.1. Morphological Regions

4.1.1. Characterization of Morphological Unit (Street Type and Street Age)

This section is designated to address the characterization of the morphological unit (recognition and delimitation) of the selected heritage site. While discussions [41,53,54], regarding the selection of the urban morphological unit may vary, distinct regions can still be recognized. The choice of the unit, as conceptualized from the previous maps (a combination of the maps), causes the results of the process on the physical structure to differentiate one part of the urban area from another and exhibit patterns (types of forms) and configuration.

In the morphological concept and temporal perspective [55], the basic backbone of the morphology of cities [48] is shaped by the nature of the hierarchy of the street networks or the regular or less orderly sequences of the streets [56]. The evolution of streets is a tangible representation of time, offering glimpses about the specific periods in which it was built. For this purpose, to clarify the characterization of the morphological unit, the research focuses on two key variables: street age and street type.

The methodology employed here aligns with Conzen's evolutionary approach, emphasizing the principle of the historical stratification concept. This principle is central to systematically investigating for the proposed variables, associated with distinct morphological periods. It lays the groundwork for understanding how elements aggregate within the urban hierarchy over time. Street types do not occur typologically without geometry, so they tend to be defined systematically. The degree of resolution of street networks can vary not only between specific typological clusters but also within any typological cluster (containing clearly different or mutually exclusive types). This means that the urban street pattern as a whole is defined by the way the character formed by the types fits together collectively; conversely, types can be defined by how they relate to each other and as a whole.

For this purpose, it is important to determine the route structures whose changes (properties of the types and the way they are connected to each other) play an important role in defining the character [42]. Figure 3 illustrates the manipulation of the different ages of the street layers within the current map of the Khan aggregate that led to the identification of five types of streets within each period. This analysis, conducted through Geographic Information Systems (GISs), involves overlaying drawn routes from each map to visualize the presence or absence of each street type in the current street structure.

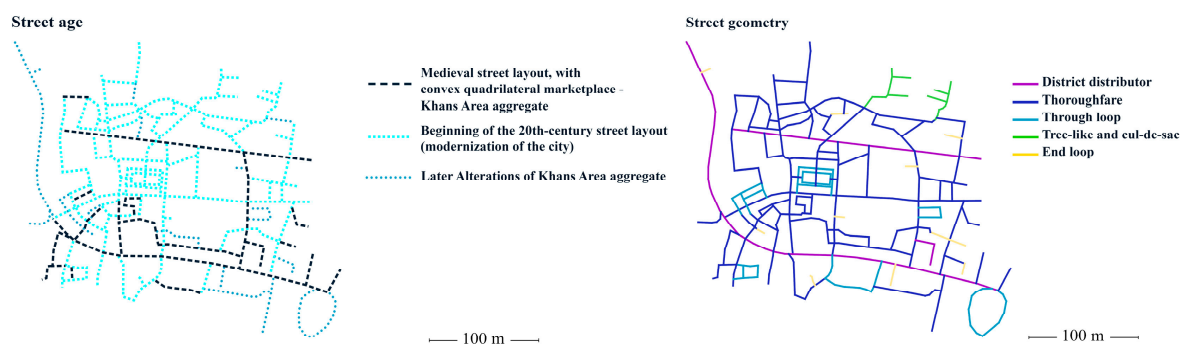


Figure 3. The manipulation of different street layer ages within the current map of the Khan aggregate has led to the identification of five street types for each period.

A few unchanged streets detected from the map of 1857 tend to show they do not respond to development as they outline the medieval street layout, which is often linked through loops, end loops, and cul-de-sac streets within the marketplace aggregation. Between the years 1857 and 1912, the hierarchy of route types and their relationship (configurational connection) show different intersections with the emergence of new route types after the modernization of the city. The connection to the Khan area developed laterally, and roads connecting the district tangentially along the marketplace connected to local routes with a distributor route. The pattern permeability of streets resulting on the current map has increased and been shaped with the intersections and redirection of new and previously established routes. So, we have identified street types according to two types of distributors—district distributor and local distributor (within the four types of roads in terms of topological connection)—that were extracted based on Marshall's framework [42] (pp. 47–92) categorization of the street pattern.

4.1.2. Size of Morphological Regions/Units (Coverage)

This section presents an overview of the initial spatial coverage of morphological regions, with a focus on block areas, building footprints, and street lengths. It is important to note that the coverage of these regions is not permanent; rather, their transformation and spatial extent are subject to various influencing factors, potentially leading to alterations in their characteristics due to aggressive transformation processes. Employing a method that analyzes the physical variables of morphological region coverage offers quantitative evidence that can be correlated with transformation processes across different scales [23,39].

The distribution of street coverage (Figure 4) holds comparable significance to land coverage, indicating a correlation with the hierarchical structure of urban elements over time. Streets tend to exhibit greater resilience to temporal changes in urban development and transformation compared to block and building coverage. However, the correlation between streets and blocks depends on street configuration. In Section 4.1.1, the research has already highlighted changes in street configurations over time. In this methodological section, we demonstrate the variability in block coverage across different street configurations, thereby differentiating within the same land area.

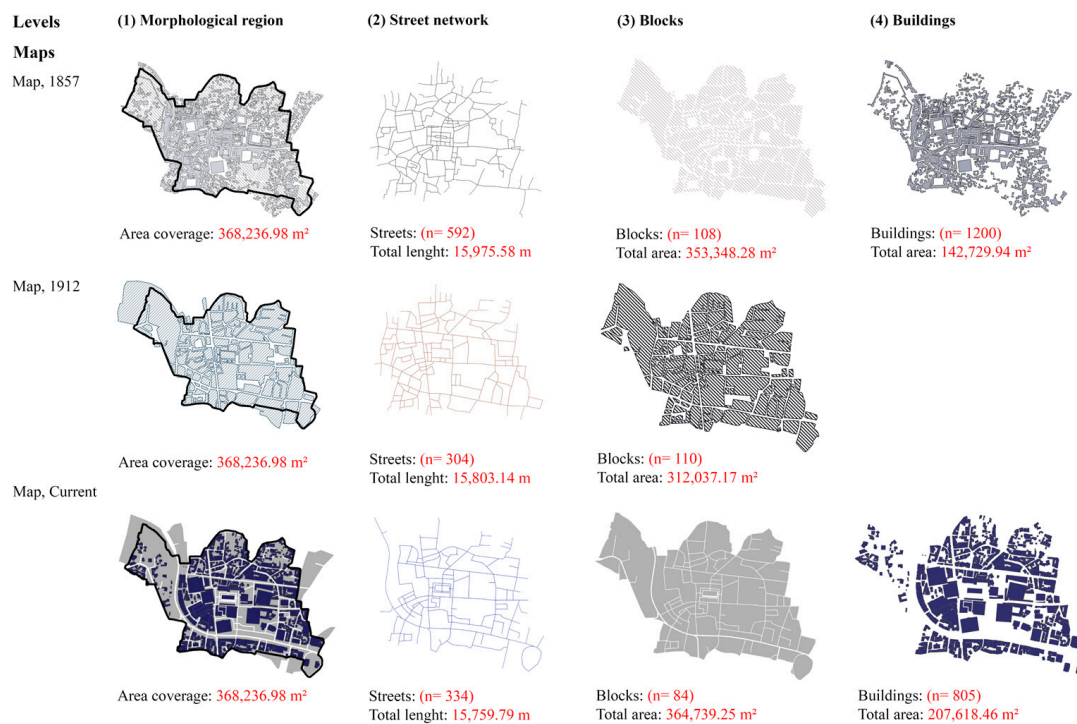


Figure 4. Transformation of the morphological region coverage of the Khan area over time, with its elements: streets, blocks, and building footprints.

