
Spatial Evolution and Urban Morphology in Traditional Settlements: A Survey

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Abstract

This survey paper investigates the intricate relationships between spatial evolution, urban morphology, and cultural heritage, emphasizing their collective impact on the development and transformation of human settlements. Organized into eight sections, the survey explores foundational concepts, examines the influence of cultural and geographical factors on traditional settlements, and analyzes urban morphology's role in shaping cultural identity. It highlights the methodological advancements in studying spatial evolution, such as UAV photogrammetry and digital modeling, which are crucial for documenting and preserving cultural heritage. Through case studies, the paper illustrates the practical applications of these methodologies in various global contexts, underscoring the challenges in documentation and preservation due to technological and financial constraints. The survey also discusses innovative preservation techniques, including augmented reality and deep learning, which enhance community engagement and support climate adaptation strategies. The conclusion synthesizes key findings, advocating for interdisciplinary approaches and technological integration to preserve cultural identity and inform sustainable urban planning. This comprehensive analysis provides a framework for future research directions, emphasizing the need for adaptive methodologies to address the evolving challenges in urban morphology and cultural heritage preservation.

1 Introduction

1.1 Structure of the Survey

This survey comprises eight sections, each addressing essential facets of spatial evolution and urban morphology in traditional settlements. The introduction outlines the study's overarching themes and significance. Section 2 provides foundational definitions and background on core concepts critical for subsequent discussions. Section 3 explores the spatial evolution of traditional settlements, emphasizing the impact of cultural, historical, and geographical factors on emerging patterns and structures. Section 4 analyzes urban morphology and regional architecture, focusing on the relationship between urban form and cultural identity, alongside methodologies for their study. Section 5 investigates the influence of cultural heritage on spatial form, detailing preservation techniques and the importance of community engagement. Section 6 presents case studies that illustrate the discussed concepts, offering practical insights into their application. Section 7 identifies current challenges and suggests future research directions, particularly in light of technological advancements. Finally, Section 8 synthesizes key findings and reflects on the implications for cultural heritage preservation and urban development. The following sections are organized as shown in Figure 1.

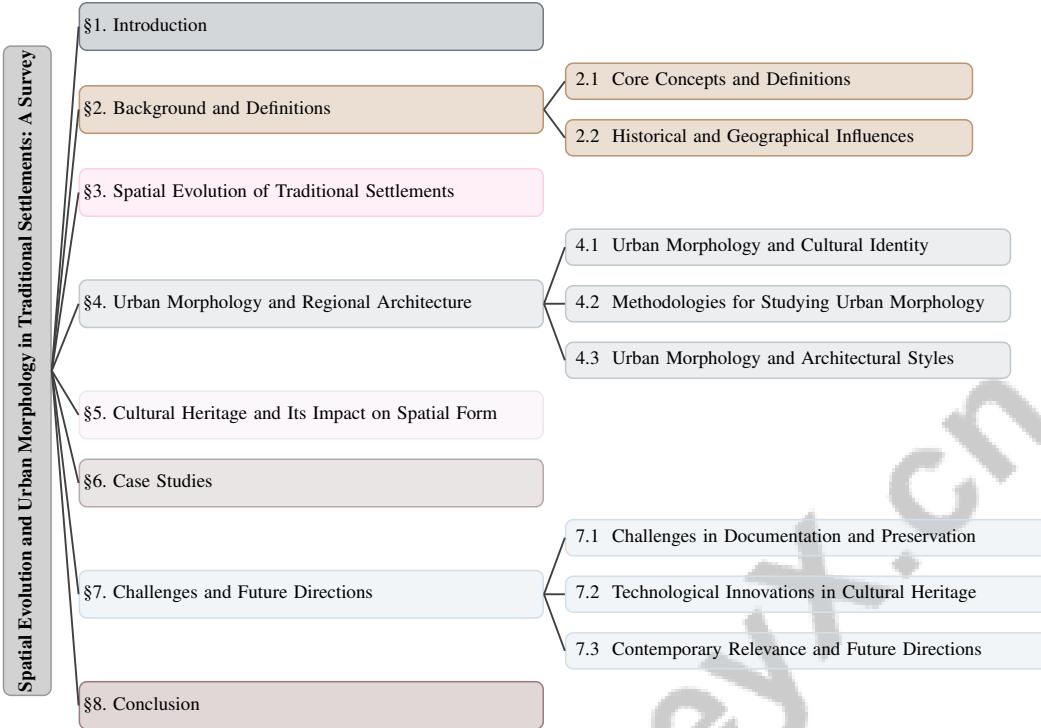


Figure 1: chapter structure

2 Background and Definitions

2.1 Core Concepts and Definitions

The framework for understanding human settlement development and transformation is grounded in spatial evolution, spatial form, traditional settlements, cultural heritage, urban morphology, and regional architecture. Spatial evolution refers to changes in settlement configurations influenced by cultural, historical, and geographical factors, while spatial form describes the physical organization of these settlements, reflecting socio-cultural dynamics. Traditional settlements maintain historical continuity, preserving architectural styles and urban planning practices [1].

Cultural heritage, encompassing both tangible and intangible aspects, profoundly influences the spatial form of settlements. Its preservation is crucial amid globalization and modernization, which threaten unique cultural practices and architectural styles. The integration of diverse data types, such as archaeological ceramics, highlights the complexity of preserving cultural heritage [2]. Effective management of cultural heritage data requires standardized frameworks and interoperability [3], though challenges persist in representing geometric forms in three-dimensional models obtained via photogrammetry [4].

Urban morphology examines how urban space form and structure reflect and influence cultural identity [5]. The disconnect between urban morphological structures and human perception necessitates an integrated approach [6]. Traditional methodologies often overlook visual and intuitive aspects, requiring more comprehensive approaches [7]. Sadeghi's survey [8] discusses the contributions of British, Italian, and French schools to urban form understanding. Urban morphology's impact on microclimates is crucial for environmental challenges like temperature and humidity regulation [9]. Fractal dimension growth models are significant in understanding urban evolution [10], while the relationship between urban morphology and land surface temperature highlights the importance of both 2D and 3D characteristics [11]. Multifractal characteristics of urban morphology, revealed through various data modalities, lead to diverse urban form interpretations [12].

Regional architecture reflects the interplay between cultural heritage and spatial form, characterized by styles and practices specific to geographical areas. Local materials, climate, and cultural traditions shape building design, contributing to a region's unique built environment [13]. Innovative

technologies, like Artificial Intelligence for automated reconstruction, are vital for documenting and preserving cultural heritage [1]. Understanding these core concepts is crucial for developing effective methodologies for cultural heritage preservation. The lack of effective tools for mobile digital storytelling limits meaningful visitor engagement [14]. Rapid urbanization and inefficient designs exacerbate energy consumption for cooling in hot-arid climates [15]. Effective archiving and management of 3D data are vital for ensuring accessibility for future research [16]. Methodological innovations in synthesizing building footprints contrast with traditional methods requiring high-resolution imagery [17]. Recognizing the morphological unity of urban form elements is emphasized in urban morphology [18]. Evaluating flood impacts on cultural heritage sites highlights the need for identifying at-risk locations [19]. This survey aims to facilitate the transfer of multiscale mathematical modeling technology to cultural heritage researchers, particularly those focused on preserving or reconstructing materials undergoing microstructural changes [20].

