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Operationalizing the Historic Urban Landscape Framework Through Heritage-Sensitive Urban Data Platforms: A Blueprint from Spa Settlements

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Abstract

Urban data platforms increasingly support heritage documentation, analysis, and management, yet their integration with the Historic Urban Landscape (HUL) framework remains fragmented, particularly in translating complex morphological and heritage knowledge into operational digital structures. This study develops a heritage-sensitive urban data platform blueprint that translates the six-step HUL implementation framework into a structured digital knowledge system and examines it through the SPATTERN heritage-sensitive urban data platform. Using 38 Serbian spa settlements as an observatory case, the research adopts a sequential knowledge-translation methodology combining methodological and empirical investigation, typomorphological analysis, expert consultation, digital knowledge modelling, and an implementation-oriented schema crosswalk. The SPATTERN blueprint organizes heterogeneous heritage knowledge through analytical dimensions, urban patterns and archetypes, user requirements, datasets, and functional modules, establishing traceable relationships between analytical interpretation and platform architecture. The HUL–SPATTERN crosswalk demonstrates correspondence across conceptual, informational, and functional levels, to differing degrees across the six implementation steps, identifies gaps in consensus-building, vulnerability assessment and local management, and shows that heritage objectives can be largely maintained throughout the transition from knowledge production to digital implementation. The study establishes a reproducible methodological roadmap for developing heritage-sensitive urban data platforms in which digital infrastructure is derived from explicit heritage knowledge requirements rather than predetermined technological capabilities. It positions knowledge translation as the critical interface between morphological interpretation, heritage values, and operational digital environments.

Keywords: historic urban landscape; urban data platforms; urban morphology; digital heritage; heritage-sensitive planning; knowledge translation; typomorphology; spa settlements

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1. Introduction

1.1. Research Motivation

Urban data platforms (UDPs) have become core infrastructures of contemporary "platform urbanism" [1–3], where urban services, knowledge production, and governance are increasingly mediated by digital platforms and data ecosystems rather than by traditional planning instruments alone [4]. The literature demonstrates how platform logics reorganize urban processes around data capture [5] and multi-sided interactions between public and private actors [2], often producing new dependencies, asymmetries of power, and challenges for democratic control over urban space. Within this broader debate, UDPs can be understood as socio-technical systems that aggregate heterogeneous datasets [6], enable data sharing and analytics [7], and support decision-making across multiple urban domains [8]. Conceptual analyses further spotlight UDPs as infrastructures for value creation in smart city ecosystems, structured around stakeholder-oriented data integration and governance models [9], while empirical analyses highlight their growing institutionalization across European cities as publicly driven platforms aligned with sustainability agendas [10].

As UDPs expand across diverse domains of urban governance, their application to cultural heritage and historic urban environments has attracted growing scholarly attention. Within this growing field, research has highlighted the transformative potential of digital data analytics [11], big data [12,13], and platform-based approaches for heritage policy and management [14], while simultaneously pointing to emerging risks related to data fragmentation and the need for new heritage-specific metrics [15]. Complementary research demonstrates how UDPs can support heritage-related tasks through geospatial data integration, spatial analytics, and open data infrastructures, including the mapping of heritage assets [16], assessment of heritage attractiveness [17], and monitoring of spatial dynamics through multitemporal analysis [18]. Parallel developments in semantic modelling and ontology-based approaches further enable the structuring and interoperability of heterogeneous heritage datasets within UDPs [19,20], while advances in HBIM-integrated systems [21] and BIM–GIS platforms [22] demonstrate the potential of multi-scale, data-driven environments for heritage conservation and management. At the same time, emerging platform paradigms such as urban digital twins [23,24] and integrated data environments [25] extend these capabilities toward real-time monitoring, predictive analysis, and decision support in heritage contexts, while open heritage data platforms and linked open data infrastructures reinforce the importance of interoperability and semantic consistency in heritage management [26,27]. In addition, recent research highlights the growing role of participatory and user-generated data, particularly through social media [28,29], in shaping the understanding, representation, and governance of historic urban landscapes.

Despite these significant advances, the integration of UDPs and heritage remains conceptually and operationally fragmented. Existing approaches tend to address specific technological components (such as GIS, HBIM, or digital twins) or focus on particular data sources, without establishing a coherent framework that connects heritage knowledge, spatial analysis, and platform architecture into a unified system [30]. This fragmentation becomes particularly critical in the context of the Historic Urban Landscape (HUL) approach [31], which provides a value-based framework for understanding and managing urban heritage [32], but remains largely disconnected from the design and implementation of digital infrastructures. In this sense, the motivation for this study emerges from the need to bridge the gap between the increasing technological sophistication of UDPs and the complex, multi-layered nature of heritage-sensitive urban environments. Specifically, there is a lack of approaches that can translate heritage knowledge (particularly morphological, spatial, and value-based dimensions) into structured, operational components of

UDPs. This challenge is especially pronounced in settlements where the interplay between natural resources, built heritage, and evolving urban patterns produces highly specific and dynamic spatial configurations. Addressing this gap requires not only technological integration, but the development of a coherent conceptual and methodological framework relevant for aligning heritage-based analytical logics, such as HUL, with the architecture and functioning of UDPs.

1.2. Research Challenges

Despite the rapid development of UDPs and their increasing application in heritage-related domains, the literature reveals a set of persistent conceptual and operational challenges that limit their effectiveness in heritage-sensitive urban contexts. These challenges are not merely technical but emerge at the intersection of disciplinary knowledge and normative planning frameworks. In particular, three interrelated issues can be identified: (1) the domain-agnostic limitation of UDPs, (2) the operational gap between the HUL framework and digital systems, and (3) the difficulty of translating complex urban morphological knowledge into platform-readable structures. Together, these challenges point to a fundamental lack of alignment between how cities are conceptualised in heritage and urban morphology research and how they are represented within contemporary digital infrastructures.

The first challenge concerns the domain-agnostic limitation of UDPs, which are typically designed as horizontal, cross-domain infrastructures intended to integrate heterogeneous urban datasets. While this generic design enables interoperability across sectors, it often results in the loss of domain-specific semantics and disciplinary meaning [33–35]. As noted in both the theoretical and technical literature [36,37] generic platform architectures tend to reduce complex urban phenomena to abstract data structures, producing either overly simplified representations or fragmented domain-specific silos that fail to interoperate. This tension is particularly evident in the context of heritage, where studies consistently demonstrate that generic smart-city platforms lack the semantic depth required to represent cultural values and context-specific attributes of built heritage [11,22]. As a result, heritage-related data is often either marginalised within broader urban data ecosystems or requires the development of specialised extensions (such as HBIM–GIS integrations [38] or semantic extension of the CityGML model [39] to compensate for the limitations of domain-neutral infrastructures.

The second challenge relates to the operational gap between the HUL framework and digital platforms, which manifests itself as a mismatch between the normative logic of the HUL approach and its practical digital implementation. The HUL approach, as defined by UNESCO [40], provides a comprehensive, value-based framework for understanding urban heritage as a layered and dynamic system integrating cultural, social, environmental, and economic dimensions [41]. However, a substantial body of literature [31,42] demonstrates that this framework remains predominantly conceptual, with limited translation into operational tools, methodologies, or digital systems. Empirical and policy-oriented insights [43] further confirm that many cities lack the institutional capacity, data structures, and digital infrastructures required to implement HUL in practice, particularly in terms of integrated inventories and multi-scalar analysis. Attempts to bridge this gap through digital technologies have shown promising results but remain fragmented and often disconnected from the holistic logic of HUL [44,45].

The third challenge addresses the limited platform-legibility of urban morphological knowledge, which remains difficult to formalise within contemporary data infrastructures. Urban morphology, particularly within Conzenian and typo-morphological traditions, operates through complex, multi-scalar concepts such as plot patterns, building fabric, spatial

configurations, and morphological regions [46,47]. These concepts are inherently relational, historically layered, and often qualitative, making them resistant to direct translation into standardized datasets [48]. Although recent advances in CityGML-based semantic modelling, HBIM–GIS integration, and data-driven morphometrics have begun to address this issue by introducing structured descriptors and computable representations of urban form [49–51], the literature indicates that these approaches remain partial and fragmented. In particular, they tend to focus on specific aspects of urban form, such as geometry, typology, or spatial metrics, without the integrative logic of morphological analysis as a knowledge system [52]. As a result, morphological knowledge is only partially incorporated into UDPs, limiting their capacity to support heritage-sensitive analysis.

Taken together, these three challenges reveal a fundamental misalignment between domain-specific knowledge, normative heritage frameworks, and the structure of UDPs. Addressing this misalignment requires moving beyond isolated technological solutions toward an integrated approach having a potential to translate complex heritage and morphological logics into coherent digital infrastructures. In response to this need, the present paper proposes a knowledge-translation framework for heritage-sensitive UDPs, structured as a systematic translation mechanism between knowledge systems, user needs, and platform architectures.

1.3. Paper Outline: Research Aim and Questions

Against this background, the study develops and examines a heritage-sensitive UDP blueprint as a methodological interface between the HUL framework, domain-specific heritage knowledge, and digital platform architecture. The research is conceived as a conceptual–methodological and design-oriented study. Its primary concern is not the technical performance of a finalized software product, but the process through which heritage knowledge can be identified, structured, translated, and made operational within a digital environment. The study therefore combines conceptual synthesis, empirical and typomorphological investigation, digital knowledge modelling, and implementation-oriented crosswalk analysis within a single research framework.

The central object of investigation is the SPATTERN digital platform and its underlying blueprint. Its development is situated within the SPATTERN research project and uses the network of Serbian spa settlements as an observatory case through which the proposed knowledge-transfer logic is developed and examined. The study builds upon three previously developed project outcomes: (1) the SPATTERN Compendium [53], which establishes the contextual and historical knowledge base; (2) the SPATTERN Decoder [54], which develops the typomorphological framework of spatial patterns and archetypes; (3) and the SPATTERN Digital Platform Blueprint [55], which translates these analytical structures into a proposed digital environment. Rather than reproducing these outcomes, the present paper brings them into a unified methodological framework and examines their correspondence with the HUL implementation logic, thereby identifying the conceptual, informational, and functional conditions through which heritage knowledge can inform the design of heritage-sensitive UDPs. Spa settlements are particularly suitable for this purpose because their spatial development is shaped by interdependent natural, cultural, morphological, functional, and historical processes. The project corpus of 38 settlements provides a sufficiently diverse comparative field in which these relationships can be observed across different spatial configurations and development trajectories, while the detailed study of 12 role model settlements provides the analytical basis for pattern and archetype extraction. Within the scope of this paper, the spa settlement context therefore serves as the empirical environment for constructing and testing the methodological logic of the platform, while the principal research focus remains the translation of HUL-oriented heritage knowledge into a

structured digital infrastructure. The detailed characteristics of the SPATTERN research context and empirical corpus are presented in Section 3.1.