Physical changes, block coverage, building coverage, and the relationships between them are crucial variables that collectively shape the characteristics of a morphological region. Comparing block and building coverage over time provides valuable insights into how the morphological region has been organized, developed, and transformed. This comparison also reveals the extent of changes in the urban fabric and how it has transformed.

In the mid-19th century, urban blocks covered nearly all the land, reflecting the early stages of Ottoman urbanization and a compact urban form. This high level of block coverage indicates that the land was primarily used for continuous urban development in the Khan area, with very little undeveloped space. However, building coverage was much lower, suggesting that while the blocks were extensive, they were not densely built upon.

At the beginning of the 20th century, block coverage decreased, reflecting a period of restructuring and reconfiguring in the Khan area to accommodate the city's modernization. This change was also driven by large fires and earthquakes that led to the demolition of certain areas.

In contemporary times, block coverage has increased again. This increase suggests that previously demolished areas have been reutilized. As the Khan area has grown and transformed, building coverage has also risen. This increase points to more intensive development, resulting in a denser urban fabric. Table 2 provides a detailed summary of the changes in the percentage coverage of blocks and building areas relative to the overall land area, offering insights into the spatial evolution and development intensity of the morphological regions.

Table 2. Summary of morphological region, percentage of blocks area coverage, and buildings area coverage.

Map Period	Total Land Area (m ²)	Total Block Area (m ²)	Block Area Coverage (%)	Total Building Area (m ²)	Building Area Coverage (%)
Map, 1857	368,326.98	353,348.28	95.93%	142,729.94	38.75%
Map, 1912	368,326.98	312,037.17	84.72%		
Map, Current	368,326.98	364,739.251	99.03%	172,956.04	46.96%

4.2. Streets

4.2.1. Size of Streets (Street Segment Length)

Street networks, morphologically, consist of intersections (vertices) and road segments, represented by lines, which accumulate over time and reflect the physical and spatial structure of cities. The geometric properties of the network, such as segment angular maps, capture the configurational characteristics of regions in relation to blocks and buildings. Road centroids are used to compare conditions before and after changes, such as spatial and physical alterations. To process the centroids of the roads and analyze the physical and spatial extent of the region, the metric length of the segments must be considered.

The distribution of segment lengths forms the basis for interpreting correlations over time among centroids, which could lead to manifesting configurational persistence. Distributions of the segment lengths for each period are examined with angular segment length analysis (Figure 5) and key statistical measures (mean, median, standard deviation, minimum, and maximum values) summarized in (Table 3).

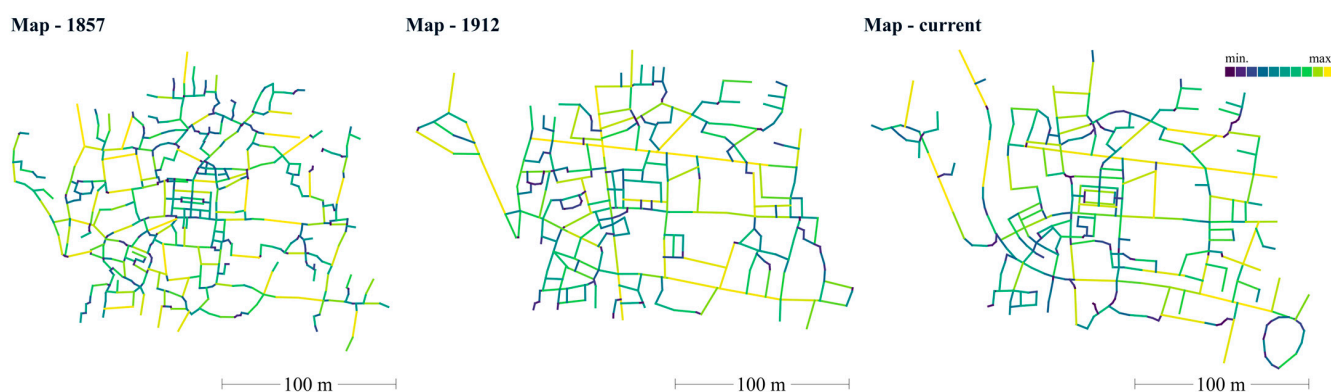


Figure 5. Angular street segment lengths analysis for each period with min. and max. value.

Table 3. Summary of the statistical properties of segment lengths for each map. The information highlighted in red indicates notable significant values for 1912 compared to the other periods.

Maps	Count	Mean	Std	Min	25%	50% (Median)	75%	Max
1857	592.0	26.99	18.26	1.09	13.94	23.84	34.95	122.44
1912	304.0	51.98	36.81	1.17	26.91	44.82	67.28	244.58
current	334.0	47.18	33.17	2.27	24.95	37.19	61.44	215.25

From the map of 1857, 592 segments were extracted, averaging 26.99 m in length. This period had the shortest average segment lengths and least variability, reflecting the permanence of the simpler Ottoman road networks and fewer urban planning practices. In 1912, 304 segments were counted, and changes in the physical layout of the region were significant, showing an increase in both average segment length and variability. This era likely represents the development of more diverse types of streets.

Additionally, the current data show the decrease in mean segment length and the variability, reflecting a trend towards longer and more organized segment lengths over time. This shift indicates a transformation of the street network from short local streets to long arterial roads.

The changes in segment length distribution over different periods reflect the transformation of the integration properties of the urban structure hierarchy, such as block and building sizes and the associated number of block faces. This transformation illustrates the concept of the city as a layered palimpsest, resulting in complex, layered structures.

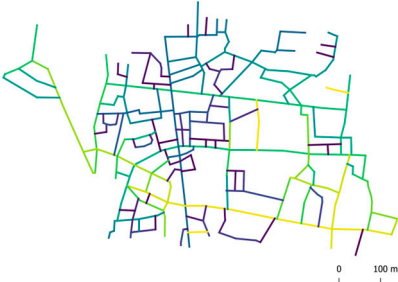
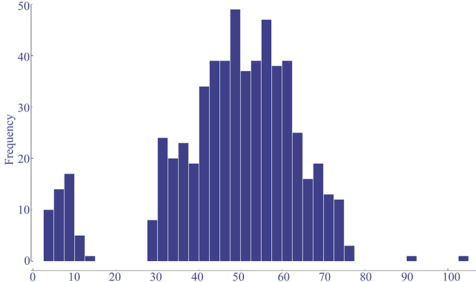
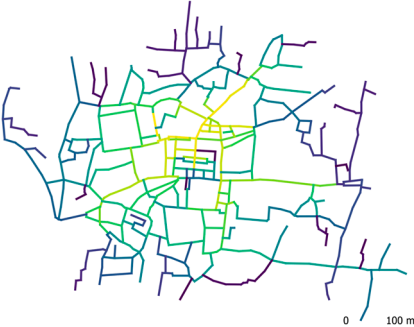
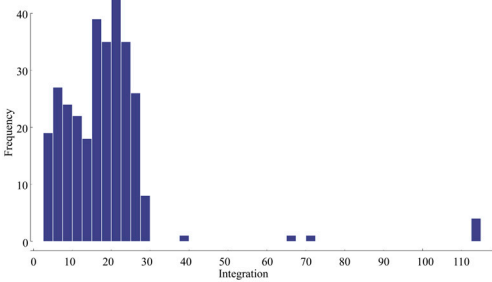

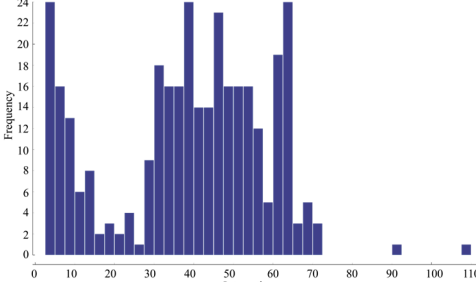
4.2.2. Proportions of Streets (Street Integration-Angular Segment Analysis)

Angular Segment Analysis (ASA) is the assessment of the quantitative and configurational properties of a street network by measuring the angular changes in street segments. These angular relationships aim to understand their influence on the way people navigate them [57] and consequently, how urban street networks evolve, utilizing integration values. The notion of configuration within morphological principles asserts that elements are defined by their position within the arrangement of parts, which is either reproduced or remains constant during the processes of formation and transformation [31] (p. 14). The exploration of integration value offers insights into the interrelationships between blocks, street spaces (street segment), and the mutual dependency of geometric parameters of blocks and buildings, shaping the outcome of the generative formation process. The angular change is a fundamental component for integration analysis in space syntax. The connectivity of geometries, particularly from junction to junction, is crucial for segment integration analysis. This connectivity creates the primary framework of the urban tissue, defining the boundaries of blocks within the urban structure. The variation in integration rates serves as interlocking measures of the blocks, which are closely tied to street segments.