2.2 Historical and Geographical Influences

Historical and geographical influences are pivotal in understanding spatial evolution, urban morphology, and cultural heritage transformation. These influences are particularly pronounced in traditional settlements, where historical contexts and geographical settings shape emerging spatial forms [21]. Current digitization methods in archaeological practices often fail to capture intricate details necessary for preserving historical contexts, underscoring significant challenges [22].

The evolution of augmented reality (AR) and virtual reality (VR) technologies has been shaped by historical and geographical factors, as evidenced by their increasing accessibility in cultural heritage preservation [23]. However, the perceived value of AR technologies for small cultural heritage organizations remains a concern, emphasizing the need for stakeholder involvement to assess potential benefits prior to implementation [24].

Urban development practices in Turkey from 1923 to the present illustrate morphological transformations driven by historical planning initiatives and geographical contexts [18]. The classification of cities based on street network forms reveals universal geometric properties arising from diverse historical and geographical conditions [25]. Despite advancements, the underutilization of big data in urban morphology presents challenges in comprehensively understanding urban spatial patterns and dynamics [26].

Environmental events, such as floods, highlight cultural heritage sites' vulnerability to geographical phenomena. The October 2024 floods in Valencia caused significant damage to infrastructure and cultural heritage, emphasizing the need for effective assessment methods to evaluate their impact [19]. Additionally, carbonation reactions affecting the durability of porous materials in cultural heritage structures underscore the importance of understanding microstructural changes influenced by historical and geographical conditions [20].

Moreover, the integration of digital sound design in historic house museums, exemplified by Bakkehuset in Copenhagen, reflects the historical context and geographical influences on preservation and presentation [27]. The complexity of metadata management for 3D data and interoperability issues complicate the archival and accessibility of historical and geographical data [16].

Technical barriers, sustainability concerns, and ethical considerations regarding the commercial use of digital heritage are increasingly relevant as immersive technologies gain prevalence in cultural heritage initiatives [28]. These factors, alongside the need for regulatory guidelines, are crucial for supporting cultural heritage preservation, ensuring that historical and geographical influences shaping these core concepts are recognized and maintained for future generations. Additionally, the historical context of artifact scanning in anthropology highlights the limitations of existing protocols, which are often time and labor-intensive, influencing the development of more efficient methods [29]. The primary challenge lies in the models' limitations in adapting to the dynamic nature of data, often resulting in overfitting or underfitting, which hinders effective problem-solving [30].

3 Spatial Evolution of Traditional Settlements

The spatial evolution of traditional settlements is shaped by the complex interplay of urban morphology, cultural identity, and environmental factors. Understanding these dynamics is crucial for analyzing the development and transformation of settlements over time. As illustrated in Figure 2, the

hierarchical structure of this evolution highlights key patterns, structures, and methodologies. This figure categorizes the influencing factors and analytical approaches that shape traditional settlements, alongside the innovative technologies and modeling techniques employed to study spatial evolution. The following subsection delves into the patterns and structures characteristic of these environments, providing insights into how urban form and sensory experiences shape the lived realities of inhabitants, thus facilitating a comprehensive analysis of spatial organization in traditional settlements.

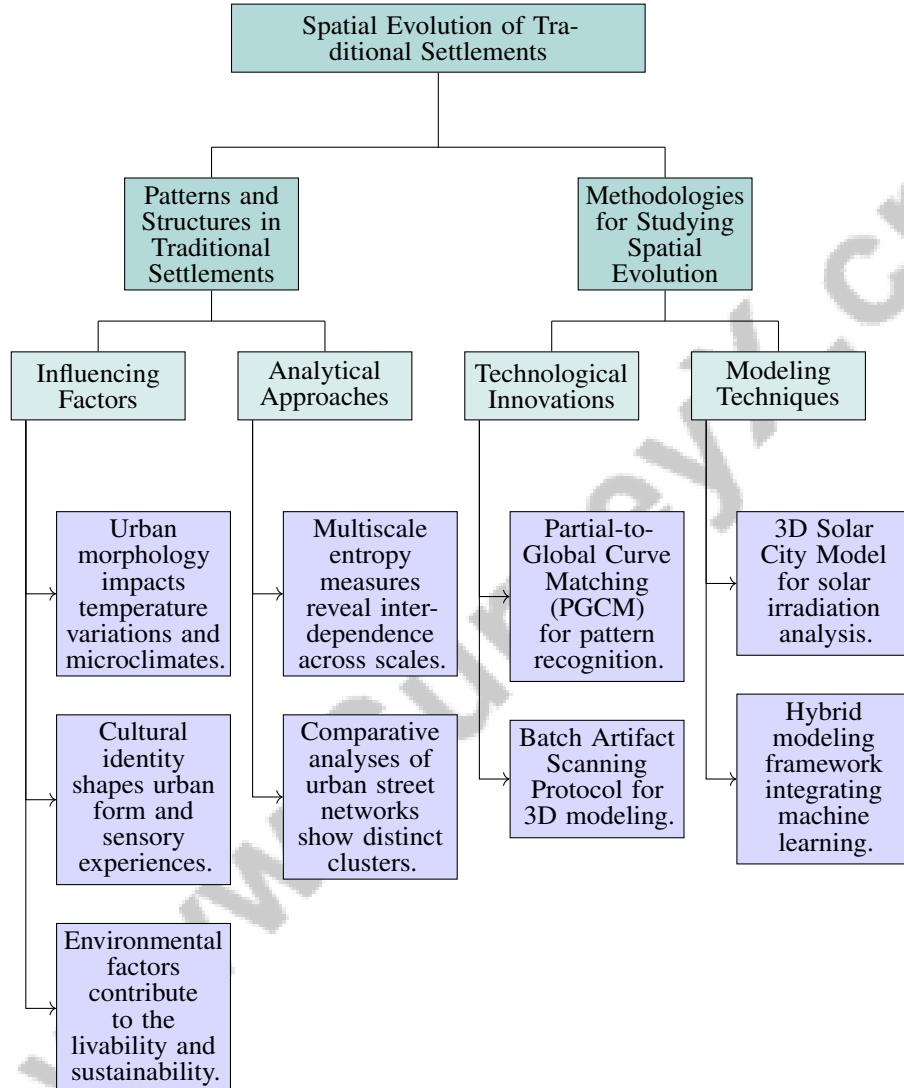


Figure 2: This figure illustrates the hierarchical structure of the spatial evolution of traditional settlements, highlighting key patterns, structures, and methodologies. It categorizes the influencing factors and analytical approaches that shape traditional settlements, alongside innovative technologies and modeling techniques used to study spatial evolution.