Accordingly, the overarching aim of the study is to establish and critically examine a reproducible methodological pathway through which the implementation logic of the HUL framework can be translated into the conceptual, informational, and functional organization of a heritage-sensitive UDP. This aim is addressed through three research questions:

- RQ1—Question addressing analytical requirements: Which analytical tools and dimensions are required to translate the objectives of the HUL implementation framework into explicit digital knowledge requirements for a heritage-sensitive UDP?
- RQ2—Question addressing heritage knowledge architecture: How can heterogeneous heritage knowledge derived from morphological, spatial, environmental, socio-cultural, and user-oriented analyses be structured into an integrated and platform-compatible digital knowledge system?
- RQ3—Question addressing HUL–UDP correspondence: To what extent, and at which conceptual, informational, and functional levels, does the SPATTERN platform blueprint correspond to the implementation logic and digital knowledge requirements of the HUL framework?

The paper is organized accordingly. Section 2 establishes the conceptual framework by interpreting HUL as a digital knowledge system (Section 2.1) and deriving digital knowledge requirements from its six implementation steps (Section 2.2). Section 3 presents the methodological framework: (1) the analytical foundation of the SPATTERN blueprint and its spa-settlement observatory context; (2) the digital structuring and platform-modelling procedure; and (3) the operational schema crosswalk used to examine HUL–SPATTERN correspondence. Section 4 presents the resulting platform blueprint through the six HUL implementation steps (each sub-section corresponding to one step, Sections 4.1–4.6), demonstrating how the structured knowledge is operationalized through specific platform components and interfaces. Section 5 discusses the operational alignment between the HUL framework and the SPATTERN blueprint and examines the correspondence at conceptual, informational, and functional levels (Section 5.1), synthesizes the methodological contribution and implications for heritage-sensitive UDPs (Section 5.2), and presents the limitations of the study and directions for future development (Section 5.3). The paper concludes in Section 6 by outlining the main findings and prospective directions for further development.

2. Conceptual Framework: Translating the HUL Framework into Digital Logic

To address the gap identified in the preceding section, this section establishes the conceptual foundation for translating the HUL framework into digital logic. The previous discussion established that the principal challenge of contemporary digital heritage research lies not in the availability of digital technologies, but in the absence of a coherent framework for translating the epistemological structure of the HUL approach into digital knowledge systems. Building upon this premise, this section develops the conceptual foundation that underpins the methodological framework of the study.

2.1. HUL as Digital Knowledge System

Recent research demonstrates a clear shift in the way the HUL approach is interpreted within digital heritage studies. Instead of focusing exclusively on the digitization of individual heritage assets, contemporary research increasingly explores how the multiple layers of urban heritage (its spatial structure, historical evolution, social values, environmental characteristics, and everyday practices) can be represented within integrated digital envi-

ronments. The first generation of digital HUL studies primarily concentrated on the spatial representation of urban landscapes through geospatial technologies. Using GIS-based visualization, Cassatella and Carlone [56] demonstrated that layered spatial information can support heritage-sensitive planning by making the relationships between urban morphology, historical evolution, and landscape structure analytically visible. Similar principles were further operationalized by Widodo, Wong, and Ismail [57], who proposed a Digital Historic Urban Landscape methodology integrating GIS-based spatial analysis into heritage impact assessment. Likewise, Wang et al. [58] combined historical cartography, aerial image modelling, and space syntax analysis to reconstruct the long-term spatial evolution, showing how historical morphology can be translated into an integrated digital information environment. More recently, Bai et al. [59] extended this approach through Historical GIS, emphasizing the database itself as a mechanism for preserving and interpreting long-term landscape transformations, while Ramírez Eudave and Ferreira [60] demonstrated how remote sensing and multi-scale GIS analysis support the characterization and monitoring of HUL across different spatial resolutions.

Although these studies significantly advanced the digital representation of HUL, they primarily conceptualize heritage as a spatially structured dataset. Subsequent research broadened this perspective by arguing that HUL cannot be adequately understood through physical morphology alone. Zhao, Marnane, and Greenop [61] demonstrated that laser scanning, photogrammetry, video, and audio recording enable the documentation of both tangible and intangible heritage attributes, allowing social practices and cultural meanings to become part of the digital record. Similarly, Van der Hoeven [62] and Ginzarly, Roders, and Teller [63] showed that social media narratives and user-generated metadata reveal place values and everyday heritage practices that remain largely absent from conventional heritage inventories. By treating digital traces as indicators of collective perception rather than merely communication artifacts, these studies expanded the informational scope of HUL beyond expert-defined datasets. This participatory perspective has subsequently evolved toward digitally mediated heritage governance. Van der Hoeven [64] demonstrated that participatory heritage platforms function not only as repositories of collective memory but also as environments through which citizens actively define heritage significance. Albuquerque, Botelho, and Crozat [65] further emphasized digital storytelling as a mechanism for articulating locally embedded heritage narratives, while Zhou, Tang, and Su [66] incorporated digital footprints into heritage corridor planning, enabling public preferences and patterns of spatial use to become explicit planning inputs. Collectively, these studies reposition digital technologies from instruments of documentation toward infrastructures relevant for framing relationships between places, communities, and values.

The progressive expansion from spatial documentation to participatory knowledge generation indicates an important conceptual shift within digital heritage research. The primary object of digitalization is no longer the historic urban fabric itself, but the heterogeneous system of relationships (spatial, cultural, environmental, and social) that defines the HUL. Nevertheless, existing research remains largely organized around individual technologies or specific application domains including GIS, photogrammetry, HBIM, remote sensing, social media analytics, and digital storytelling, each contributing valuable yet largely isolated representations of heritage knowledge. Systematic review by Aliakbari and Dinler [67] similarly observe that digital heritage research has become increasingly diversified, while remaining fragmented across technological approaches and disciplinary perspectives. From the perspective of HUL implementation, this fragmentation represents a fundamental methodological limitation. Individual digital tools effectively document particular dimensions of the landscape, yet they rarely establish a coherent knowledge structure. Even recent attempts to strengthen systemic thinking within HUL implementa-

tion [45,68] emphasize integrated heritage systems and operational planning logics without explicitly addressing how these heterogeneous knowledge domains should be structured within a digital platform. Consequently, the central challenge is no longer how to digitize heritage resources, but how to translate the epistemological structure of the HUL into an interoperable digital knowledge system.

2.2. Operational Translation of the Six HUL Implementation Steps

Understanding the HUL as a digital knowledge system shifts the focus from individual technologies toward the underlying logic through which heritage knowledge is organized, interpreted, and operationalized. Rather than asking which digital tools can support HUL, the central inquiry shifts to what kinds of digital capabilities are required to implement the six-step process set out in the 2011 UNESCO Recommendation on the Historic Urban Landscape and elaborated in the HUL Guidebook [69]. Each implementation step implies a distinct set of both informational and organizational requirements that must be addressed before they can be translated into platform functionalities. From this perspective, the six HUL implementation steps can be interpreted as a sequence of progressively expanding knowledge requirements. The initial stages emphasize the identification and documentation of heritage resources through the integration of spatial, historical, environmental, and socio-cultural information. Subsequent stages introduce participatory processes for establishing shared understandings of heritage values, followed by the assessment of vulnerability to socio-economic, environmental, and development pressures. The later stages extend these requirements toward the integration of heritage considerations into wider urban development frameworks, the prioritization of conservation and development actions, and the establishment of partnerships and local management mechanisms relevant for coordinating implementation. Within a digital environment, monitoring remains relevant as a cross-cutting capacity supporting several of these stages, but is not treated here as a separate HUL implementation step.

Existing research demonstrates that these requirements are addressed through a wide spectrum of digital heritage approaches. Geospatial technologies, historical GIS, remote sensing, photogrammetry, and three-dimensional documentation have substantially improved the representation of spatial and temporal heritage layers [56,58,59,70], while participatory platforms, social media analytics, digital storytelling, and digital ethnography have expanded the capacity to capture community values, everyday practices, and collective perceptions [42,64,65]. Other studies have explored integrated workflows for heritage impact assessment, GIS–HBIM integration, online heritage information systems, and planning support environments [57,60], illustrating the growing diversity of digital responses to individual HUL objectives. Despite these advances, the literature remains predominantly organized around technological approaches rather than around the implementation logic of the HUL framework itself. As a consequence, it remains difficult to understand how different digital methods collectively contribute to the realization of the six implementation steps. The relationship between normative objectives and digital implementation therefore remains largely implicit, with individual technologies addressing specific aspects of HUL without establishing a common conceptual structure for their integration.

To make this relationship explicit, Table 1 reorganizes the existing body of knowledge according to the implementation sequence of the HUL Recommendation, as elaborated in the HUL Guidebook [69]. Instead of classifying digital technologies by discipline or methodological family, the table synthesizes the reviewed literature through the operational logic of the six HUL implementation steps. For each step, it identifies the corresponding digital knowledge requirement and illustrates it through representative digital approaches reported in the literature. The selected approaches are not intended to provide a systematic

review of available technologies, but rather to demonstrate the principal methodological directions through which individual HUL implementation requirements have been addressed in contemporary digital heritage research. Their selection was guided by three complementary criteria: (1) conceptual relevance to each HUL implementation step, (2) demonstrated applicability to the corresponding digital knowledge requirement, and (3) methodological diversity, reflecting distinct modes of digital knowledge organization and operationalization. In this way, the table establishes a conceptual framework that connects the normative structure of the HUL steps with the digital capabilities required for its implementation, independently of any specific technological solution or platform architecture.

This synthesis establishes the conceptual basis for the methodological framework developed in the following section. Rather than proposing additional digital tools, the present research builds upon these identified knowledge requirements to develop a structured translation process through which the implementation logic of the HUL Recommendation can be systematically operationalized within a UDPs environment.