According to the angular segment integration analysis of the 1857 map (Table 4), the distribution of high integration values is more central, with fewer segments acting as outliers that significantly impact the mean and median. Peripheral angular changes representing low integration values are common. The histogram confirms that most values are clustered around the mean integration value (47.84). The standard deviation of integration values (16.28) indicates a spread around the mean integration value, visible in the range of values from approximately 30 to 70. The presence of outliers with higher integration values contributes to the distribution being slightly skewed to the right (right-skewed). Comparing this with the period of 1912, most of the segment integration values (decreased mean, median and standard deviation) are concentrated between 0 and 30, with the lower mean integration value (18.28) aligning with the peak of the histogram, though there is a slight skew to the right that demonstrates a sharp concentration of lower values. The results show that the distribution of integration values is less balanced, likely due

to the modernization process of the region, which probably led to the creation of local distributor routes.

Table 4. Distribution and angular segment integration analysis over time with their key statistical parameters. The integration values range from purple, indicating high values, to yellow, indicating low values. The information highlighted in red indicates notable differences in 1912, specifically showing a sharp concentration of lower mean, standard deviation, and median values.

Angular Segment Integration Analysis (1857–1912–Current)	Distribution (1857–1912–Current)	Parameter (1857–1912–Current)
		<p>Mean: 47.84</p> <p>Std.: 16.28</p> <p>Min.: 3.64</p> <p>Median: 49.75</p> <p>Max.: 104.73</p>
		<p>Mean: 18.28</p> <p>Std.: 13.71</p> <p>Min.: 2.75</p> <p>Median: 17.77</p> <p>Max.: 113.78</p>
		<p>Mean: 38.76</p> <p>Std.: 19.83</p> <p>Min.: 2.69</p> <p>Median: 40.73</p> <p>Max.: 109.71</p>

The standard deviation is highest in the current map, indicating a more diverse and variably integrated street network. This variability results from the layered urban structure, showing that contemporary urban development has introduced a greater range of integration values, reflecting a complex and multifaceted urban fabric.

4.3. Blocks

4.3.1. Shape of Blocks (Block Elongation)

Segment analysis for each period indicates that increasing the complexity of integration values and connectivity geometries significantly impacts the morphology of urban spaces. This results in either compact or elongated urban blocks. In layered cities, urban blocks expand geometrically based on their three variables: area, diameter, and perimeter [58]. This expansion can occur through the incorporation of new plot cells or transformations in street segment integration (angular). The geometrical transformation of blocks can be

measured by their elongation. The examination of the block elongation index enables the assessment and tracking of the retention of block outlines or alignments. This process also helps identify any tendencies for the new forms to become inflected variants. To determine whether blocks develop into elongated shapes, their longest axis should be considered [41] (p. 98). The shape of the blocks is measured by the calculation of the block elongation based on Vialard’s formula [41] (p. 218) including the longest axis.

A total of 108 blocks were analyzed for the calculation of elongation values (Table 5) in the 1885 map. The elongation values ranged from 0.28 to 0.65. The mean elongation was 0.495, and the median elongation was 0.494, which are very close, indicating a symmetric elongation distribution, as evident in the distribution histogram. The standard deviation of 0.082 indicates that while there was some variability in elongation values, most values were clustered around the mean. Additionally, the distribution of elongation values shows a noticeable peak around 0.45 to 0.50, suggesting that many blocks had similar elongation characteristics during this period, with relatively few blocks deviating significantly from this range.

Table 5. Distribution of the block elongation values over time and their statistical parameters. The information highlighted in red indicates notable differences in the period compared to the two maps, specifically pointing to a significant increase in the variability of elongation values.

Elongation Range (1857–1912–Current)	Distribution (1857–1912–Current)	Parameter (1857–1912–Current)
		<p>Mean: 0.495 Std.: 0.082 Min.: 0.28 Median: 0.494 Max.: 0.65</p>
		<p>Mean: 0.498 Std.: 0.071 Min.: 0.30 Median: 0.514 Max.: 0.62</p>
		<p>Mean: 0.481 Std.: 0.091 Min.: 0.19 Median: 0.495 Max.: 0.65</p>

In 1912, a total of 110 blocks were analyzed for elongation. The elongation values ranged from 0.30 to 0.62, demonstrating a wide range of block elongation characteristics and reflecting diversity in block elongation. The mean value was 0.498, the median was 0.514, and the standard deviation of 0.071 indicated some variability. This diversity was confirmed by the relatively balanced distribution around the mean.

From the current map, 84 blocks were analyzed for elongation value interpretation. The elongation values range from 0.19 to 0.65, indicating a very wide range of block elongation characteristics with several peaks, as reflected in the histogram. The standard deviation of 0.091, the highest among the three time periods, indicates significant variability in elongation values. This suggests a diverse nature of block dimensions in the current data, reflecting transformation processes within the block scale.

Overall, the transformation of block elongation characteristics is significant, reflecting changes from a balanced distribution to a significant spread of values that collectively shaped the region's overall spatial organization. The elongation values in 1885 reference the block dimensions in the cohesive urban fabric, which provided underlying uniformity. In contrast, the mix of consistent and varied elongation values in the 1912 layer reflects both the order of the earlier period and the beginning of a more diverse urban form, serving as a bridge between the Ottoman urban structure and contemporary urban formation.

4.3.2. Size of Blocks (Block Area)

The examination of block sizes, specifically their area and perimeter, aims to identify transformations of the geometric properties. By analyzing these measurements, we can logically identify variations and consistencies. This analysis helps us understand how features adapt or respond to changes in block size, as transformations in elements do not occur uniformly. This non-uniformity represents variable behavior in the geometric properties of the blocks within an intermediate level of specificity detailed in the built morphological framework.

The distribution of the block area (Table 6) ranges from 41.24 m² to 55,912.13 m² in 1857. The mean area is significantly higher than the median, and most blocks have smaller areas, resulting in a right-skewed distribution. A few significantly larger blocks influence the mean and the standard deviation, which are considered outliers compared to the rest of the distribution. The high standard deviation also confirms the large variability in the block areas. A significant number of blocks are below 2000 m², indicating that smaller blocks are common. The spatial distribution of these smaller blocks corresponds to marketplace concentration. The presence of some exceptionally larger blocks, mainly positioned around the Khan aggregate, pulls the mean values upwards.

Compared to 1912, the distribution is quite similar; there is substantial overlap in the block areas between the two years. Most block areas are clustered towards the lower end, but 1912 shows greater variability (a broader distribution) with more extreme values than 1857. This is because some small blocks in 1857 combined to create larger blocks in 1912. The distribution remains right-skewed over time, while the frequency of smaller blocks has decreased, and the presence of larger blocks has increased. This is evident in the rising standard deviation, indicating the highest variability among the three periods.