3.1 Patterns and Structures in Traditional Settlements

Traditional settlements display distinct patterns and structures influenced by urban morphology, cultural identity, and environmental factors. Urban morphology significantly impacts temperature variations across urban functional zones (UFZs), affecting microclimates and, consequently, the livability and sustainability of these settlements [11]. Bridging the gap between urban design practices and human sensory experiences has led to a deeper understanding of how inhabitants perceive and experience traditional settlements [6]. This underscores the importance of sensory modalities

in shaping spatial experiences, suggesting that urban space design should consider multisensory interactions.

The application of multiscale entropy measures reveals the interdependence of urban places and their characteristics across multiple scales [31]. This methodological advancement provides a nuanced understanding of spatial context and its influence on urban structure, uncovering complex patterns that contribute to the unique identities of traditional settlements. Comparative analyses of urban street networks show that while cities may share universal geometric patterns, differences in street lengths and centrality distributions create distinct clusters of cities [25]. These findings reflect the historical and cultural influences shaping traditional settlements over time.

These studies collectively illustrate the intricate patterns and structures defining traditional settlements, emphasizing the need for a comprehensive approach to understanding their evolution. By synthesizing insights from urban morphology, sensory experiences, and advanced spatial analysis techniques, researchers can gain a deeper understanding of the dynamics shaping the development and transformation of enduring human habitats. This multifaceted approach enhances appreciation of urban complexity and informs effective urban design and planning strategies [8, 32, 6, 26].

3.2 Methodologies for Studying Spatial Evolution

The study of spatial evolution in traditional settlements is enriched by advanced methodologies incorporating technological innovations, data analytics, and modeling techniques. The Partial-to-Global Curve Matching (PGCM) methodology exemplifies an innovative approach that extracts curve patterns from pottery sherds, matching them to known designs and contributing to the understanding of spatial configurations [33]. This highlights the importance of pattern recognition in analyzing historical artifacts.

Integrating conceptual modeling with spatial computing, as discussed by Fill, provides a framework that contextualizes spatial data, enhancing interpretative accuracy [23]. The Batch Artifact Scanning Protocol, introduced by Yezzi-Woodley, allows for efficient creation of high-quality 3D models, contrasting with traditional methods requiring extensive manual intervention [29]. This protocol improves the efficiency and accuracy of 3D modeling in archaeological studies, aiding in documenting spatial transformations.

Zhu's 3D Solar City Model quantifies solar irradiation on urban surfaces by representing them as 3D point clouds, calculating direct and reflective solar radiation effects, and considering shadows cast by buildings [34]. This model provides insights into environmental factors influencing urban morphology and spatial evolution. The development of a hybrid modeling framework that integrates machine learning with domain-specific knowledge enhances predictive accuracy in spatial evolution studies [30].

These methodologies underscore an interdisciplinary approach to understanding spatial evolution, showcasing the integration of advanced technologies, such as AI-driven deep learning models for analyzing historical cadastral maps, alongside mathematical frameworks that quantify urban morphology through entropy and complexity concepts. This comprehensive perspective enables researchers to uncover intricate patterns and transformations of traditional settlements while facilitating public engagement and preserving cultural heritage by identifying historically significant areas within urban landscapes [35, 36].

As shown in Figure 3, various methodologies have been developed to analyze and understand the dynamics of urban morphology in traditional settlements. This figure illustrates key methodologies for studying spatial evolution, emphasizing pattern recognition, 3D modeling, and hybrid frameworks. Specifically, it highlights innovative approaches like the PGCM methodology for pattern recognition, the Batch Artifact Scanning Protocol for efficient 3D modeling, and hybrid frameworks integrating AI and domain knowledge for enhanced predictive accuracy. The figure presents three distinct methodologies: "Urban Morphometrics: A Method for Analyzing Building and Street Networks" focuses on fundamental urban morphology units, such as buildings and tessellation cells, and their relationships within street networks. This method is crucial for dissecting urban environments' physical structures. The "slope.moran" example employs a choropleth map to visualize spatial autocorrelation across Europe using Moran's I statistic, highlighting spatial patterns and variable clustering. Lastly, "Temporal and Spatial Patterns in the Distribution of Urban Areas" analyzes urban distribution over time and space, emphasizing the probabilistic nature of area sizes within urban

settings. Together, these methodologies provide a comprehensive toolkit for examining the intricate processes driving the spatial evolution of traditional settlements [37, 38, 39].

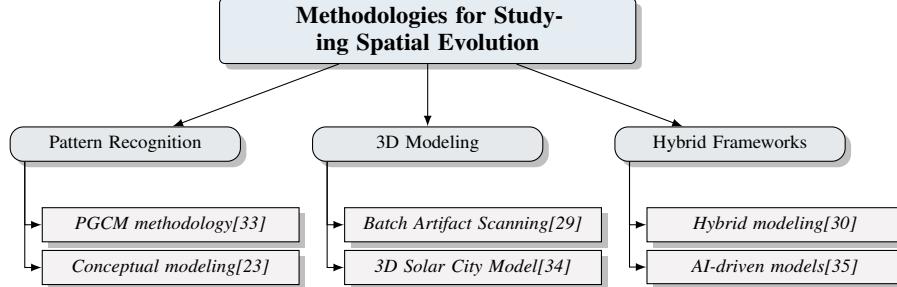


Figure 3: This figure illustrates key methodologies for studying spatial evolution, emphasizing pattern recognition, 3D modeling, and hybrid frameworks. It highlights innovative approaches like the PGCM methodology for pattern recognition, the Batch Artifact Scanning Protocol for efficient 3D modeling, and hybrid frameworks integrating AI and domain knowledge for enhanced predictive accuracy.

4 Urban Morphology and Regional Architecture

Category	Feature	Method
Urban Morphology and Cultural Identity	Multisensory Engagement Urban Integration Models	PTP[40], CHVARF[41] IUBERM[42]
Methodologies for Studying Urban Morphology	Analytical and Evaluation Methods Machine Learning Applications Aerial and Imaging Techniques Visualization and Interaction	NTUF[37], GBE[4], ETnC[43] DL-UMC[44], BMM3D[45], UCDM[46] UIPA[47], IRMA[22], HBIM[48] MV[49], LBKA[50]
Urban Morphology and Architectural Styles	Non-Invasive Techniques	MSI-CT[51]

Table 1: This table presents a comprehensive overview of the methodologies and techniques employed in the study of urban morphology. It categorizes the methods into distinct areas such as urban morphology and cultural identity, methodologies for studying urban morphology, and architectural styles, highlighting key features and corresponding methods utilized in each category. The table serves as a detailed reference for understanding the diverse approaches and technological innovations applied in urban morphological research.

Urban morphology serves as a key framework for analyzing the form, structure, and layout of urban spaces, which in turn shape cultural identity and influence urban design. Table 3 provides a detailed categorization of the methodologies and techniques used in urban morphology research, illustrating the integration of technological advancements and interdisciplinary approaches. This section examines how urban morphology delineates the spatial characteristics of cities, reflecting and shaping cultural narratives. By analyzing urban form, we can understand how it embodies and influences cultural identity within urban landscapes. The subsequent subsection will specifically explore the relationship between urban morphology and cultural identity, highlighting its implications for urban design and community engagement.