Table 1. Digital Knowledge Requirements Derived from the Six HUL Implementation Steps. The HUL implementation steps and objectives are synthesized from UNESCO World Heritage Centre [40,71], WHITRAP [69], and Rey-Pérez and Pereira Roders [31]. The digital knowledge requirements are conceptually formulated based on the operational interpretation of digital HUL [45,72]. Representative digital approaches illustrate characteristic methodological directions identified in the literature that address each knowledge requirement (they are included as illustrative examples rather than as an exhaustive review of available digital methods).

HUL Step	HUL Objective	Digital Knowledge Requirement	Representative Examples of Digital Approaches in the Literature
Step 1. Mapping resources	Identify, document and understand natural, cultural, tangible and intangible heritage attributes as interconnected urban layers	Multi-layer documentation, spatial integration, historical reconstruction and semantic organization of heterogeneous heritage information	• Remote sensing for landscape characterization [60] • 3D laser scanning, photogrammetry, digital photography and audio recording for documenting tangible and intangible heritage values [61] • urban heritage information systems and historical GIS databases (GIS and HGIS) for integrated knowledge organization [58,59] • BIM–GIS integration for 3D heritage documentation [44]
Step 2. Reaching consensus	Establish shared understanding of heritage values and attributes through participatory planning and stakeholder consultation	Shared, spatially referenced knowledge environments that integrate diverse stakeholder perspectives and provide an informational basis for participatory consultation and subsequent consensus-building processes	• Participatory heritage websites [64] • Social media analysis for value mapping [42] • Digital storytelling and digital ethnography [65] • Cultural mapping and public participation platforms [73] • Educational digital strategies [74] • Crowdsourced urban memory mapping and community engagement platforms [72]

Table 1. *Cont.*

HUL Step	HUL Objective	Digital Knowledge Requirement	Representative Examples of Digital Approaches in the Literature
Step 3. Assessing vulnerability	Assess the vulnerability of heritage attributes to socio-economic pressures, environmental change and development impacts	Multi-criteria vulnerability, risk and impact assessment integrating spatial, environmental, heritage and socio-economic information	• GIS–BIM–HBIM integration [70] or multidimensional GIS framework for vulnerability assessment [75] and categorization [76] • GIS-based risk-mapping and vulnerability-ranking tool [77] • GIS-based digital twin for climate risk [78] • Heritage impact assessment platforms [57] • Space syntax for spatial configuration analysis [58]
Step 4. Integrating into urban development	Integrate heritage values and vulnerability considerations into the wider urban development framework	Interoperable information infrastructures capable of connecting heritage knowledge with planning workflows and decision-support systems	• BIM-GIS web platform for planned maintenance [50] • GIS-supported digital twin for urban silhouette/zoning compliance [79] • Digital twins at city/town scale [80] • Digital conservation handbooks and guidance systems [81] • Smart heritage governance tools supporting evidence-based planning [82]
Step 5. Prioritizing actions	Define conservation priorities and identify appropriate development strategies	Decision-support environments integrating comparative analysis, scenario evaluation and multi-criteria assessment	• Heritage impact assessment platforms [57] • WebGIS + multi-criteria decision analysis [83] • GIS 3D spatial decision-support system with solution catalog [84] • AI-driven decision-support system for heritage-sensitive regeneration [85] • Digital twins for scenario testing [72] • Heritage data visualization supporting comparative interpretation [86]
Step 6. Establishing partnerships and local management frameworks	Establish appropriate partnerships, local management frameworks and coordination mechanisms among public and private actors	Stakeholder and institutional mapping, role-based access and interaction, collaborative workflows, information exchange and coordination mechanisms	• Participatory and contributory heritage inventory [57] • Partnership directory [87] • A visual dashboard tracking implementation of conservation, regeneration, risk-management, public-engagement, and monitoring measures [88] • Georeferenced reporting of deterioration, unauthorized construction, accessibility problems, visual intrusions, environmental risks, or maintenance needs, with institutional response status [87]

3. Materials and Methods

The methodological framework of this study was designed as a sequential knowledge translation process aimed at operationalizing the HUL framework within the conceptual

architecture of a heritage-sensitive UDP. Rather than developing the platform through conventional software engineering procedures, the research adopts a knowledge-driven methodology in which analytical findings generated through urban morphological research are progressively transformed into platform logic. Accordingly, the methodology does not focus on the development of individual technological solutions, but on establishing a transparent and reproducible process for translating heritage knowledge into an interoperable digital framework.

The methodological procedure is organized into three consecutive stages. The first stage (Section 3.1) establishes the analytical foundation of the research by presenting the empirical scope of the SPATTERN project together with the methodological, empirical, and typomorphological investigations that constitute the knowledge base for subsequent platform development. The second stage (Section 3.2) describes the process of digital structuring and platform modelling, explaining how the analytical outputs are systematically translated into analytical dimensions, typological relationships, user requirements, data architecture, and system logic. Finally, the third stage (Section 3.3) introduces the HUL alignment procedure, in which a schema crosswalk analysis is employed to evaluate the conceptual and operational correspondence between the implementation logic of the UNESCO HUL Recommendation and the components of the proposed SPATTERN digital platform. Together, these three stages define the methodological pathway through which the proposed platform is conceptually developed.

3.1. Analytical Foundation of the Blueprint

The development of the proposed knowledge-translation framework is grounded in a structured analytical foundation established within the SPATTERN research framework. This foundation integrates methodological, empirical, and typological components developed across multiple research phases, forming a coherent basis for the subsequent digital structuring and platform modeling. This analytical foundation serves as a prerequisite for translating heritage-sensitive and morphologically grounded knowledge into structured, platform-compatible formats.

3.1.1. SPATTERN Project Context and Scope

The SPATTERN project (Future Heritage of Spa Settlements: Digital Platform for Advancing Knowledge and Innovation in Urban Morphology Approach for Environmentally Sensitive Development in Serbia) is a research initiative focused on the analysis, classification, and interpretation of urban patterns in spa settlements, with the overarching aim of developing a digital platform for the analysis, comparison, and visualization of urban patterns in heritage-sensitive environments [89].

Spa settlements provide a particularly relevant knowledge space for developing and testing a heritage-sensitive urban data framework because their spatial identity is generated through the long-term interaction of natural resources, built form, landscape structures, therapeutic practices, and socio-cultural life [53]. Rather than constituting conventional urban settlements in which heritage assets can be treated as discrete objects, spa settlements have evolved around naturally occurring mineral and thermal resources that act as generative elements of urbanization, shaping settlement location, spatial organization, architectural typologies, public-space systems, infrastructure, and patterns of everyday use. From this perspective, they can be understood as integrated geo-cultural heritage systems, in which geoheritage and hydrothermal resources cannot be separated analytically from the cultural landscapes and urban morphologies that have developed around them. This relational condition underpins the concept of spascapes introduced in [90] as an analytical framework for interpreting spa settlements as dynamic socio-spatial formations

shaped by the interplay of natural resources, urban form, institutional structures, and socio-cultural practices.

The heritage significance of this relationship is also recognized internationally through the UNESCO World Heritage property The Great Spa Towns of Europe [91], comprising eleven spa towns in seven countries. UNESCO [91] identifies natural mineral springs as the catalyst for a distinctive model of spatial organization in which therapeutic facilities, spa architecture, public spaces, recreational landscapes, infrastructure, and social functions developed as an interconnected urban ensemble. This international framework demonstrates that the heritage value of spa towns resides not only in individual monuments or natural resources, but in the systemic relationship between resource, landscape, morphology, architecture, infrastructure, and cultural practice. Against this background, the Serbian spa network offers [53,54] a particularly productive observatory framework: its diversity of geographical settings, natural-resource conditions, morphological structures, historical trajectories, and contemporary development pressures enables these relationships to be examined comparatively across multiple scales. As established in previous SPATTERN research, the Serbian context is therefore approached not as an isolated geographical case, but as a structured testing ground in which local specificities become generative inputs for developing and evaluating transferable analytical models.

The project is implemented over a three-year period and is structured as an integrated research and development process in which analytical investigations and platform design evolve in parallel. The project is based on a comparative framework of 38 spa settlements in Serbia, which constitute the primary empirical corpus for analysis. Within this framework, a subset of 12 role model settlements is selected to represent a diverse range of spatial configurations, developmental trajectories, and relationships between natural and built systems. These cases are not treated as exemplary models in a normative sense, but as analytical drivers that enable the identification and extraction of key urban patterns. The remaining 26 settlements are defined as replicators, serving as a broader comparative base for testing, validating, and contextualizing the identified patterns across different spatial and institutional conditions. The central objective of the SPATTERN project is to establish a pattern-based approach to understanding spa settlements, in which urban form, heritage values, and environmental systems are analysed as interrelated components of complex spatial structures. The research is organized through four interrelated work packages (WPs), which collectively support both the analytical and developmental dimensions of the project. These include:

- WP1: the development of a methodological and data foundation, encompassing (1) a review of relevant digital approaches [92], (2) the construction of a structured database of 38 spa settlements [93], and (3) an expert-based questionnaire aimed at identifying key analytical needs and user perspectives [94];
- WP2: the implementation of contextual and typological analyses, including the (1) comparative study of role model settlements (Compendium of spascapes) [53] and the development of a rulebook for pattern definition (Decoder of spascapes) [54];
- WP3: the development of an atlas of all 38 spa settlements, providing a multi-scalar visualization framework that synthesizes and spatially articulates the analytical findings;
- WP4: the design and development of the digital platform, formalized through a georeferenced database and a system architecture that integrates data, analytical modules, and user interaction logic.

A key methodological characteristic of the project is the use of parallel research frameworks, within which analytical research, data structuring, and platform development are continuously aligned (Figure 1). These frameworks ensure that the platform is not de-

veloped as a standalone technical system, but as a direct extension of the analytical logic generated through the study of urban patterns. In this sense, the SPATTERN project establishes a coherent research environment in which pattern-based urban analysis and digital platform design are intrinsically linked, providing the foundation for the development of a heritage-sensitive UDP presented in this study.

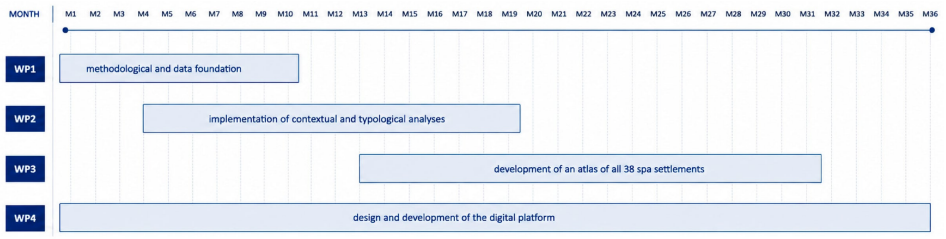


Figure 1. Methodological organization of the SPATTERN project and interrelations between work packages (WPs). Source: Authors.