The block pattern size established during the initial formation was exposed to significant constraints, which were replaced within the patterns, resulting in transformations in urban tissue over time.

Table 6. Spatial distribution of block area values over time and their statistical parameters. The information highlighted in red indicates a significant increase in the variability of block area values in the period compared to the two maps.

Spatial Distribution of the Block Area–1857	Spatial Distribution of the Block Area–1912	Spatial Distribution of the Block Area–Current
Parameters		
Mean: 3314.30 Std.: 6763.94 Min.: 41.24 Median: 1326.42 Max.: 55,912.13	Mean: 2878.48 Std.: 7119.17 Min.: 60.18 Median: 1243.52 Max.: 70,001.35	Mean: 4432.72 Std.: 8261.46 Min.: 73.10 Median: 1985.24 Max.: 67,549.64

4.3.3. Points of Block Access (Number of Block Frontage)

At the block level, the investigation of access and block frontage establishes the internal orientation of the blocks (plots and buildings) and the arrangement that constitutes the urban tissue. Block fronts interface necessarily with a road segment in a way that geometrically associates buildings with access points, revealing the spatial structure of the urban fabric and their process of transformation over time.

The basic principle for identifying the point of access within the different types of frontage is as follows: the total count of points within each block boundary is associated with the shortest distance (line) between the road segments.

The concentration of points of access (Figure 6) tends to be located at the periphery of the marketplace, which has higher active block frontage. This shaped the block and building fabric of the Khan region in 1857. Most likely, those areas represent the residential structure of the Ottoman fabric, where the roads were very narrow, and buildings faced the street with a single facade. In the Ottoman era’s city order, the entrance of individual houses was directly connected to public spaces (one-step depth) and faced the street. However, in the current period, traditional block frontage patterns have almost been erased or transformed due to changes in land use or the occupation of parcels. This transformation is evident and correlates with changes or persistence in the geometric properties of the blocks.

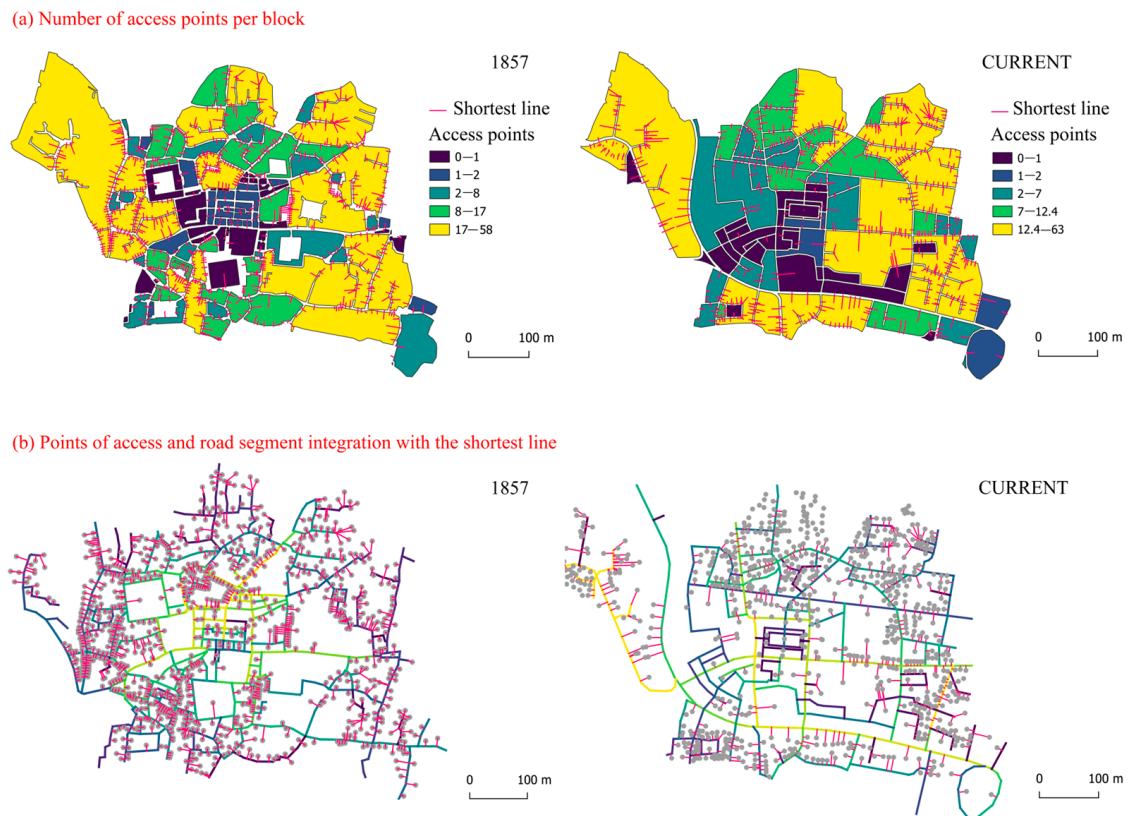


Figure 6. Number of access points per block and road segment integration with the shortest line for the periods 1857 and current.

4.4. Buildings

Specific Type of Building Parts and Configuration of Buildings (Building Type and Building Types per Block)

The built fabric is the most tangible element in the urban fabric, including their boundaries and locations. These elements outline the internal structure of blocks and streets that constitute the visible part of the urban tissue, which is the basic unit in the productive process of towns and cities. Evolutionary changes in building types, involving the details of the structure that emerge with development and innovation (cultural evolutionary processes), give rise to different parts of the whole.

The overall layout and arrangement of buildings (geographical distributions of past patterns) and structures within an urban area can give a sense of character, but monuments are unique features that distinguish one area from another [31]. The geographical position of buildings and their polygonal characteristics allow for the extraction of typological information, such as the orientation of a building within a block's internal arrangement. This information can also characterize changes in the internal layout of the blocks over time, providing insights into how the internal structure evolves. By analyzing these changes, we can understand the continuity and transformation of the internal structure over time.

The block types extracted from the 1857 block typologies were formed into 107 different shapes and sizes, while those from current maps formed 85 different shapes and sizes, encompassing various block and building types (Figure 7). Irregular, trapezoidal, or rectangular block patterns generally surround the Khan marketplace during both periods. Monumental buildings appear to be shaped with blocks, but their complex structures within the same blocks should also be considered. This is why monumental buildings and their complexes often have irregular or polygonal patterns due to the varying positions and sizes of the buildings within the block over time.