4.1 Urban Morphology and Cultural Identity

Urban morphology plays a crucial role in reflecting and shaping cultural identity through cities' physical and symbolic landscapes. Structural similarities in urban street networks facilitate classifying cities based on unique geometric traits, which express cultural identity [25]. This classification highlights urban form's role in conveying cultural and historical narratives embedded in cityscapes. Interdisciplinary approaches, combining urban morphology with environmental psychology, offer a comprehensive perspective on urban design, emphasizing sensory and psychological dimensions [41]. This view is essential for understanding how urban spaces contribute to cultural identity by shaping inhabitants' lived experiences and sensory perceptions.

Technological advancements, such as augmented reality (AR), enhance user engagement and knowledge retention through immersive narratives and interactive tasks, reinforcing cultural identity [40].

Stakeholder surveys on AR adoption underscore the importance of understanding diverse perspectives in technology adoption to preserve cultural narratives [24]. Urban morphology also impacts thermal environments in residential and green spaces, where spatial arrangements affect local climate conditions and quality of life [42]. This interplay between urban form and environmental factors shapes urban areas' cultural and social dynamics.

Distinct analytical frameworks from the British, Italian, and French schools of urban morphology explore the relationship between cultural identity and urban form. The British school emphasizes historical processes and methodological precision, while the Italian and French schools offer unique perspectives on classifying and interpreting urban elements and their interactions [52, 32, 8, 6, 18]. These frameworks illustrate the multifaceted nature of cultural identity manifesting in urban environments. Figure 4 illustrates the hierarchical structure of urban morphology's influence on cultural identity, highlighting urban form's role, technological integration, and analytical frameworks.

Comparative analyses of urban land cover and impervious surface patterns reveal monofractal characteristics, while population density patterns exhibit pronounced multifractality, highlighting variations in urban morphology dependent on data modality. Calculating Renyi's generalized dimensions across urban modalities, including land cover, impervious surfaces, population density, and street intersections, indicates that different urban patterns possess unique morphological traits. Specifically, land cover and impervious surfaces align with monofractal structures, whereas population density patterns display strong multifractality, suggesting that data modality can lead to differing interpretations of urban form [8, 12]. These findings suggest that urban morphology is a complex system where local interactions lead to emergent patterns, reflecting cultural identity through spatial dependencies.

Incorporating urban design variables to enhance energy efficiency and ventilation exemplifies how urban morphology can contribute to sustainable urban development while reinforcing cultural identity. These approaches underscore urban morphology's significant role in promoting both cultural preservation and innovation. By systematically analyzing urban environments' form, structure, and historical development, urban morphology aids in maintaining and celebrating the unique cultural landscapes of cities, enabling planners and designers to understand the intricate relationships between urban elements while respecting historical contexts and fostering contemporary advancements in urban design [6, 8, 32, 18].

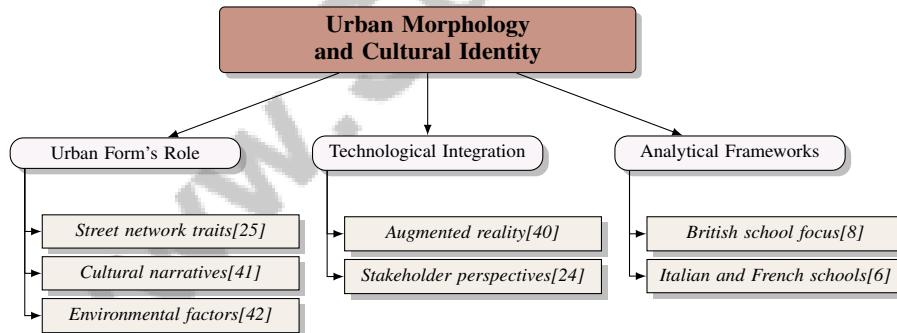


Figure 4: This figure illustrates the hierarchical structure of urban morphology's influence on cultural identity, highlighting urban form's role, technological integration, and analytical frameworks.

4.2 Methodologies for Studying Urban Morphology

The exploration of urban morphology benefits from diverse methodologies integrating technological innovations, data analytics, and interdisciplinary approaches. A notable framework categorizes urban morphology studies into three distinct schools—British, Italian, and French—each offering unique methodologies and focuses, thus providing a structured understanding of urban forms [8].

UAVs (Unmanned Aerial Vehicles) enhance urban morphological analyses' precision by capturing aerial imagery, which is processed into orthoimages and integrated with architectural designs to develop Building Information Models (BIM) [48]. This method exemplifies aerial data's potential in enriching urban analysis. Photogrammetry techniques, such as the embedded shape matching methodology, analyze two-dimensional maps to recognize features of three-dimensional structures,

Method Name	Technological Integration	Interdisciplinary Approaches	Data Modality Fusion
HBIM[48]	Uav Photogrammetry	Architectural Data	Orthoimages Architectural Designs
GBE[4]	Photogrammetry	Data Analytics	3D Models
LBCA[50]	-	-	-
IRMA[22]	Imaging Technologies	Cultural Insights	3D Interactive Modalities
UIPA[47]	-	Cultural Insights	Depth Map Generation
MV[49]	Interactive Visualizations	Cultural Heritage Data	Multiple Interactive Formats
UCDM[46]	Cnn Architectures	-	Rgb Image Patches
ETnC[43]	-	Multiple Criteria Decision-making	-
NTUF[37]	-	-	-
BMM3D[45]	Machine Learning Techniques	Information Retrieval Techniques	3D Urban Models
DL-UMC[44]	Deep Learning	Deep Learning-based	Visual Data

Table 2: This table presents a comprehensive overview of various methodologies employed in the study of urban morphology, highlighting the integration of technological innovations, interdisciplinary approaches, and data modality fusion. Each method is characterized by its unique combination of technological integration, interdisciplinary application, and data modality, demonstrating the diverse and dynamic nature of urban morphological research.

providing insights into urban form [4]. This underscores visual data's importance in understanding urban spatial dynamics.

Local betweenness centrality analysis introduces a robust visualization method that highlights road segments' significance and characteristics, addressing previous clustering methods' shortcomings [50]. This method facilitates a deeper understanding of urban connectivity and spatial dynamics. The IRMA method, combining medical imaging technologies with interactive 3D restitution modalities, exemplifies innovative methodologies in urban morphology studies [22]. This approach leverages advanced imaging techniques to enhance the analysis of archaeological sites and urban landscapes.

Additionally, aligning 3D woodblock models with 2D images through depth map generation and normalization offers a novel technique for urban morphology analysis, focusing on integrating different data modalities [47]. This highlights the potential of combining 3D and 2D data for comprehensive urban analysis. MuseumViz, designed to enhance cultural heritage artifacts' visualization, employs various interactive visualizations to facilitate urban morphology exploration [49]. This framework underscores interactive technologies' role in engaging users with urban spaces and cultural heritage.