3.1.2. Analytical Basis: Methodological Review, Settlement Database, and Expert Questionnaire

The analytical basis of the SPATTERN project was established through three complementary research components: (1) a structured review of digital approaches, (2) the construction of a comparative database of spa settlements, and (3) an expert-based questionnaire survey.

The first component consisted of a review of methodological approaches, conceived as a structured analytical survey of concepts and tools relevant to the study of urban patterns and their possible digital translation. This review was based on a previously conducted systematic literature review [30], from which 30 distinct features, terms, and methodological notions were identified and selected as the basis for further examination. For each of these 30 terms, a structured factsheet was developed, following a unified format that enabled their systematic comparison. Each factsheet included (Figure 2) (1) a definition of the term, (2) related concepts, (3) relevant scales of application, (4) practical implications, and (5) identified limitations or risks, thereby allowing the review to function not merely as a glossary, but as an analytical instrument for evaluating the applicability of different methodological concepts to the SPATTERN research framework.



Figure 2. Layout of factsheet for structured analytical survey of concepts and tools relevant to the study of urban patterns and their possible digital translation. Source: Authors.

The second component was the development of a comparative database of spa settlements in Serbia, covering all 38 settlements included in the project. The purpose of this database was to establish a structured empirical basis for comparative analysis and to assess the availability and validity of relevant data for further research. Data collection and systematization were organized around five categories of sources: (1) planning framework, (2) strategic framework, (3) previous studies, (4) archival material, including historical maps and postcards, and (5) photo database collected during field surveys. For each settlement, these five data categories were reviewed and evaluated in terms of their availability, content relevance, and usability for subsequent analytical phases. The database was therefore not conceived simply as a repository of collected materials, but as an evaluative instrument that identified both the research potential and the data gaps across the full corpus of spa settlements (Figure 3). In this way, it established the empirical groundwork for distinguishing between settlements with richer analytical potential and those requiring more adaptive or limited forms of investigation.

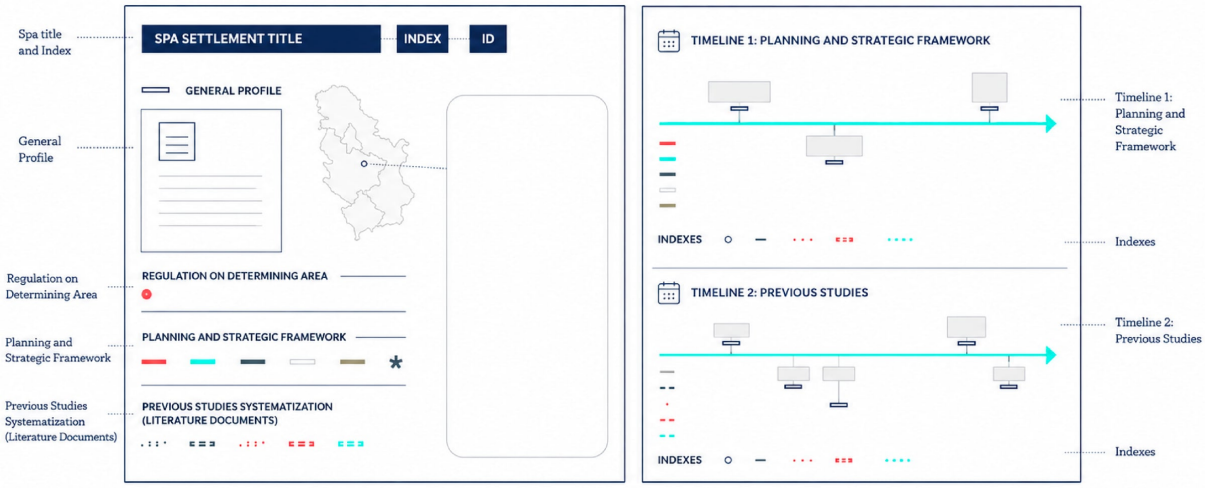


Figure 3. Layout of factsheet for a settlement profile (completed for all 38 settlements included in the project). Source: Authors.

The third component was a structured questionnaire addressed to experts and stakeholders (hereafter the expert questionnaire), designed to collect insights from relevant stakeholders and to introduce an applied and user-oriented dimension into the analytical framework. The questionnaire was addressed to the 38 spa settlements of the initial sample and was conceived to gather responses from eight respondent groups (including representatives of local self-government, urban planning and architecture, resource and heritage management, tourism organizations, the health sector, the academic sector, students of architecture and urbanism (included as the future professional and academic community), and other stakeholders such as local associations, NGOs, and the hotel industry), with a target of at least three respondents per settlement. In total, the survey yielded 141 valid responses (Figure 4), providing a substantial body of qualitative and semi-structured input regarding development conditions, planning practices, and digital readiness in spa settlements. The results also indicated the availability of data for individual settlements. For Bečej, which was part of the initial sample and is therefore shown in Figure 4, insufficient data were available for the analysis and operationalization of the case, and unresolved property-law issues and the cessation of water use further limited its inclusion. Bečej was therefore replaced by Jodna Banja—Novi Sad, an iodine spa with comparable characteristics, which keeps the corpus at 38 settlements.

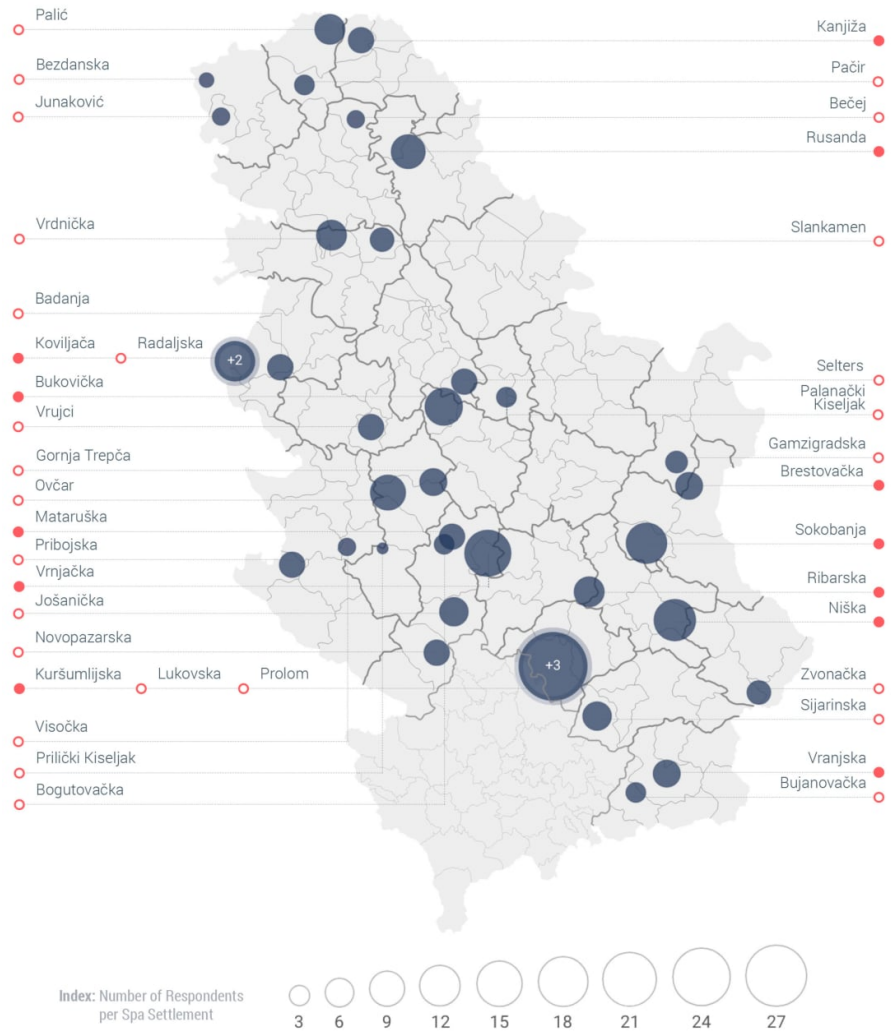


Figure 4. Spatial distribution and number of questionnaire respondents across the 38 spa settlements. The term "banja" is Serbian for "spa" and is retained as an integral part of the original settlement names. Source: Authors.

The study was organized into five key sections, reflecting the internal logic of the questionnaire: (1) Respondent Background, (2) Functions and Decision-Making, (3) Development Capacities, (4) Planning and Strategic Framework, and (5) Digital Technologies and Planning. This structure made it possible to capture not only institutional and professional profiles of respondents, but also their perspectives on spatial development, governance capacities, planning constraints, and the role of digital tools. Methodologically, the questionnaire was particularly important because it introduced stakeholder knowledge into the project at an early stage, enabling the identification of practical priorities, perceived limitations, and prospective directions for platform use.

Taken together, these three components formed the initial analytical basis of the SPATTERN project. The methodological review established the conceptual vocabulary and identified potentially relevant approaches, the comparative database provided a structured and evaluative empirical foundation across the 38 settlements, and the expert questionnaire introduced a stakeholder-based perspective on planning conditions, development needs, and digital capacities.

3.1.3. Typomorphological Study of Urban Patterns in Spa Settlements

Building upon the established analytical basis, the SPATTERN project advances toward a typomorphological interpretation of spa settlements through two complementary compo-

nents: (1) a contextual and comparative analysis of role model settlements (Compendium of spascapes [53]), and (2) the development of a rulebook for pattern definition (Decoder of spascapes [54]).

The first component is structured as a comparative contextual study of 12 role model settlements followed a purposive, diversity-oriented sampling strategy rather than a statistically representative approach. The selection sought to capture contrasting geographical settings, historical development trajectories, settlement morphologies, functional profiles, and relationships between built structures and natural resources. These settlements served as detailed analytical cases for identifying recurring spatial patterns and archetypes, which subsequently informed the comparative interpretation of the broader corpus of 38 spa settlements.