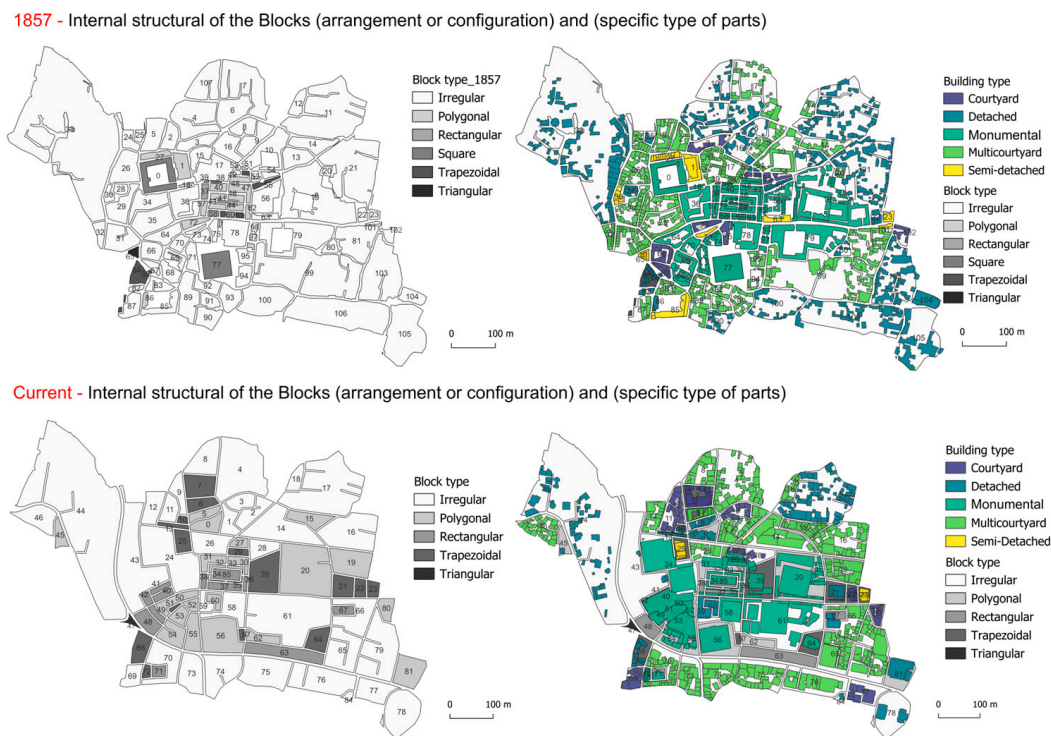


Figure 7. The maps of the typologies of the blocks and building types.

Most irregular patterns, aside from monumental irregular block patterns, are bordered by multi-courtyards or detached configurations in the current period, which enclose some empty corners of the irregular shapes. Both periods demonstrate consistency and a high frequency of irregular block patterns (75 in 1857, 33 currently), though building types within these blocks have evolved in different ways.

Each individual building pattern within all block combinations must be considered to identify the specific tangible patterns of selected heritage sites, as each combination could characterize different building patterns. This approach reveals the patterns and provides predictive information, offering the opportunity to discover historic character and hidden layers in contemporary heritage sites.

Although the variations in block patterns in heritage sites are not very diverse, blocks with the same characteristics may not always have the same typology. The diversity in variation is organic and influenced by the number of buildings, their positions, and other variables in building patterns. The monumental architectural patterns that make up the landmark's typology integrate with the patterns of the built environment. Monumental blocks are generally surrounded by courtyard-type complex buildings, harmonizing with the surrounding courtyard-type typologies. While the purpose of the blocks remains somewhat consistent, the arrangement of the buildings has changed over time. Blocks surrounding the monumental blocks with multi-courtyard building typologies have transformed into more regular typologies. The reduction in the variation in building types within the blocks reflects changes in the urban layout of the region.

4.5. Green Spaces

Size of Green Spaces (Green Area)

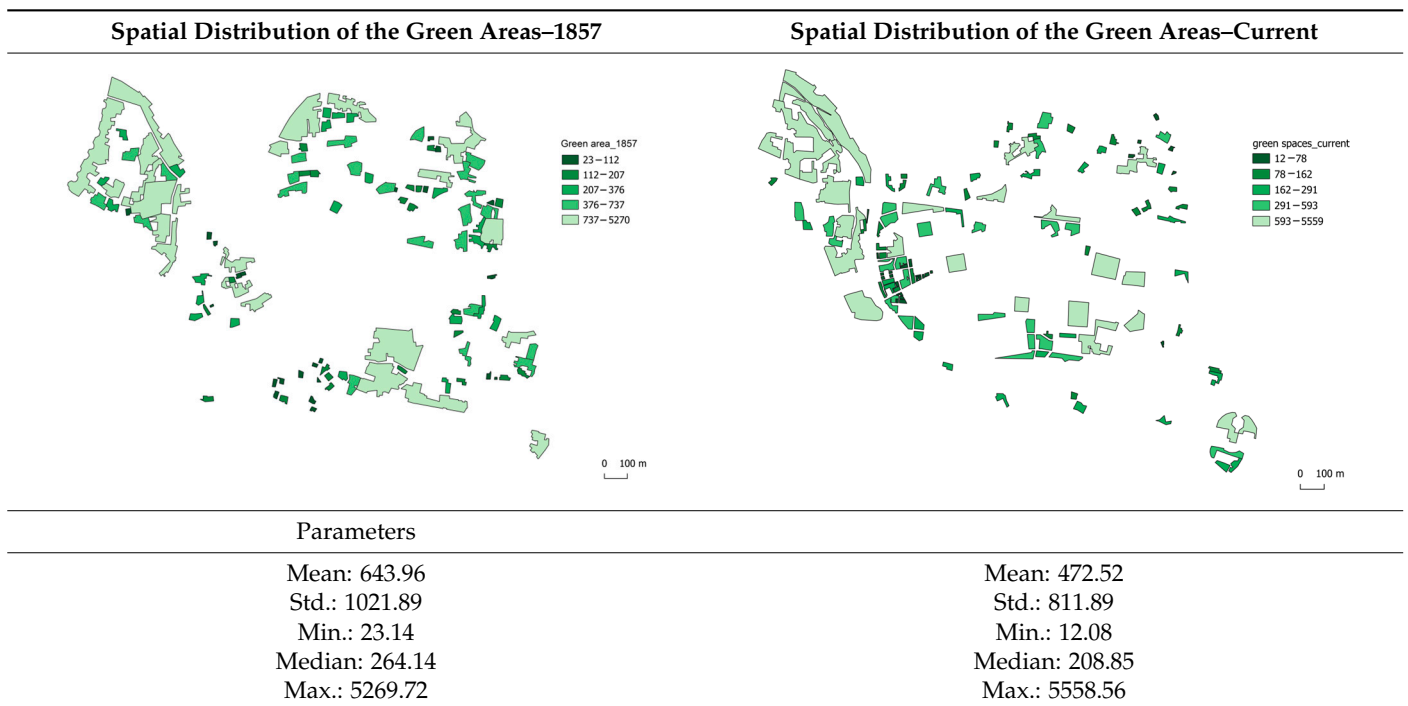
To analyze the transformation of cities, it is significant to trace the changes in green areas throughout their growth. Examining the rates of change in urban green areas through different historical periods provides a deeper understanding of how the physical environment of modern urban areas has developed.

In many historically stratified cities, continuous green spaces are generally located adjacent to former physical limitations on urban growth, most notably surrounding city

walls, a pattern characterized morphologically as fringe belts [59]. Urban green spaces within the inner parts of cities, often in historical cores, have changed in terms of their position and size over time.

In Bursa, a sizeable portion of the green areas (Table 7) in 1857 was located around the urban growth limit of the Khan region. The small green areas were fragmented from this inner green fringe belt to residential areas. In the current era, the green areas have become more uniformly sized, which is evidence of the influence of urban transformation. Statistical results prove the regression in the sizes of green areas from 1857 to the present. The decrease in variability reflects that the sizes of green areas have become more consistent, though generally smaller over time.

Table 7. Spatial distribution of block area values over time and their statistical parameters.



The continuous survival of green areas surrounding the region indicates that none of the phases of change have created significant pressure on these areas. These continuous green areas are embedded in the urban fabric over time and are recognized as aspects of heritage.

5. Result of Cluster Analysis

5.1. Classification by the Morphological Unit Character

Clustering was based on the key results of character analysis, utilizing two variables—street type and street age—to re-evaluate morphological units both qualitatively and quantitatively. The four clusters identified by K-means clustering appear to be well-defined and reflect the palimpsest approach. To implement the proposed clustering method, label encoding was used to convert the categorical attributes of street type and street age into numerical values. This method aims to analyze these continuous variables in urban form, describe the characteristics of the morphological region, assess their spatial distribution over time, and evaluate their statistical distribution. Figure 8 illustrates the spatial and statistical distribution of character areas within the measured clusters, categorizing four types of characters. Table 8 presents the percentage distributions of values within the clusters.