The incorporation of CNNs (Convolutional Neural Networks) for unsupervised crack detection in complex urban environments demonstrates deep learning's capability to extract and classify features with minimal data requirements [46]. This method emphasizes machine learning's potential in urban morphological research. Moreover, applying a multiple criteria methodology that incorporates qualitative and quantitative evaluations provides a holistic approach to prioritizing urban projects, ensuring a balanced assessment of urban development initiatives [43].

The methodologies employed in urban morphology research are diverse and interdisciplinary, reflecting a dynamic integration of technological advancements, analytical frameworks, and cultural insights. This approach enhances our understanding of urban forms and their evolution, drawing from various schools of thought—British, Italian, and French—each contributing unique perspectives on the historical and spatial processes shaping urban environments. By leveraging big data and computational tools, researchers can analyze urban fabric patterns and spatial orders more effectively, enriching the discourse on how cities develop and change over time [37, 8, 32, 26].

Table 2 provides a detailed overview of the methodologies utilized in urban morphology research, illustrating the integration of technological advancements, interdisciplinary approaches, and data modality fusion.

As shown in Figure 5, the study of urban morphology and regional architecture involves various methodologies aimed at understanding urban environments' complexities. The examples illustrate different approaches, each offering unique insights into urban areas' spatial and functional dynamics. The first example, "Urban Planning and Spatial Analysis: Comparative Maps and Dendrogram," utilizes comparative maps of cities like Prague and Amsterdam to visually differentiate urban clusters through color-coding and a cophenetic distance dendrogram, highlighting spatial relationships and planning variations. The second example, "Urban Form Optimization: A Bi-directional Link Between Urban Form Generation and Performance Evaluation," presents a flowchart exploring the iterative process of optimizing urban forms, emphasizing the reciprocal relationship between design proposals and their performance evaluations. Lastly, the "Urban Vitality and Morphology Measurement

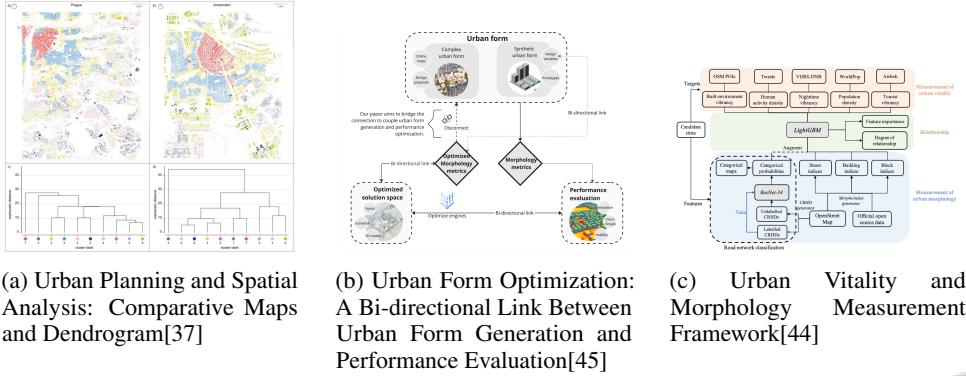


Figure 5: Examples of Methodologies for Studying Urban Morphology

Framework" provides a flowchart for assessing urban vitality and morphology, focusing on built environments' vibrancy and human activities across candidate cities. Together, these examples demonstrate diverse methodologies employed in urban morphology studies, ranging from spatial analysis and form optimization to vitality measurement, each contributing to a comprehensive understanding of urban landscapes. [37, 45, 44]

4.3 Urban Morphology and Architectural Styles

Urban morphology significantly influences architectural styles by dictating the spatial organization and aesthetic principles defining built environments. The relationship between urban form and architectural expression is evident in how cities evolve, with morphological characteristics shaping buildings' design and functionality. Analyzing urban forms through fractal dimensions offers a nuanced perspective, revealing intricate patterns often overlooked by traditional area measures [53]. This approach underscores urban landscapes' complexity and their impact on architectural design, suggesting that fractal analysis can yield deeper insights into the spatial logic governing architectural styles.

The architectural elements of historical structures, such as the Barolo Palace, exemplify integrating cosmological and cultural narratives into architectural design. The alignment of the palace's features with Dante's cosmological descriptions illustrates how urban morphology influences architectural styles by embedding cultural and symbolic meanings within the built environment [54]. This intersection of urban form and cultural identity highlights architecture's role in reflecting and reinforcing a city's cultural context.

Innovative methodologies, including non-invasive analysis techniques, significantly enhance studying architectural styles within urban contexts. These approaches facilitate comprehensive documentation of large-format artworks and architectural details, providing essential data for informed conservation practices [51]. The ability to analyze architectural elements without physical intervention enriches our understanding of the stylistic and structural characteristics defining urban morphology.

The influence of urban morphology on architectural styles is further illustrated by adapting architectural designs to urban areas' spatial and environmental constraints. Integrating local materials and traditional building practices within cities' morphological framework exemplifies the complex interaction between architectural form and functional requirements, ensuring contemporary designs honor cultural heritage while adapting to urban environments' evolving needs. This approach reflects a critical understanding of urban morphology, emphasizing the historical context and relational dynamics of urban elements essential for developing responsive and sustainable planning practices [45, 8, 18].

5 Cultural Heritage and Its Impact on Spatial Form

In examining the intricate relationship between cultural heritage and spatial form, it is essential to recognize how these elements interact to shape the identity and character of urban environments.

Feature	Urban Morphology and Cultural Identity	Methodologies for Studying Urban Morphology	Urban Morphology and Architectural Styles
Data Modality	Monofractal, Multifractal	3D And 2D Data	Fractal Dimensions
Technological Integration	Augmented Reality	Uavs, Photogrammetry	Non-invasive Analysis
Analytical Focus	Cultural Identity	Urban Connectivity	Architectural Expression

Table 3: This table presents a comparative analysis of methodologies employed in urban morphology research, focusing on their data modalities, technological integrations, and analytical focuses. It highlights the diverse approaches used to study urban morphology, including the role of augmented reality, UAVs, and non-invasive techniques in understanding cultural identity, urban connectivity, and architectural expression.

The subsequent subsection will delve into the specific ways in which cultural heritage influences the spatial organization and architectural expression of settlements, highlighting the significance of innovative techniques in preserving these vital connections. By exploring the nuances of this relationship, we aim to elucidate the role of cultural heritage in informing and transforming spatial forms, setting the stage for a deeper understanding of its implications in contemporary urban contexts.

5.1 Cultural Heritage and Spatial Form

The intricate relationship between cultural heritage and the spatial form of settlements is a critical area of study, as it reveals how historical and cultural narratives are embedded within the physical landscapes of human habitats. Cultural heritage, encompassing both tangible and intangible elements, significantly influences the spatial organization and architectural expression of settlements. The accurate segmentation of curve structures is vital in preserving cultural heritage, as it ensures that the complex geometries integral to cultural narratives are maintained within the spatial form of settlements [21].