The analysis is conducted through a multi-dimensional framework of urbanization [95], defined across three interrelated dimensions: (1) material transformation (including historical trajectories of spa urbanism and naturescape of urbanization processes), (2) territorial regulation (including the transformation of public spaces and the programming of the spascape), and (3) everyday life (including everyday use patterns and the therapeutic dimension of spa environments). The contextual analysis is conducted through a multi-scalar and comparative approach, integrating spatial, historical, and functional data for each case. Each settlement is systematically examined across all three dimensions and their corresponding thematic strands, enabling both in-depth case-based interpretation and cross-case comparison. The comprehensive analytical protocol of comparative analysis is published separately [90], while general structure of analysis is presented in Figure 5.

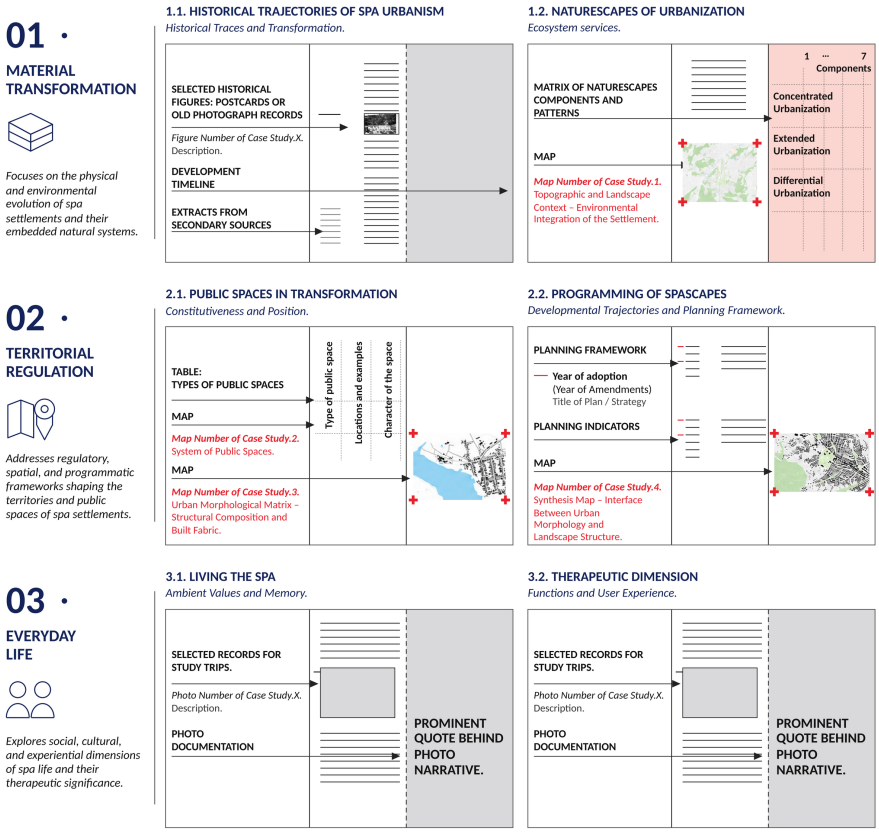


Figure 5. The structure of contextual analysis defined across three interrelated dimensions and six topics. Source: Authors.

The second component, the rulebook for pattern definition, builds directly upon the insights generated through the contextual study. While the comparative analysis provides a

rich interpretative understanding of individual cases, the Decoder introduces a formalized system for identifying and classifying urban patterns and archetypes (Figure 6). The development of the Decoder is based on a process of pattern extraction and abstraction, in which recurring spatial configurations, functional relationships, and heritage-related characteristics are identified across the analyzed cases. These recurring elements are then synthesized into a set of archetypes, representing generalized types of spatial elements (such as spring pavilions, promenades or spa villas) that capture the essential structural and functional logic of spa settlements. Urban patterns, in turn, describe recurrent spatial configurations at the settlement scale, which are composed of such elements. Each archetype is defined through a combination of morphological, functional, and contextual attributes, allowing it to serve as a transferable analytical unit. In this sense, archetypes do not represent fixed typologies, but rather flexible analytical pattern constructs that can be identified, compared, and interpreted across different settlements. By formalizing morphological knowledge into a system of identifiable and comparable units, it provides a critical step toward increasing the translatability of complex spatial structures, enabling their subsequent integration into data-driven and platform-based environments.



Figure 6. Layout of factsheet for an archetype specification (**left**), and for a pattern specification (**right**). Source: Authors.

Building upon these two components, a third step was introduced in order to consolidate the analytical findings into a structured and scalable typological framework. Specifically, the insights derived from the contextual study and the pattern-based decoding process were synthesized through the development of a preliminary categorization of spa settlements, encompassing the full set of 38 cases within the SPATTERN empirical scope. The objective of this categorization was to establish a typological matrix capable of reflecting the diversity and complexity of urban morphology across spa settlements, while simultaneously ensuring compatibility with the requirements of digital structuring. The categorization was developed based on a set of general criteria, including location setting, historical significance, dominant function, transport connectivity, spatial boundaries, prevailing form, settlement size, and landscape embedding. These criteria were selected for their dual relevance—on the one hand, they capture the structural logic and spatial identity of spa settlements; on the other, they correspond to parameters that can be translated into data categories suitable for digital representation. The criteria were applied through a comparative qualitative assessment of all 38 settlements, drawing on the contextual and typomorphological findings established in the preceding analytical stages. Rather than employing numerical scoring or fixed thresholds, the classification involved interpreting the combined characteristics of each settlement to identify its dominant spatial, morphological, and functional profile. This approach allowed the categorization to reflect the interrelated nature of the criteria,

recognizing that individual settlements may share characteristics across different conceptual groups. The resulting matrix provides a conceptual framework that differentiates spa settlements according to their spatial configuration, functional role, and environmental context. In this sense, the categorization operates not only as an analytical tool, but also as a data-oriented structuring mechanism, bridging morphological interpretation and digital integration. Based on the established criteria, all 38 spa settlements were classified into ten conceptual groups (Figure 7), each representing a distinct morphological and functional profile. This classification constitutes the final step of the analytical consolidation phase and provides the necessary framework for the subsequent translation of typologies into analytical dimensions and platform logic, as elaborated in Section 3.2.

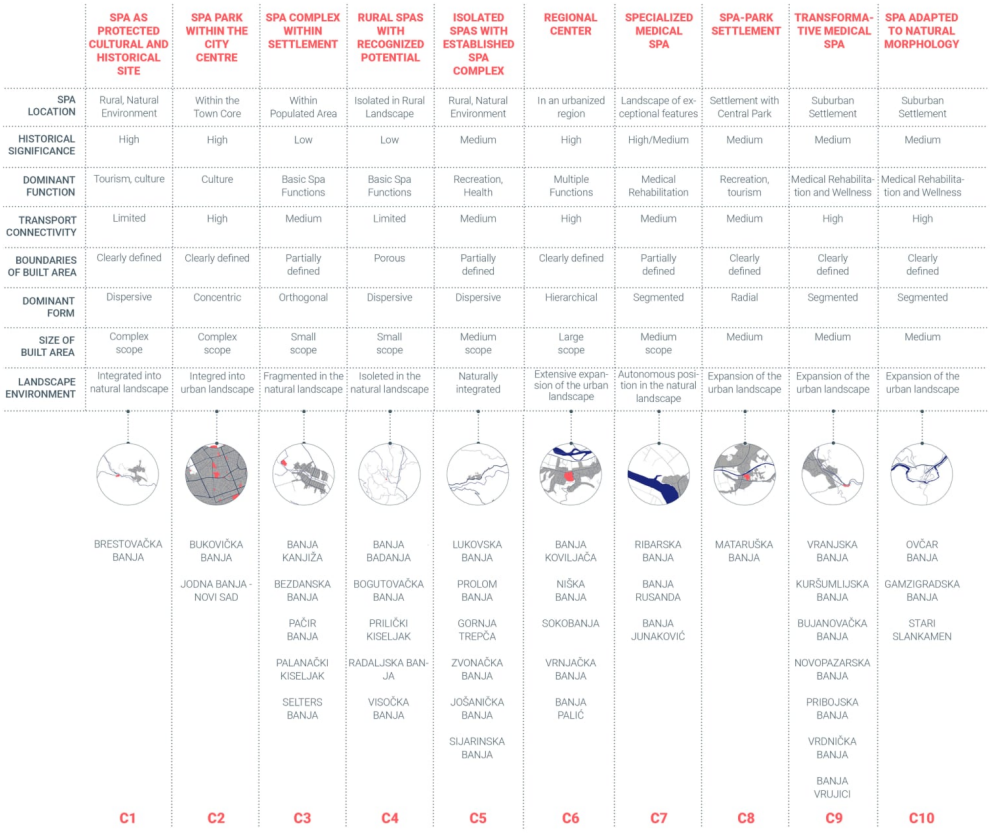


Figure 7. Matrix of settlement classification. Source: Authors.

3.1.4. Expert Workshop

To strengthen the methodological robustness of the proposed blueprint, an expert workshop was conducted after the completion of the knowledge structuring phase and prior to the full operationalization of the platform model. The workshop brought together 22 experts from 10 spa settlements in Serbia, representing urban planning and development units on local level. The workshop was designed as a structured consultation exercise aimed at assessing the practical relevance of the proposed analytical framework and was organized as an interactive expert session combining a presentation of the research framework, moderated discussion, and structured real-time feedback. Participants were first introduced to the typomorphological blueprint developed through the previous research phases, including the identified urban patterns and archetypes, the six analytical dimensions in their preliminary form, and the relational approach to spa settlements. These dimensions were subsequently formalised and mapped to the thematic strands of the contextual analysis during digital structuring (Section 3.2.1). The consultation process was then carried out using a structured questionnaire administered through the Mentimeter online presentation

tool, allowing participants to submit anonymous responses and immediately visualize collective results during the discussion. The questionnaire was organized into three consecutive phases: (1) Relational Recognition (identification of spatial relations and dominant urban patterns), (2) Planning Translation (transfer of analytical findings into planning priorities and intervention needs), and (3) Scenario Orientation (development scenarios for future transformation of spa settlements). To provide a transparent and systematic account of the workshop findings, Appendix A presents a consolidated analysis of the Mentimeter responses across these three phases (Table A1), together with a synthesis of expert feedback and its methodological and functional implications for the SPATTERN digital blueprint (Table A2). The appendix distinguishes between the empirical findings, their analytical interpretation, and their relevance to the subsequent digital structuring process. The responses collected in the second phase (planning translation) additionally served as input for formulating planning guidance associated with the identified urban patterns. Participation varied by item (see notes to Table A1); results are therefore reported as observed counts and should be read as indicative.