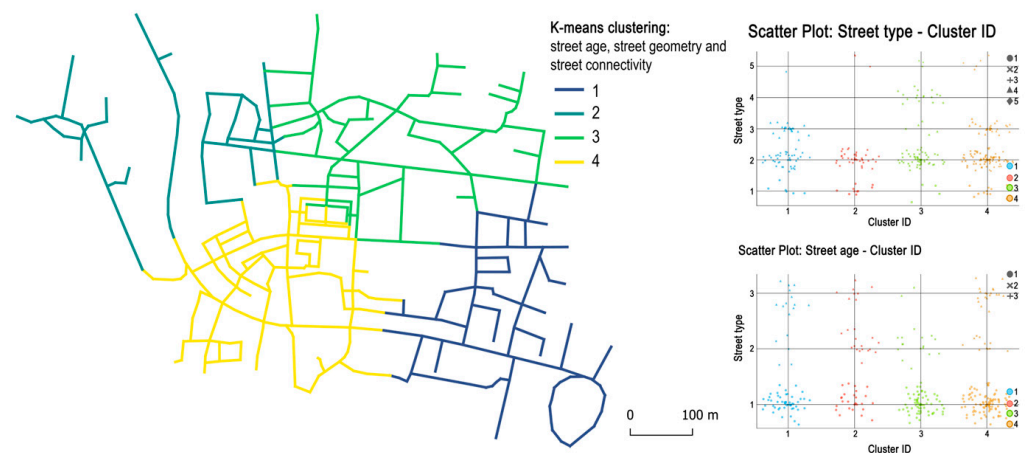


Figure 8. Spatial and statistical distribution of the K-means clustering results of the street age and street type values.

Table 8. The percentage distributions of the street types and street ages within each cluster. The information highlighted in red indicates the absence of street types within the clusters. The information in bold black specifically highlights the clusters with the highest rates of values.

Cluster ID	1	2	3	4
Street Type (%) 1: District distributor	8.82	19.61	4.65	8.53
Street Type (%) 2: Thoroughfare	57.35	74.51	66.28	66.67
Street Type (%) 3: Through loop	32.35	0.00	5.81	20.93
Street Type (%) 4: Tree-like and cul-de-sac	0.00	0.00	19.77	0.00
Street Type (%) 5: End loop	1.47	5.88	3.49	3.88
Street Age (%) 1: Medieval street layout	75.00	52.94	79.07	76.74
Street Age (%) 2: Beginning of the 20th century (modernization of the city)	7.35	31.37	18.60	8.53
Street Age (%) 3: Later alteration	17.65	15.69	2.33	14.73

Starting from the bottom right corner, Cluster 1 delineates the medieval thoroughfare and continuous loop patterns. This character tends to remain within the surroundings of the marketplace. The bottom left corner, Cluster 4, is the largest cluster with 129 features, showing a more diverse distribution of street types and street ages, and has similarities with Cluster 1. Cluster 3, located in the top right corner, is characterized by its predominantly medieval street age pattern (79.07%), a combination of thoroughfare routes, tree-like routes, and cul-de-sac routes, with a lower rate of later alterations in the region. The top left corner, Cluster 2, represents patterns of predominantly medieval street geometry (74.51% thoroughfare) with a soft transition to the modernization era. This includes a significant presence of district connector routes from the modernization of the city (type 1) at 19.61%.

In summary, this analysis highlights that the variations in street age and type within these clusters not only reflect statistically similar patterns to those in the surrounding region but also exhibit a more diverse distribution. This diversity is particularly evident in Cluster 4, influenced by modernist planning practices. This variety suggests that while certain clusters, such as Cluster 1 and Cluster 3, maintain medieval street patterns, Cluster 4 demonstrates a stronger alignment with modern planning principles. In contrast, Cluster 2, despite its medieval street geometry, shows a gradual shift towards modernity, notably featuring district connector routes from the modernization era. Additionally, streets surrounding heritage sites within these clusters are closely associated with subsystems, which enhances the configurational properties of these sites by affecting street traffic volumes. This association underscores the challenges of topological discontinuity, where historic street layouts coexist with newer developments, resulting in a complex and layered urban fabric.

5.2. Classification by the Blocks Shape and Size

Shape and size is the fundamental characteristic in seeking to understand how and why forms take the shape they do. Identifying and classifying shape and size components is essential, as their transformation or formation involves geometric properties that vary over time. In examining urban form at the block level, the properties of these blocks' elongation and blocks' area may change as the voids in the urban form take shape over time and as occupancy patterns transform. Therefore, classifying blocks based on their elongation and area can reveal the diversity of species and spaces over time and block-level change detection. K-means can define clusters based primarily on the width/length ratio, effectively distinguishing different types of elongation and area. The five clusters identified by K-means clustering (Figure 9) appear to be well-defined for elongation types.

The distribution of clusters in 1857 proves the orientation of the Khan areas and zonal differences, displaying well-identified specific block patterns of the Ottoman structure. By 1912, the clusters demonstrate reorganization and differences in distribution, evidencing significant changes in the urban layout. Between 1857 and 1912, Cluster 2 (C2) remained relatively stable in size and shape, while Clusters 1 (C1), 3 (C3), and 4 (C4) showed a decrease in size. This trend illustrates the broader transformation of the urban fabric, where modifications—such as the straightening of medieval street patterns—have resulted in more compact spaces and a shrinking of block sizes. The internal heterogeneity of blocks has increased, impacting tissue boundaries, access routes, and the arrangement of urban elements, all of which affect the historical appearance of the environment. By 1912, current clustering results indicate an adaptation to the revised urban structure, with significant changes in C2 since 1857. These findings underscore that changes in block parameters are driven by practical needs to make urban planning more efficient and functional.

The K-means clustering method effectively captures the variation in block outline attributes over time, illustrating the inherent challenges associated with maintaining topological continuity during the syntactic transformation of heritage sites.