The integration of UAV photogrammetry with Historic Building Information Modeling (HBIM) has proven effective in documenting and preserving cultural heritage buildings. This approach provides a reliable digital representation that aids in future renovations and educational activities, ensuring that the architectural and cultural significance of these structures is preserved [48]. Moreover, the use of multiscale modeling to understand carbonation in cultural heritage materials underscores the necessity of collaborative efforts between mathematicians and experimentalists, facilitating a deeper understanding of the material processes that affect spatial form [20].

Computer vision techniques, particularly for detecting building pathologies, have been pivotal in cultural heritage preservation. These methodologies highlight the importance of maintaining the structural integrity of heritage sites, which directly influences the spatial form of settlements [46]. The identification of stone deterioration patterns, challenged by weathering and human-induced damage, emphasizes the need for ongoing preservation efforts to protect the cultural heritage embedded in these monuments [55].

The accessibility of digitization methods plays a crucial role in cultural heritage preservation. The adoption of techniques that require only standard smartphone images, as proposed in recent studies, makes digitization more widely adoptable and ensures that cultural heritage sites are accurately documented and preserved [56]. These digital methods facilitate the creation of comprehensive records that capture the spatial form of cultural heritage, contributing to the continuity of cultural narratives within urban landscapes.

Collectively, these insights underscore the complex interplay between cultural heritage and spatial form, emphasizing the need for innovative approaches to preserve and celebrate these relationships within urban environments. The integration of advanced imaging techniques, such as 3D holoscopic imaging and AI-driven data extraction, alongside digital technologies and collaborative preservation initiatives, is crucial for maintaining the integrity of cultural heritage. These efforts not only enhance the visualization and accessibility of historical assets but also ensure that the rich narratives and spatial forms of settlements are preserved and reflected in modern human habitats. By employing cost-effective and time-efficient methods for digitalization, such as smartphone-compatible 3D modeling and immersive technologies, we can foster a deeper understanding of our cultural landscapes and promote sustainable practices in heritage management. [57, 58, 56, 35, 59]

5.2 Innovative Techniques in Cultural Heritage Preservation

Innovative techniques in cultural heritage preservation are increasingly utilizing technological advancements and interdisciplinary approaches to ensure the safeguarding of cultural assets. The integration of UAV photogrammetry with Historic Building Information Modeling (HBIM) exemplifies this trend, providing comprehensive documentation of heritage sites like the Averof Museum by integrating various data sources [48]. This approach not only aids in preservation but also enhances the accuracy and detail of heritage documentation.

The use of medical imaging technologies and interactive 3D applications has significantly advanced the study and preservation of archaeological artifacts. These technologies allow for non-invasive analysis, enhancing the understanding and conservation of cultural heritage [22]. Similarly, the development of techniques like Gaussian Heritage automates the creation of 3D models from RGB images, simplifying the digitization process and making it more accessible [56].

Deep learning methodologies have been pivotal in advancing preservation techniques. For instance, the application of unsupervised crack detection methodologies has demonstrated high accuracy in localizing structural issues within heritage sites, even with limited training data [46]. This highlights the potential of AI in identifying and addressing preservation challenges.

Augmented reality (AR) is another innovative tool enhancing cultural heritage preservation. By providing immersive experiences, AR technologies improve user engagement and understanding of complex heritage systems, thereby supporting educational and preservation efforts [23]. The focus on recognizing and classifying stone deterioration patterns further emphasizes the importance of advanced analytical tools in conservation efforts [55].

Future research is poised to expand these innovations, exploring applications of comprehensive analytical instruments that integrate additional techniques for cultural heritage analysis [60]. Collectively, these advancements underscore the dynamic and interdisciplinary nature of cultural heritage preservation, emphasizing the integration of cutting-edge technologies and collaborative approaches to safeguard cultural legacies for future generations.

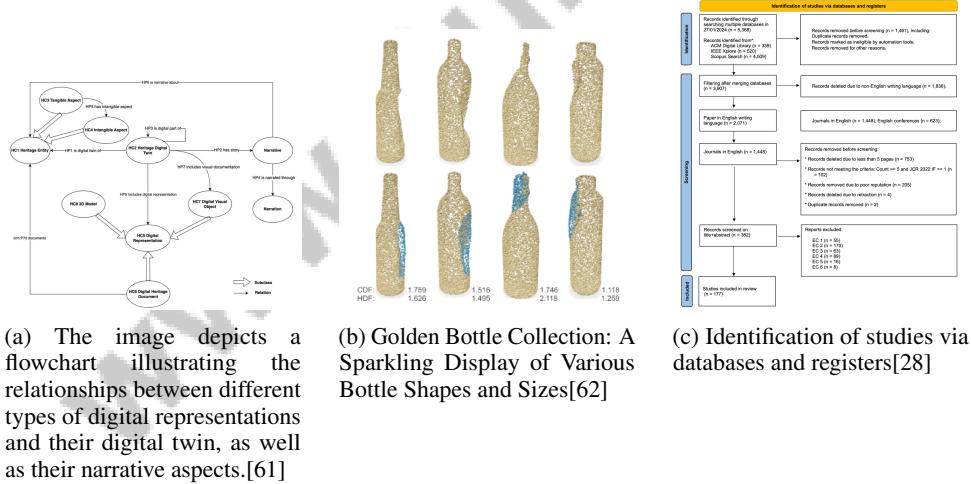


Figure 6: Examples of Innovative Techniques in Cultural Heritage Preservation

As shown in Figure 6, The exploration of cultural heritage and its impact on spatial form is a fascinating area that delves into how innovative techniques in cultural heritage preservation can transform our understanding and interaction with historical artifacts and narratives. The example provided highlights three distinct yet interconnected visual representations that collectively underscore the role of digital technology in preserving and interpreting cultural heritage. The first image is a flowchart that visually maps the intricate relationships between various digital representations and their digital twins, emphasizing the narrative potential of these digital formats. This flowchart serves as a conceptual framework for understanding how digital technologies can create immersive and interactive experiences of heritage entities, such as 3D models and visual objects. In contrast, the second image, the "Golden Bottle Collection," showcases a tangible

example of cultural artifacts—golden bottles of varying shapes and sizes—captured in a visually striking manner that highlights both their aesthetic and historical significance. This depiction underscores the importance of preserving the physical characteristics of heritage items, even as they are digitized. Finally, the third image presents a systematic approach to identifying relevant studies through databases and registers, illustrating the methodological rigor involved in cultural heritage research. Together, these images exemplify the multifaceted strategies employed in the preservation and study of cultural heritage, demonstrating how digital innovation can enhance our engagement with the past while ensuring its protection for future generations. [?]nic-colucci2024digitaltwinsensorscultural,jaramillo2024culturalheritage3dreconstruction,wang2025grandchallengesimmersivetechno

5.3 Community Engagement and Cultural Heritage Management

Community engagement plays a pivotal role in managing cultural heritage by fostering collaboration between local communities, heritage authorities, and researchers. The integration of community perspectives is crucial for the sustainable preservation and documentation of cultural assets. The Tirtha platform exemplifies a cost-effective and accessible solution for documenting cultural heritage sites through crowdsourced image contributions, enabling the creation of detailed 3D models for research and preservation purposes [63].