The workshop outcomes provided an expert-informed assessment of the practical applicability and planning relevance of the proposed analytical framework. As documented in Appendix A, the findings highlighted the relevance of examining spa settlements through interconnected spatial, functional, environmental, and institutional relationships, while identifying differences in their local configurations and planning conditions. The responses also revealed limited systematic recognition of these relationships in planning documents and emphasized the importance of integrated analytical approaches addressing natural resources, heritage, public spaces, and infrastructural constraints. These findings informed the subsequent development of the platform blueprint by reinforcing the relevance of differentiated analytical dimensions, relational spatial interpretation, and the integration of contextual and planning information within a unified digital knowledge structure. Rather than constituting comprehensive validation of the methodology or the operational performance of the platform, the workshop provided empirical support for the practical relevance of the analytical framework and informed its translation into the platform's informational and functional architecture. In this way, the workshop helped translate the analytical framework into a more coherent digital knowledge structure, while maintaining its methodological foundations.

3.2. Digital Structuring and Platform Modeling

Building on the preliminary analytical structure of knowledge, which was discussed at the expert workshop (Section 3.1.4), the next phase formalised and translated the consolidated blueprint into a platform-compatible knowledge model. This stage summarises the digital structuring procedure through which the SPATTERN digital platform blueprint [55] was developed, presented here in a form that makes its knowledge-translation logic explicit. Analytical insights are progressively transformed into a coherent data-driven and user-responsive system architecture. Methodologically, this process is conceived as a sequence of interrelated transformation steps, through which typological knowledge is translated into analytical dimensions, user logics, functional modules, and data structures.

3.2.1. Definition of Analytical Dimensions

The six dimensions were first formulated during knowledge structuring and tested at the expert workshop; this section presents their final definition and their mapping to the thematic strands (Table 2). The first step in the digital structuring process consisted of the definition of analytical dimensions, which establish the primary interpretative and organizational framework of the SPATTERN digital platform. This step translates the conceptual

structure of the contextual study, articulated through three dimensions of urbanization and six thematic strands, into a set of operational analytical dimensions suitable for digital processing. The analytical dimensions are conceived as intermediary constructs between morphological knowledge and data structures. While the contextual study captures the complexity of spa settlements through interpretative categories, the analytical dimensions reorganize this knowledge into a format that enables classification, comparison, and integration within a platform environment. In this sense, they function as a translation layer, bridging qualitative spatial interpretation and quantitative or structured data representation. Six analytical dimensions were defined: (1) Spatial Links with Natural Resources (SLNR), (2) Architectural Heritage and Cultural–Historical Monuments (AHCHM), (3) Specificities of Matrix and Organization (SMO), (4) Functional Hierarchy of Space (FHS), (5) Public Space System (PSS), and (6) Urban Tissue Character (UTC). Each dimension represents a distinct yet interrelated lens through which spa settlements are analyzed, framing key aspects of their spatial structure, functional organization, and heritage context. Importantly, the dimensions are not isolated categories, but are designed to operate as a multi-scalar and relational system, allowing different aspects of urban form and development to be examined both independently and in combination. Methodologically, the definition of analytical dimensions is grounded in a cross-referential mapping between the six SPATTERN thematic strands and the emerging platform logic. As illustrated in Table 2, each analytical dimension is associated with one or more thematic strands derived from the contextual study. This cross-matrix does not establish a one-to-one correspondence, but rather a network of relationships, in which each dimension captures specific aspects of multiple thematic domains. This mapping serves two key methodological purposes: (1) it ensures the conceptual continuity between the analytical phase and the digital structuring phase, preserving the interpretative depth of the initial research, and (2) it defines the structural logic of the platform, as analytical dimensions become the primary units through which data is organized.

Table 2. Cross-referential mapping between SPATTERN analytical dimensions and thematic strands of the contextual analysis.

	Material Transformation		**Territorial Regulation**		**Everyday life**	
Analytical Dimension	Historical Trajectories of Spa Urbanism	Naturescapes of Urbanization	Public Spaces in Transformation	Programming of Spascapes	Living the Spa	Therapeutic Dimension
SLNR		+		+		+
AHCHM	+		+		+	
SMO	+	+		+		
FHS				+	+	+
PSS	+	+	+	+	+	
UTC	+		+		+	

3.2.2. Typology–Dimension Integration and Analytical Scope

Following the definition of analytical dimensions as the primary structuring framework of the platform (Section 3.2.1), the next methodological step establishes the interrelation between typological categories and analytical dimensions, with the aim of operationalizing the diversity of spa settlements within a unified analytical system. This step builds directly upon the preliminary categorization of spa settlements (Section 3.1.3), translating typological distinctions into differentiated analytical and data requirements. To achieve this, a typology–dimension matrix was developed, mapping each of the ten spa categories (C1–C10) against the six analytical dimensions (SLNR, AHCHM, SMO, FHS, PSS, UTC). This matrix represents a structured evaluation of how each typological group engages with the analytical framework, not only in terms of presence or absence of specific dimensions,

but also in terms of their relative intensity and relevance. In methodological terms, this mapping introduces a graded model of analytical engagement, where typologies are no longer treated as discrete categories, but as configurations of dimension-specific attributes.

The matrix is visualized in Figure 8, where each radial segment corresponds to a spa category, while the associated bars indicate the number and type of analytical dimensions activated by that category. As shown in the diagram, different spa types exhibit distinct patterns of dimensional activation, revealing differences in the scope and configuration of analytical requirements associated with their morphological, functional, and heritage characteristics. Certain categories, such as C2 (Spa Park within the City Center) and C6 (Regional Centers), activate all six analytical dimensions, indicating the broadest analytical coverage within the typology–dimension matrix. This indicates a greater diversity of analytical perspectives to be accommodated within the platform and, consequently, more extensive data integration requirements. In contrast, categories such as C1 (Protected Cultural and Historical Sites), C3 (Spa Complexes within Settlements), and C4 (Rural Spas with Recognized Potential) each activate three dimensions, although their specific combinations differ. This demonstrates that the number of activated dimensions does not necessarily reflect the overall spatial or heritage complexity of a settlement, but rather the scope and configuration of analytical requirements associated with its typological characteristics. Methodologically, this differentiation enables the characterization of the analytical scope of each category, which function as an intermediary layer between typological classification and platform design. Rather than assigning fixed categories, each spa type is positioned along a spectrum of analytical scope, ranging from three to six activated dimensions and determined by their number and combination. The typology–dimension matrix thus serves three key methodological purposes: (1) it enables the anticipation of the analytical scope and data requirements of the platform, informing how analytical depth and functional scope should vary across different cases, (2) it supports the modular structuring of the platform, allowing functionalities and data inputs to be tailored according to typological characteristics, and (3) it facilitates the integration of replicator settlements, providing a reference framework for positioning them within the existing analytical logic and adapting the platform accordingly.

3.2.3. User Scope and Functional Intentions (User Profiling)

The third step in the digital structuring process introduces a user-centered layer of the platform, translating analytical structures into user-relevant interaction logics. While previous steps define how spa settlements are interpreted and differentiated, this stage defines who uses the platform and for what purposes, thereby establishing the operational interface between data structures and decision-making processes. The development of the SPATTERN platform is grounded in a user-centered design approach, recognizing that diverse stakeholders engage with spa settlements through different objectives, disciplinary perspectives, and decision-making frameworks. In this context, a typology of six user profiles was defined based on functional mindsets and core use intentions, serving as an interpretative bridge between the platform's analytical dimensions and its functional architecture. These profiles were derived from the questionnaire results (Section 3.1.2) during knowledge structuring and are formalised here as the basis for functional user profiles. Instead of reflecting formal institutional roles, the profiles were constructed through the clustering of shared functional orientations, or mindsets, expressed by respondents across multiple stakeholder groups. Each profile is associated with one or more of the identified main user groups (G1–G6) including local self-government (G1), planning and design professionals (G2), heritage and resource managers (G3), tourism stakeholders (G4), the health sector (G5), and the academic community (G6), and is defined by a specific core use intention, representing the primary mode of interaction with the platform. The

eight respondent groups of the questionnaire (Section 3.1.2) were consolidated into these six user groups. Methodologically, this step performs a translation from stakeholder input to operational user logic, enabling the alignment of platform functionalities with real-world decision-making needs. By defining user profiles in terms of intentions rather than institutional categories (Table 3), the platform ensures flexibility, allowing different actors to engage with the system through shared analytical perspectives.