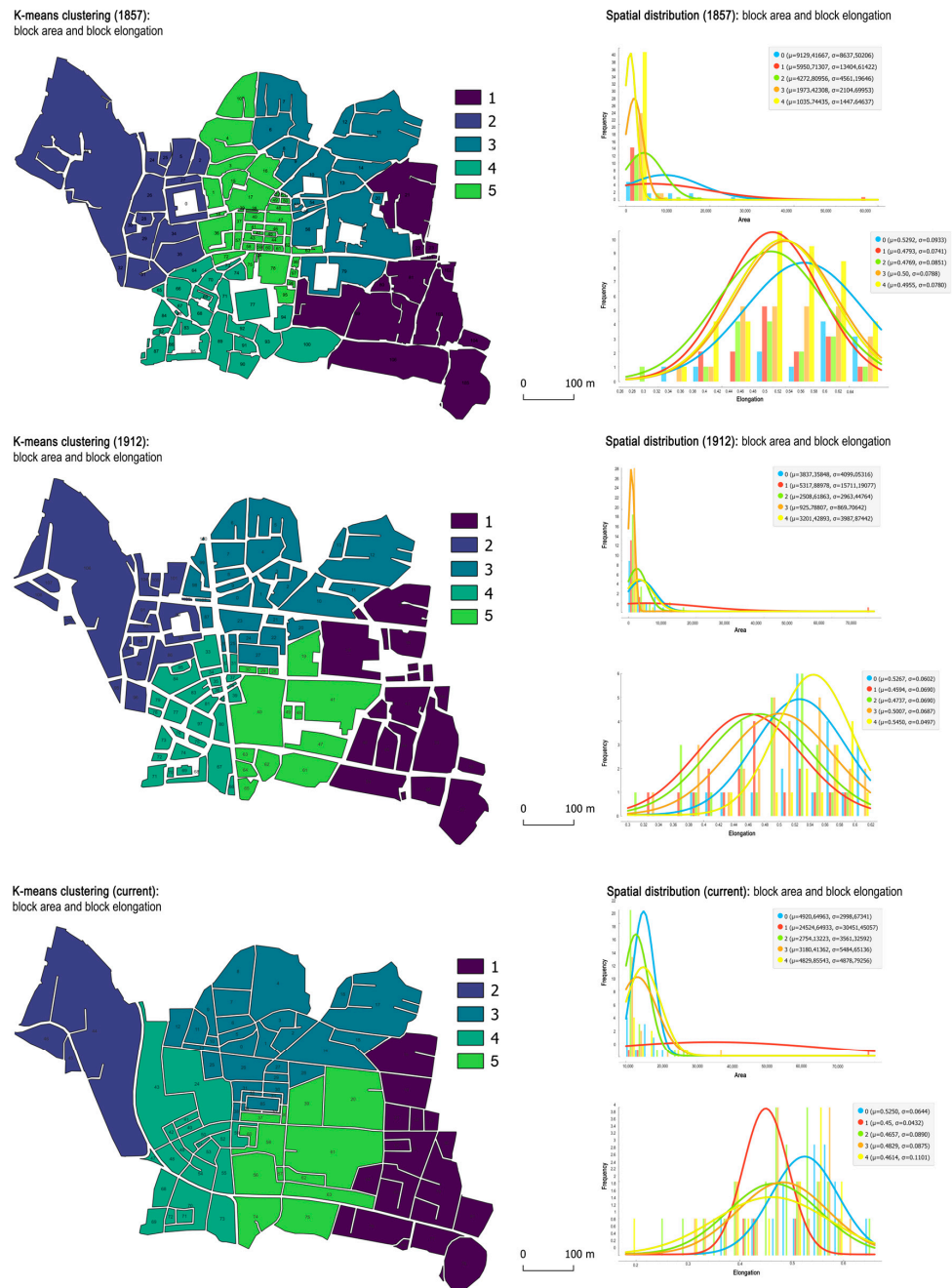


Figure 9. Spatial distribution of the K-means clustering results of the block elongation and block area values.

5.3. Classification by the Building Types

The method for classifying buildings involves hierarchical clustering of the results from K-means clustering at the block level, based on their conceptual morphological properties. This approach provides a level of specificity (typological similarity) in the classification.

The decision on the number of clusters requires several trials until the minimum cluster variances are merged into a single cluster. After several processes, at the block level, four internal arrangement clusters are identified based on their building morphological variables. Five block clusters are classified into four levels of building type classification within different spatial distributions. To compare the distribution of value types between periods, descriptive statistical analysis is conducted to capture typological types that remained or changed.

According to the cluster results presented in (Figure 10), the transition in building types across the different clusters is evident.

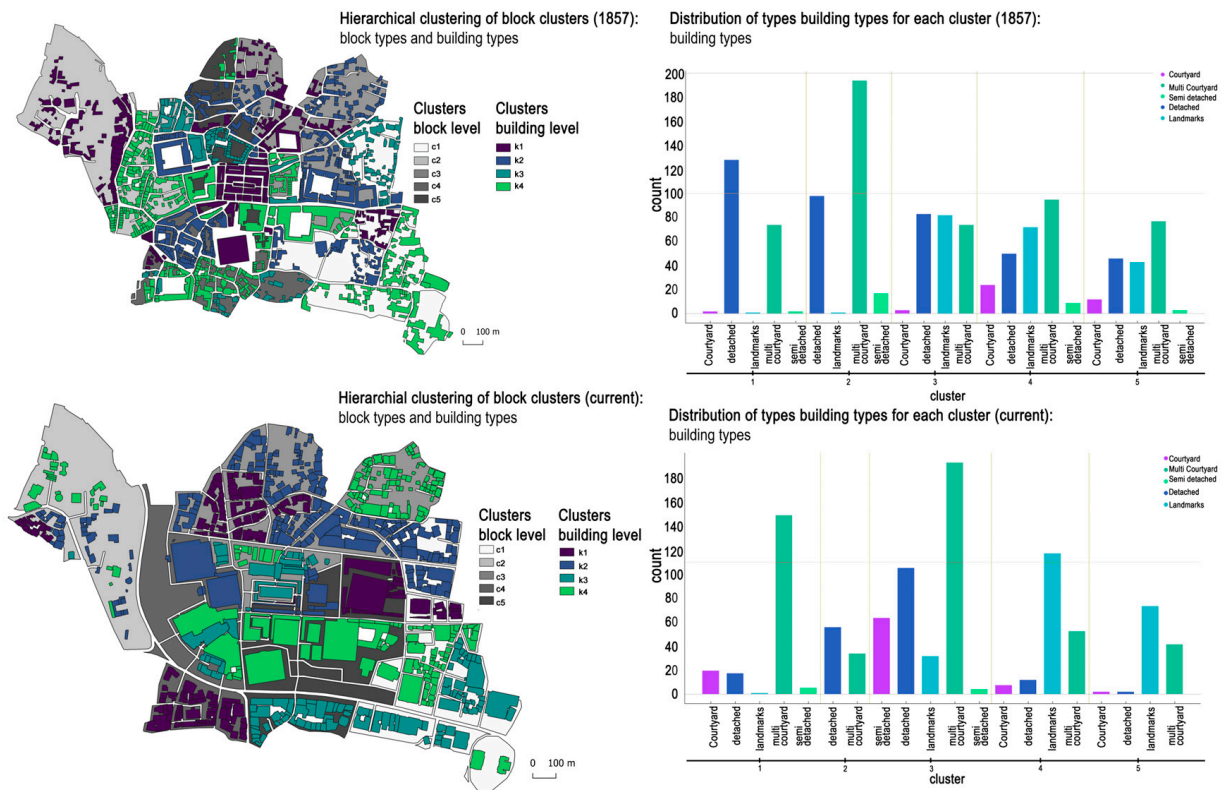


Figure 10. Spatial distribution of the hierarchical clustering results of the building types.

In Cluster 1 ($n = 207$ in 1857 and $n = 176$ currently), the multi-courtyard type remains consistent and reflects the most dominant type in the current period. However, there is a significant decrease in the detached type (from 128 to 16) and a noticeable increase in the courtyard type (from 2 to 18) over time, proving the shift towards more diverse building types.

Cluster 2 had $n = 310$ buildings in 1857, but currently, the number of buildings has decreased to $n = 82$ due to the shrinkage of the blocks over time. This reduction has significantly decreased both the number and diversity of building types (typology) within the cluster. However, two types—detached and multi-courtyard—have maintained their presence.

Cluster 3 had $n = 242$ buildings in 1857 and has increased to $n = 363$ buildings currently. The number of detached buildings has increased from 83 to 96, and the number of multi-courtyard buildings has risen from 74 to 176. This growth, along with the appearance of a new building type—semi-detached—has led to greater diversification of building types within the cluster. The multi-courtyard type still characterizes the typology of the cluster region.

Due to the decrease in size of Cluster 4 and Cluster 5 over time, the number of buildings has decreased from $(n = 250/181)$ in 1857 to $(n = 173/81)$ currently. Despite this reduction, the multi-courtyard buildings have maintained their significance. Throughout this period, the clusters have retained their typological character, dominated by multi-courtyard (95/77 in 1857 and 48/38 currently), and landmark buildings (72/43 in 1857 and 107/67 currently).

Overall, the analysis reveals that while the multi-courtyard building type has remained a stable and decisive factor in defining block typologies, other building types, such as detached and semi-detached, have evolved, reflecting broader changes in urban morphology, block usage, and social preferences over time.