The iCommunity method further highlights the importance of community engagement by improving communication between local communities and heritage authorities, allowing for adaptive engagement processes based on user feedback [64]. This approach ensures that heritage management practices are inclusive and responsive to the needs and insights of the communities they aim to serve.

Cultural heritage serves as a medium for fostering recognition and dialogue between institutions and citizens, as proposed by Sokka and colleagues [65]. This dialogue is essential for building trust and collaboration, which are critical for the effective management and preservation of cultural heritage.

Technological advancements, such as the digital twin framework, support stakeholders in making informed decisions to enhance the structural integrity of heritage sites, which is vital for their preservation [66]. These technologies facilitate the monitoring and management of cultural heritage, ensuring that preservation efforts are both effective and sustainable.

The application of deep learning methodologies, such as the automated defect detection process described by Bahrami et al., reduces human error and increases efficiency in conservation practices [67]. This automation allows for more precise management of heritage sites, addressing potential issues before they become critical.

Future research should focus on improving the robustness of models against diverse data and refining training datasets to enhance performance in cultural heritage management [62]. By integrating community engagement with technological innovations, heritage management can be more effective, ensuring that cultural legacies are preserved for future generations.

6 Case Studies

6.1 Case Studies in Urban Morphology and Regional Architecture

Examining urban morphology and regional architecture through specific case studies reveals diverse methodologies and contextual applications. In Hangzhou, spatial analysis and population density data elucidate urban morphology's implications for planning and development [68]. Similarly, Tehran's study on Building Mass Configuration (BMC) highlights urban form's impact on cooling loads and ventilation potential, emphasizing environmental sustainability through comparisons of 1600 urban cases [15].

The HDT ontology in cultural heritage contexts enhances interoperability of heritage datasets, enriching understanding of regional architectural styles [69]. At the Longmen Grottoes, deep learning methods, specifically autoencoder techniques, advance digital heritage management [70]. The LUX platform demonstrates LOUD principles' application in cultural heritage management, emphasizing usability and interoperability in urban morphology and digital technologies [3]. Naples showcases a multiple criteria methodology, integrating diverse perspectives in urban planning and the significance of urban morphology in preserving cultural identity [43].

The Batch Artifact Scanning Protocol's use in scanning 2,474 bone fragments shows high-throughput digital documentation's potential in cultural heritage studies, enhancing archaeological data collection efficiency [29]. Collectively, these case studies highlight urban morphology and regional architecture's evolving nature, emphasizing methodological innovation and contextual analysis. By exploring various schools of thought and integrating advanced spatial technologies and big data, researchers gain insights into historical and contemporary dynamics shaping urban environments. This multifaceted analysis underscores the diversity of urban forms and the necessity of combining quantitative and qualitative perspectives to address urban planning challenges in Smart Cities [8, 32, 26]. The integration of digital technologies, interdisciplinary approaches, and cultural narratives further enriches understanding of the complex relationships defining urban environments and architectural expressions.

6.2 Cultural Heritage and Climate Adaptation Strategies

The intersection of cultural heritage and climate adaptation strategies is critical as environmental changes pose significant risks to heritage sites. In Odisha, India, the Tirtha platform uses expert-sourced and crowdsourced image datasets for documenting State Protected Monuments, supporting climate adaptation through detailed records [63]. Historical urban areas of Rome and Florence demonstrate how earthquake scenarios inform climate adaptation strategies, incorporating historical data into contemporary measures to protect heritage sites against environmental threats [71].

Technological advancements, like haptic rendering, improve accessibility and user experience with cultural heritage objects, fostering broader community engagement in heritage preservation aligned with climate adaptation efforts [72]. H3D technology's application in digitizing small cultural heritage assets provides a cost-effective method supporting climate adaptation through comprehensive documentation [57].

These case studies reveal the complex relationship between preserving cultural heritage and adapting to climate change, underscoring the urgent need for innovative methodologies and collaborative approaches. Insights from cultural heritage experts across Europe highlight weather patterns' impacts on cultural assets and the necessity for strategic planning incorporating climate adaptation measures. There is consensus on cultural heritage adaptation's feasibility and identifying barriers and resources essential for effective implementation. This emphasizes further research and practical tools development to integrate climate change adaptation into cultural legacy management and preservation amidst environmental challenges [73, 74]. By integrating digital technologies and adaptive strategies, stakeholders can ensure cultural heritage's resilience and continuity amidst changing climatic conditions.

7 Challenges and Future Directions

The preservation of cultural heritage is confronted with numerous challenges in documentation and conservation, influenced by technological limitations, financial constraints, and methodological shortcomings. Addressing these obstacles is essential for the effective safeguarding of cultural artifacts. The following subsection delves into the specific challenges in documentation and preservation, offering insights into the current landscape and the factors impeding progress in this critical field.

7.1 Challenges in Documentation and Preservation

Cultural heritage documentation and preservation face significant challenges due to technological, methodological, and contextual factors. Financial constraints limit resources for restoration and preservation, exacerbating difficulties amid urban development pressures [18]. High costs and lengthy acquisition times for generating high-quality 3D models, particularly for medium-sized objects, are core obstacles, with conventional structured light techniques requiring up to 20 hours [57].

Technological limitations include dependency on high-quality input images, resulting in inaccuracies in digital reconstructions over time [27]. Inaccessibility of certain structures complicates traditional data acquisition methods, hindering accurate digital representations [48]. Current digitization methods often fail to capture the structural and contextual information of archaeological artifacts, limiting their effectiveness [22]. Additionally, computational complexity in feature extraction and the need for meticulous parameter tuning pose substantial challenges [75].

Methodologically, the historical focus on descriptive rather than practical applications in urban morphology studies limits their effectiveness in addressing contemporary urban issues [25]. The lack of comprehensive validation against experimental data in carbonation reaction studies underscores the need for more robust empirical approaches [20]. Furthermore, potential subjective bias in criteria weighting and the complexity of integrating diverse stakeholder perspectives complicate preservation efforts [43].

Community engagement faces significant barriers due to the absence of recognized methods and appropriate tools for involving local communities in decision-making processes [24]. While crowd-sourced data can enhance participation, it may lead to inaccuracies in site listings and assessments, necessitating further validation [21].

Additionally, the lack of standardized methodologies for 3D model documentation limits the effective capture of cultural artifacts [16]. Misalignment of depth maps with RGB images can lead to substantial discrepancies in digital reconstructions [48].