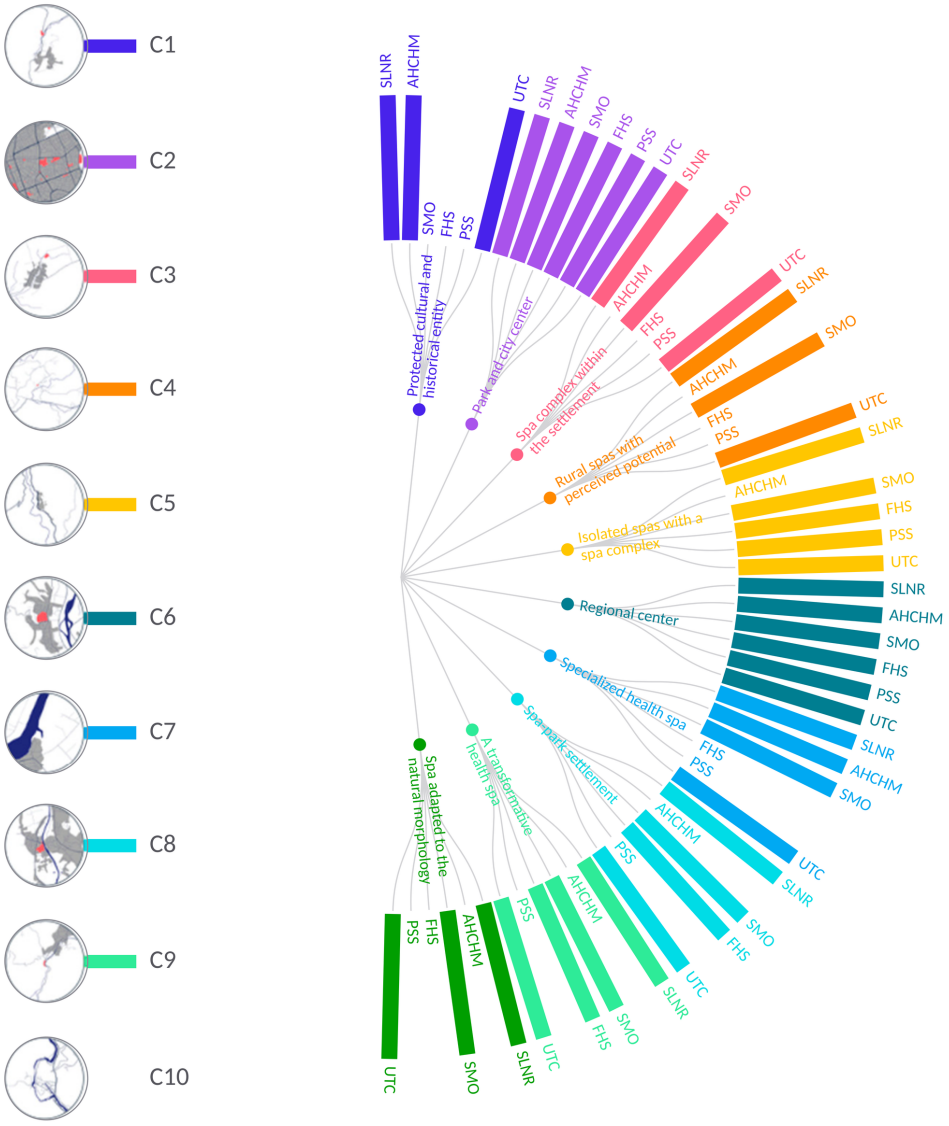


Figure 8. Relational structure of spa settlement categories (C1–C10) against the six analytical dimensions (SLNR, AHCHM, SMO, FHS, PSS, UTC). Bars indicate the analytical dimensions activated for each category; dimensions shown without a bar are not activated. Source: Authors.

Table 3. User Profiles Based on Mindsets and Core Use Intentions.

Profile ID	Mindset Title	Core Use Intention	Main User Groups (G1–G6)
P1	Development Potential Investigator	To assess market-driven opportunities for new development and investment, aligned with planning regulations	G1, G2

Table 3. *Cont.*

Profile ID	Mindset Title	Core Use Intention	Main User Groups (G1–G6)
P2	Sensitive Design Analyst	To evaluate spatial logic, urban pattern principles, and the impact of design on natural and cultural assets	G2, G3, G6
P3	Heritage and Environment Guardian	To observe and interpret how new developments affect heritage, ecosystems, and protected resources	G3, G5
P4	Tourism-Oriented Explorer	To understand spa settlement capacities, narratives, and spatial attractiveness for touristic development and promotion	G4
P5	Health-Driven Evaluator	To assess wellness, environmental quality, and therapeutic potential of spaces in relation to health infrastructure	G5
P6	Knowledge-Oriented Researcher	To conduct comparative studies, data extraction, or pattern-based insights in academic or pedagogical contexts	G6, G2

Note: G1—local self-government (including investors); G2—planning and design professionals; G3—heritage and resource managers; G4—tourism stakeholders; G5—the health sector; G6—the academic community (including students).

3.2.4. Functional Mapping: Linking User Profiles, Functionalities, and Analytical Dimensions

Following the definition of user profiles based on functional mindsets, the next step in the digital structuring process involved the development of a functional mapping framework. The objective of this step was to systematically translate user intentions into a structured set of functional requirements and to align these requirements with the analytical dimensions of the platform. Rather than directly defining platform modules, this phase establishes the procedural basis for module definition, by identifying the relationships between user-driven tasks, analytical scope, and potential system functionalities. The mapping process was structured through three sequential operations:

- Identification of Key Functionalities: For each user profile (P1–P6), the core use intention was translated into a set of key functionalities, representing concrete analytical or operational tasks that users are expected to perform within the platform. These functionalities include actions such as identifying spatial potentials, interpreting urban patterns, assessing environmental and heritage impact, exploring tourism narratives, or conducting comparative analyses. This step ensures that all subsequent system components are grounded in explicitly defined user needs.
- Alignment with Analytical Dimensions: The identified functionalities were then systematically mapped against the six analytical dimensions (SLNR, AHCHM, SMO, FHS, PSS, UTC). This alignment defines the analytical scope required to support each functionality, indicating which aspects of spatial data and interpretation must be activated. In this way, analytical dimensions function as structuring parameters that determine the depth and type of analysis associated with each user task.

- Derivation of Functional Clusters: Based on the relationships between user profiles, functionalities, and analytical dimensions, functionalities were grouped into coherent functional clusters. These clusters represent sets of operations that share similar analytical requirements and interaction logic. Importantly, these clusters do not yet correspond to finalized modules, but rather define the functional logic from which modules are subsequently derived.

3.2.5. Data Architecture Definition

Building upon the analytical framework defined through six dimensions of analysis (SLNR, AHCHM, SMO, FHS, PSS, UTC), the data architecture is conceived as a multi-layered system in which each dimension functions as a primary organizing axis for data classification and integration. These dimensions act as semantic containers that structure heterogeneous datasets, ranging from geospatial geometries and attribute tables to temporal records and narrative content, into a unified and relational schema. The database integrates both primary and secondary data sources, classified according to origin, format, and analytical purpose, ensuring analytical depth (Appendix B).

A key conceptual distinction within the data architecture is established between passive and active datasets, which correspond to different roles in the platform logic. Passive datasets provide the contextual and geometric substrate of the system (e.g., topography, street networks, cadastral structures), while active datasets function as analytical drivers, directly enabling pattern/archetype recognition and interpretative outputs. This distinction reflects a shift from data as static input toward data as an operative component within analytical workflows. The role of a dataset is defined at the level of individual modules: the same dataset may serve as a passive substrate in one module and as an active analytical driver in another. These module–dataset relations are specified in the blueprint [55] and Supplementary Materials S2, while Table A3 classifies datasets by origin, source, type and purpose.

Furthermore, the architecture is inherently relational, structured through explicit mappings between: (1) analytical dimensions, (2) classifications derived from the rulebook for pattern definition, (3) platform modules, and (4) user-driven functionalities. In this regard, the data architecture functions as a semantic interface between knowledge production (WP1–WP3) and digital execution (WP4), embedding the logic of urban pattern decoding directly into the data layer. An additional defining characteristic of the architecture is its multi-scalar capacity. The integration of datasets across different spatial resolutions, from territorial context to micro-morphological detail, enables the platform to support both comparative and site-specific analyses. This aligns with the SPATTERN objective of addressing spa settlements as complex socio-spatial systems, where patterns emerge through interactions across scales and domains.

3.2.6. System Modelling and Platform Logic

System modelling is grounded in a modular, data-driven, and user-responsive architecture, where the interaction between components is formalized through a series of UML-based representations, including use case diagrams, package structures, module relationships, and data flow schematics. These models collectively define both the structural organization of the system and its behavioral dynamics, ensuring that each functionality is traceable to specific data inputs and analytical objectives. At the core of the system lies the Central Data Repository (CDR), which consolidates all datasets defined in the data architecture into an integrated storage and retrieval environment. This repository serves as the foundational layer from which all analytical and visualization processes are initiated. The CDR is directly interfaced with the Platform Engine, which hosts the primary processing

services, including analytical computation and visualization generation (scenario-based simulation is foreseen in the blueprint design as a future extension, Section 5.3). These services operate as mediating mechanisms between raw data and user interaction, enabling the transformation of structured datasets into actionable insights. This interaction is not linear but cyclical, with continuous feedback loops between data processing, user input, and output generation. A defining feature of the system modelling approach is its strong alignment with user profiles and functional intentions. Each of the six identified user profiles is associated with specific use-case scenarios, which define the pathways through which users interact with platform modules and datasets. In this sense, system modelling embeds a user-centered epistemology, where system behavior is shaped by differentiated modes of inquiry and decision-making.

The platform is further structured through a layered architecture consisting of:

- A presentation layer (user interfaces such as dashboards and map viewers);
- An application layer (functional modules and analytical tools);
- And a data layer (geospatial and relational database).

This separation ensures clarity of roles, scalability, and interoperability, while maintaining strong interdependencies between layers. Modules operate as semi-autonomous analytical environments, each integrating specific datasets and functionalities, yet interconnected through shared processing services and data flows.

3.3. Operational Schema Crosswalk Between the HUL Framework and the SPATTERN Blueprint

To examine the correspondence between the HUL framework and the SPATTERN digital platform, a structured implementation-oriented schema crosswalk analysis was conducted. Schema crosswalk analysis is a comparative mapping procedure used to establish systematic correspondences between two conceptual or operational frameworks while preserving the internal logic of each framework and avoiding artificial equivalencies. In the present study, the crosswalk was employed to evaluate how the implementation logic embedded within the six steps of the UNESCO HUL Recommendation is reflected in the conceptual, informational, and functional organization of the SPATTERN platform. Rather than assessing technological performance, the procedure focused on identifying the degree of conceptual and operational correspondence between the normative requirements of the HUL framework and the platform blueprint. The scope of the analysis was explicitly defined by two reference frameworks: (1) the source framework consisted of the six implementation steps of the UNESCO Historic Urban Landscape Recommendation, interpreted through the digital knowledge requirements established in Section 2.2, and (2) the target framework comprised the conceptual and technical components of the SPATTERN blueprint developed throughout Sections 3.1 and 3.2, including the analytical dimensions, typological framework, user profiles, functional modules, data architecture, and system model. Following the principles of crosswalk analysis, the comparison was conducted unidirectionally, from HUL implementation requirements toward the platform components, without attempting to reinterpret the platform independently of the HUL framework. The unit of analysis was defined as each individual HUL implementation step. To ensure methodological consistency, every step was analysed using an identical comparison protocol (summarized in Table 4) based on three consecutive analytical operations (Sections 3.3.1–3.3.3).

3.3.1. Operation 1: Identification of Digital Knowledge Requirements

The first operation established the analytical baseline of the crosswalk. For each HUL implementation step, the corresponding digital knowledge requirements were identified through the conceptual synthesis developed in Section 2.2. These requirements describe the informational and operational capacities necessary to support each implementation

step, including, where appropriate, multi-layer representation, semantic organization of heterogeneous datasets, participatory knowledge capture, interoperability, decision support, and long-term monitoring. This operation generated a standardized analytical profile for each HUL step, providing a common level of abstraction for the subsequent comparison. For each implementation step, the identified requirements were documented as discrete analytical units, allowing one-to-one, one-to-many, or supporting relationships to be established during the subsequent mapping procedure, depending on the complexity of the corresponding platform component.