6. Discussion

This paper analyses the morphological, qualitative, and quantitative properties of urban morphology to interpret the transformation process in the urban form of Bursa, specifically the Khan urban heritage site. The differences in street age and street type in clusters where the landmarks are located show statistically similar patterns compared to the surrounding region, but they also display a more diverse distribution of patterns. This can be explained by several factors: the street network hierarchy is influenced by modernist planning practices, while the historic core has maintained its organic structure due to the preservation of the monuments' layout, reflecting the persistence of the city's basic layout and plans. Streets around the heritage surroundings are designated to have a high level of correlation to the subsystems, enhancing the configurational properties of the heritage sites in terms of street traffic volumes. This clearly illustrates the problems on the topological discontinuity is purely inherent.

Clustering results based on the blocks, considering their sizes and shapes, show statistically significant differentiation. This is related to the increased topological depth over time, resulting from the combination of different blocks to create contiguous block typologies. The block shapes are well-organized due to the transformation of medieval-age streets, with modifications making the block lines straighter. This has resulted in more compact spaces with the shrinking of block sizes over time, and the internal loads of blocks becoming more heterogeneous. These changes contribute to alterations in tissue boundaries, access, and the arrangement of elements, which affect the historical appearance of the environment. Undoubtedly, changes in block parameters are derived from practical reasons to make urban planning more effective and functional. This clearly illustrates that the problems with topological continuity are inherent and related to the syntactic transformation of the heritage site.

Through the hierarchical clustering analysis, significant trends and building patterns in the transformation process of building types have been revealed. The stability of the multi-courtyard building types in each cluster is decisive in determining block typologies. These derivational practices of the multi-courtyard type reflect the modes of morphological existence in the urban fabric. However, the materials and functions of these buildings change over time and cannot remain the same. Conversely, the significant reduction in detached type buildings and the emergence of new semi-detached types undoubtedly reflect changes in block usage and social preferences.

Moreover, the transformation of morphological units, characterized by variations in block shapes and sizes, serves as significant qualitative and quantitative indicators for understanding the configuration of buildings. The urban fabric emerges either from a part-to-whole process [29,48]—ranging from buildings to blocks, blocks to streets, and streets to urban tissue (morphological regions)—or through a part-to-part relationship, such as from buildings to open spaces and from open spaces to street spaces. This reflects the complex relationships between elements at different levels of resolution.

The findings show that, in the case of the Khan area, the continuity of building types and street geometry plays a critical role in the organic transformation of the city, often more significantly than block properties. The transformation of the urban fabric in this area is a gradual process, shaped by both historical preservation and modern urban planning. The syntactic context, which refers to the arrangement and connectivity of elements within the urban environment, is particularly important for assessing urban fabric transformation in the Khan area. The continuity of building patterns across blocks has shaped the configuration of certain routes, imposing limitations on the transformation process [42]. Furthermore, streets around the heritage area are strongly correlated with subsystems, enhancing the configurational properties of these heritage sites, particularly in terms of street traffic volumes. This contributes to a better understanding of urban fabric changes in the Khan area, where building patterns tend to be stable within the core, leading to less fragmentation in the urban fabric.

Our study provides a novel methodological contribution by extending the descriptive and analytical framework of urban morphology, emphasizing the role of GIS and statistical analysis in quantifying urban form [34]. This approach provides valuable insights into the transformation of the urban fabric. By focusing on temporal dimensions [26], spatial scales, and the concepts of copresence and derivation [14] within urban form, we address a notable gap in the existing knowledge of urban morphology. Moreover, clustering analysis simplifies the more 'quantitative' changes in urban form, which enhances the comparability of variables when studying different types of maps. Palimpsest approaches, which consider the layering and persistence of urban forms over time, are still underrepresented in both qualitative and quantitative analyses, and this study seeks to fill that void.

This new theoretical and empirical study represents a novel attempt to demonstrate the reliability of measurable components of urban form. The study examines these components in relation to urban form principles, such as position, outline, and internal arrangement. Additionally, it analyzes their geometric characteristics, including size, shape, proportions, points of access, specific types of parts, and the configuration of these types [31]. These metrics are essential for understanding the dynamics of urban transformation. By introducing a novel theoretical and empirical framework, we establish that the relationship between temporal (time-based) and spatial (space-based) elements within the built environment can be better understood when descriptive frameworks of urban form are coupled with precise geometric descriptions. This dual approach enhances our ability to analyze how the urban fabric evolves over time and across different scales.

Furthermore, our findings reveal that interactions between urban elements at various levels of scale and across different temporal dimensions are not isolated but interlocking. These interactions significantly influence the transformation of the urban fabric, suggesting that the qualities of individual elements cannot be fully understood without considering their relationships within the broader urban context. This challenges previous studies that focused narrowly on individual elements without considering their interactions with the surrounding urban environment.

One key insight from our research is the varying degrees of persistence in the temporal response to changes within urban elements. We observed a powerful constancy in the relationships between these elements over time, despite the dynamic nature of urban transformation. The degree of historical stratification—how elements from different periods coexist and interact—plays a crucial role in shaping the urban landscape [2]. This suggests that urban morphology is not just a product of individual changes but also a reflection of the cumulative effects of these persistent relationships across time.

Despite these findings, the proposed methodology has certain limitations, such as the exclusion of variables like building age, height, and plot sizes due to data constraints. Future research should include these parameters to provide a more comprehensive understanding of the transformation process in different urban contexts. This would allow for a more rigorous analysis of both the quantitative and qualitative aspects of urban fabric transformation.

7. Conclusions

This study examines the qualitative and quantitative properties of urban form at different scales—morphological units/regions, streets, blocks, buildings and green spaces—in the case study of the Bursa Khan urban heritage site by utilizing cartographic maps and current data. Layering principles of different maps form the basis of the study. The quantitative properties analyzed include measurable variables such as the size of morphological regions/units (coverage), block shape and size, the number of block frontages, the size of streets (street segment length), the proportions of streets (street integration), and the size of green areas which were derived through statistical analysis, while qualitative properties are assessed include the characterization of morphological units (street type and street age), specific type of building parts, and configuration of buildings, evaluated using a descriptive framework of urban morphology. This paper confirms that it is possible to

rigorously identify similarities and differences between the abstract and dynamic pattern characteristics of urban form and their variation over time at different scales by integrating descriptive and analytical approaches to urban morphology.

Specifically, we examined seven primary character categories—morphological unit, shape, size, proportions, points of access, specific types of parts, and arrangement or configuration—for morphological, qualitative, and quantitative analysis to address the main research question: how can urban transformation be described in terms of changes in structural and numerical parameters. The research revealed that using k-means and hierarchical clustering methods effectively simplifies changes in urban form and that measurable variables (quantitative properties) of urban form are correlated with the spatio-temporal patterns of urban morphology. The clusters around monumental buildings, where the urban form is well-preserved, quantitatively exhibited continuity in the urban fabric, aligning with the urban transformation process. Additionally, our findings indicated that changes in topological parameters are related to changes in the numerical parameters of block characteristics, facilitating new and unexpected urban development.

The findings prove that the methodological approach applied in this study is a robust and reproducible framework for examining urban form. By combining descriptive and analytical frameworks of urban morphology, this method provides a reliable means to identify historical stratification processes in different cities, enhancing our understanding of how cities evolve and stratify over time.

The integration of historical analysis with modern methodological approaches provides a holistic framework for addressing the complex challenges of urban transformation. In conclusion, the discipline of urban morphology remains crucial for understanding and directing the transformation of modern cities. The incorporation of new theoretical and methodological frameworks, as illustrated in the Bursa study, deepens our comprehension of urban complexities. By combining qualitative and quantitative approaches, urban morphology supplies tools for analyzing historical continuity and change, ensuring that urban spaces can fulfill contemporary needs while preserving their historical and cultural significance.

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