To address these complex challenges in cultural heritage research and dissemination, innovative strategies are essential. These strategies should leverage the latest technological advancements—such as immersive technologies and visual analytics—while promoting interdisciplinary collaboration across diverse fields. Moreover, approaches must be sensitive to the socio-political contexts surrounding cultural heritage, ensuring that the integration of heterogeneous data is accessible and engaging for researchers and the broader public. Initiatives like the "HeritageS" digital platform and the "Renaissance Transmedia Lab" exemplify this holistic framework by enhancing communication between scholars and audiences while upholding rigorous scientific standards [28, 76, 74]. By fostering tailored solutions and improving data integration and representation, the field of cultural heritage documentation and preservation can progress towards more comprehensive and effective practices.

7.2 Technological Innovations in Cultural Heritage

Technological innovations are revolutionizing the preservation and study of cultural heritage, offering novel methodologies and tools that enhance documentation, analysis, and conservation efforts. The Tirtha platform exemplifies the democratization of cultural heritage documentation, employing crowdsourced images and advanced photogrammetry techniques to create accurate 3D models, thereby increasing accessibility and engagement [63]. This approach underscores the potential of participatory technologies to broaden the impact of heritage preservation.

The integration of low-cost tools and methods for photogrammetric reconstructions addresses challenges faced by archaeologists, facilitating the creation of detailed digital reconstructions that enhance archaeological studies [77]. Furthermore, advancements in computer vision, such as novel view synthesis and Gaussian Splatting, significantly improve cultural heritage digitization by enabling more sophisticated and accurate representations [56].

The H3D method, which efficiently captures 3D data using a single aperture camera with a micro lens array, exemplifies innovations in the rapid acquisition of small cultural heritage assets [57]. This technology facilitates swift documentation and enhances the accessibility of cultural heritage data.

Future research directions should focus on optimizing applications for augmented reality (AR) devices, enhancing interaction capabilities, and integrating voice commands to facilitate more natural user interactions [78]. These advancements in AR technologies are crucial for enhancing user engagement and knowledge retention, providing immersive experiences that support educational and preservation efforts [23].

The Neo-deterministic Seismic Hazard Assessment (NDSHA) represents a significant advancement in assessing seismic hazards for cultural heritage sites, offering a robust framework for risk management and safeguarding heritage sites against natural disasters [71]. Complementing this, unsupervised crack detection methodologies provide fast and efficient solutions, requiring fewer training epochs and less computational power, thereby enhancing structural integrity assessments [46].

Future work will concentrate on refining ontologies, testing them in varied real-world scenarios, and exploring automatic data enrichment methods using AI to enhance cultural heritage data management and interoperability [69]. Additionally, the exploration of machine learning techniques for improved analysis, particularly in tropical climates, along with the potential of blockchain technologies to

address preservation challenges, presents promising avenues for enhancing the security and longevity of cultural heritage data [58].

The convergence of advanced technological innovations—such as the development of Heritage Digital Twin ontologies for comprehensive cultural asset representation, the application of supervised machine learning in visual analytics for cultural heritage, and the use of scalable linked data frameworks like IIIF and LUX—highlights an interdisciplinary approach to cultural heritage preservation. These innovations facilitate the integration of state-of-the-art tools and methodologies, ensuring effective safeguarding and accessibility of cultural legacies for future generations [74, 56, 3, 69]. As the field continues to evolve, ongoing research and development will be crucial in refining these technologies and expanding their applications across diverse cultural contexts.

7.3 Contemporary Relevance and Future Directions

The contemporary study of spatial evolution, urban morphology, and cultural heritage is increasingly pertinent in addressing challenges posed by rapid urbanization and the need for sustainable urban development. These fields provide critical insights into the interactions between urban form, cultural identity, and architectural styles, which are essential for guiding urban planning and heritage conservation efforts. The integration of technological advancements, such as autonomous reality modeling, enhances the adaptability of robotic agents in diverse environments, advancing the study of spatial evolution and urban morphology [79].

Future research should prioritize refining methodologies to ensure applicability across diverse urban contexts. This involves integrating historical insights from the British school with contemporary socio-economic analyses for a holistic understanding of urban morphology [8]. Empirical studies investigating the relationship between urban design elements and sensory experiences in real-world settings could yield deeper insights into the lived experiences of urban spaces [41]. Additionally, exploring emerging trends in urban morphology through large datasets that integrate various urban characteristics will be crucial for understanding the evolution of urban street networks and their implications for urban planning.

The integration of digital technologies presents promising avenues for advancing cultural heritage preservation. Improving the sensitivity and resolution of digital tools, such as muography, will significantly contribute to the preservation of cultural assets [80]. Future efforts should also focus on refining applications like the iCommunity platform based on user feedback, expanding its functionalities, and assessing its applicability in other cultural heritage contexts [64]. Furthermore, implementing augmented reality (AR) across various cultural heritage contexts should be explored to evaluate its ecological value and quantitatively test perceived value constructs [24].

In urban morphology, expanding frameworks to encompass diverse cultural and geographical settings will ensure that urban analysis tools remain adaptable and comprehensive [45]. Future research should also enhance community engagement in heritage management by developing platforms that facilitate cultural dissemination and education [81]. Moreover, refining data sources and methodologies for more accurate assessments of heritage site vulnerabilities will be crucial for safeguarding cultural legacies [19].

The exploration of multi-dimensional urban models and the incorporation of diverse transportation systems can enhance the understanding of social interaction performance in urban settings [82]. Future studies should focus on refining model parameters, exploring different network growth heuristics, and applying methodologies to various urban contexts for validation [38]. Enhancing the robustness of DOSM technology and expanding its application to more cultural heritage sites could significantly influence contemporary studies on spatial evolution and urban morphology [83].

As the field continues to evolve, ongoing research and development will be critical in refining these technologies and expanding their applications across diverse cultural contexts. Future work should focus on improving data integration techniques and expanding methods to incorporate a broader range of cultural heritage datasets for wider applicability. Additionally, enhancing datasets and exploring advanced domain adaptation techniques will improve the scalability of location recognition methodologies to larger datasets and more diverse locations [84].

8 Conclusion

This survey examines the intricate relationship between spatial evolution, urban morphology, and cultural heritage, highlighting their significant influence on the development and transformation of human settlements. An analysis of traditional settlements reveals the complex social and spatial dynamics that inform their design, underscoring the necessity for effective strategies to enhance and sustain these environments [85]. Furthermore, the exploration of urban morphology through fractal dimension growth offers critical insights into the patterns and structures of urbanization, which are essential for understanding spatial dynamics and guiding future urban development [10].

The incorporation of technological innovations, such as UAV photogrammetry and advanced digital modeling techniques, illustrates the potential for preserving cultural heritage while meeting contemporary urban needs. These tools enable the documentation and analysis of cultural sites, ensuring that the historical narratives embedded in urban landscapes are preserved for future generations. As rapid urbanization increasingly threatens cultural identity, comprehending the spatial evolution of settlements becomes vital. This understanding not only supports the safeguarding of cultural heritage but also informs sustainable urban planning practices that respect and enhance the distinctive characteristics of each region.

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