Table 4. Analytical Protocol of the HUL–SPATTERN Schema Crosswalk.

Methodological Component	Application in this Study
Crosswalk approach	Schema crosswalk analysis conducted to establish conceptual and operational correspondence between the UNESCO HUL implementation framework (source schema) and the SPATTERN platform blueprint (target schema)
Scope	Comparison between the six implementation steps of the UNESCO Historic Urban Landscape Recommendation and the conceptual, informational, and functional components of the SPATTERN blueprint
Source framework	UNESCO Historic Urban Landscape Recommendation (six implementation steps interpreted through digital knowledge requirements)
Target framework	SPATTERN Blueprint (analytical dimensions, typological framework, datasets, user profiles, functional modules, data architecture, and system model)
Directionality	One-way mapping from HUL implementation requirements toward SPATTERN platform components. Reverse mapping was not performed
Unit of analysis	Six HUL implementation steps
Analytical granularity	Harmonized comparison at three equivalent levels: conceptual structures, informational structures and functional structures
Crosswalk instrument	Matrix-based comparison documenting the correspondence between HUL requirements and SPATTERN blueprint components
Gap identification	HUL requirements without a corresponding platform component explicitly retained as analytical gaps rather than assigned artificial correspondences
Correspondence levels	Conceptual correspondence; Informational correspondence; Functional correspondence
Output of the procedure	Operational alignment matrix (Tables 5 and 6) documenting the conceptual, informational and functional correspondence between the HUL framework and the SPATTERN blueprint, with each step characterised as direct, supportive or partial

3.3.2. Operation 2: Crosswalk Mapping

The second operation consisted of the systematic mapping between the identified digital knowledge requirements and the components of the SPATTERN blueprint. A crosswalk matrix was constructed in which the six HUL implementation steps formed the primary analytical units (source framework), while the corresponding SPATTERN components constituted the comparison framework (target framework). The mapping was performed at an equivalent level of analytical granularity, ensuring that conceptual requirements were compared with conceptual platform elements, informational requirements with data structures, and operational requirements with functional components. During this process, conceptual, informational and functional correspondences were identified and documented for each implementation step. HUL requirements an explicit correspondence in the blueprint were

retained as analytical gaps, thereby avoiding artificial equivalencies while preserving the conceptual distinctions between the two frameworks.

3.3.3. Operation 3: Operational Alignment Analysis

The final operation synthesized the results of the crosswalk into an operational alignment profile for each HUL implementation step. Rather than assigning numerical scores or compliance ratings, the assessment documented how each HUL requirement was translated across three complementary implementation levels. The overall correspondence of each step was then characterized descriptively as direct (the requirement is addressed through dedicated platform functionality), supportive (the platform provides an analytical basis that informs the HUL operation without establishing it), or partial (an informational basis is provided, while the operational mechanism remains outside the current blueprint):

- Conceptual correspondence, examining how the normative intent of each HUL implementation step was reflected in the conceptual organization of the SPATTERN blueprint;
- Informational correspondence, identifying the knowledge assets, datasets, semantic structures, and metadata through which the conceptual framework was represented within the platform;
- Functional correspondence, documenting the platform features and digital interface components through which the corresponding knowledge structures became operational for end users.

For each implementation step, these three levels were examined consecutively, allowing the relationship between the HUL framework and the SPATTERN blueprint to be traced from conceptual principles to information structures and finally to platform implementation. Rather than measuring performance or assigning compliance scores, the procedure established a transparent chain of correspondence demonstrating how normative HUL requirements were translated into an operational digital environment. The resulting correspondence profiles constitute the methodological basis for the operational alignment presented and discussed in Section 5.1 (Tables 5 and 6), while the underlying platform components are presented in Section 4.

Table 5. Operational alignment between the HUL framework and the SPATTERN blueprint.

HUL Step	How SPATTERN Addressed the Digital Knowledge Requirement	Knowledge Basis	SPATTERN Implementation (Features)	Platform Tools	Core Analytical Dimensions Involved *	Primary User Mindsets	Evidence and Correspondence Level **
Step 1	Establishes a multi-layer semantic representation of natural, cultural and spatial information within a unified digital 3D environment, including temporal organization and historical reconstruction of spatial change	Contextual analysis; historical development timeline; archetype factsheets; pattern factsheets; planning and strategic database; historical maps, postcards and archival materials; OSM (field survey updates); GlobalBuildingAtlas	Multi-layer documentation; Spatial integration; Historical reconstruction and semantic organization; Historical Timeline	Layer filters; semantic map layers; Entity/Object ID; historical period selector; import/edit map tools; timeline controller; historical period visualization	SLNR, AHCHM, SMO	P2, P3, P6	Figures 9 and 10 direct correspondence
Step 2	Establishes a shared spatial knowledge environment for community contributions and diverse heritage perspectives, providing an informational basis for stakeholder consultation without formal consensus-building mechanisms	Expert questionnaire; stakeholder perspectives; archetype factsheets; narrative attributes; community-contributed records; educational repository	Archetype-based Narrative Mapping; Community Contribution; Educational Digital Strategies	Archetype browser; narrative cards; Import Features interface; Educational Digital Strategies panel	AHCHM, PSS, UTC	P3, P4, P6	Figure 11 partial correspondence
Step 3	Provides a structured analytical evidence base that can support the assessment of heritage vulnerability through the combined interpretation of urban patterns, comparative settlement conditions, protected heritage and three-dimensional spatial context	Analytical dimensions; pattern factsheets; pattern affiliation matrix; settlement typology (C1–C10); protected cultural heritage dataset; protected natural heritage dataset; natural risk and ecological dataset (contextual)	Urban Patterns; Comparative Assessment; Protected Heritage Layer; 3D Visualization Engine	Urban Patterns panel; settlement comparison; Protected Heritage Layer; 3D viewer; Entity/Object ID	SLNR, AHCHM, SMO, FHS, PSS, UTC	P1, P2, P3, P4, P5, P6	Figure 12; partial correspondence
Step 4	Converts analytical knowledge into planning-support information through interoperable thematic layers and transferable planning guidance	Base map layers; protected heritage datasets; settlement typology (C1–C10); pattern factsheets; expert workshop input (planning recommendations)	Planning Layers; Comparative Planning; Planning Support through Urban Patterns	Feature Type filters; Base Map Layers; settlement comparison; planning recommendation panel	SMO, FHS, PSS, UTC	P1, P2, P3, P5	Figure 13 direct correspondence
Step 5	Supports evidence-based prioritization through comparative interpretation of recurring spatial patterns and archetypes without introducing formal ranking or action-selection procedures	Pattern factsheets; archetype factsheets; pattern affiliation matrix; archetype affiliation matrix; natural risk and ecological dataset (contextual)	Pattern Similarity; Comparative Pattern Analysis; Archetype Comparison	Pattern similarity search; Comparative Pattern Analysis workspace; pattern comparison table; archetype comparison panel	SLNR, AHCHM, SMO, FHS, PSS, UTC	P1, P2, P3, P6	Figure 14; supportive correspondence

Table 5. *Cont.*

HUL Step	How SPATTERN Addressed the Digital Knowledge Requirement	Knowledge Basis	SPATTERN Implementation (Features)	Platform Tools	Core Analytical Dimensions Involved *	Primary User Mindsets	Evidence and Correspondence Level **
Step 6	Provides a shared digital knowledge environment structured around differentiated stakeholder needs and user mindsets, establishing an informational basis for coordination among actors involved in heritage and urban development	Expert questionnaire; stakeholder groups; sectoral expectations and priorities; user profiles and core use intentions	Stakeholder-informed User Profiling; differentiated user logic; shared platform knowledge environment	Six functional user profiles (P1–P6); user-oriented access to common analytical and spatial information	SLNR, AHCHM, SMO, FHS, PSS, UTC	P1, P2, P3, P4, P5, P6	No figure; partial correspondence

* Codes: Analytical dimensions: SLNR—Spatial Links with Natural Resources, AHCHM—Architectural Heritage and Cultural–Historical Monuments, SMO—Specificities of Matrix and Organization, FHS—Functional Hierarchy of Space, PSS—Public Space System, UTC—Urban Tissue Character; Primary user mindsets: P1—Development Potential Investigator, P2—Sensitive Design Analyst, P3—Heritage and Environment Guardian, P4—Tourism-Oriented Explorer, P5—Health-Driven Evaluator, P6—Knowledge-Oriented Researcher. ** Correspondence level: Direct: requirement addressed through dedicated platform functionality; supportive: analytical basis provided without a mechanism for the HUL operation itself; partial: informational basis provided, with the operational mechanism remaining outside the current blueprint.

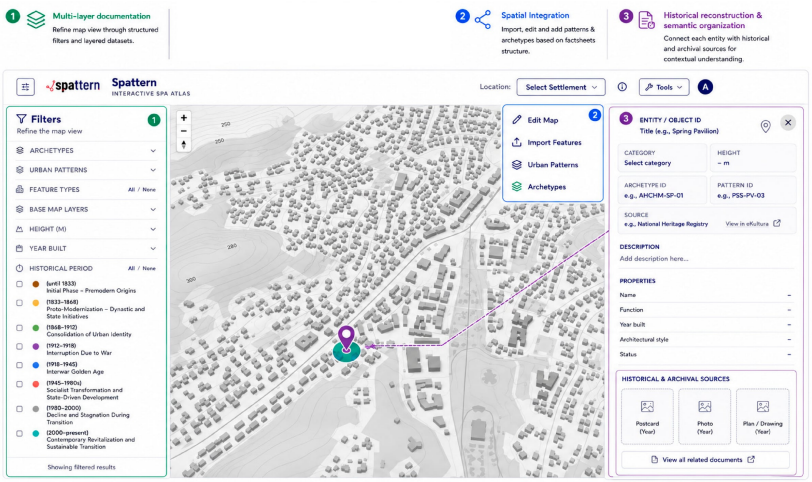


Figure 9. Platform interface highlighting multi-layer documentation, spatial integration, and historical reconstruction and semantic organization functionalities supporting HUL Step 1—Mapping Resources. Source: Authors.



Figure 10. Platform interface highlighting the Historical Timeline and temporal exploration functionalities supporting HUL Step 1—Mapping Resources. Source: Authors.

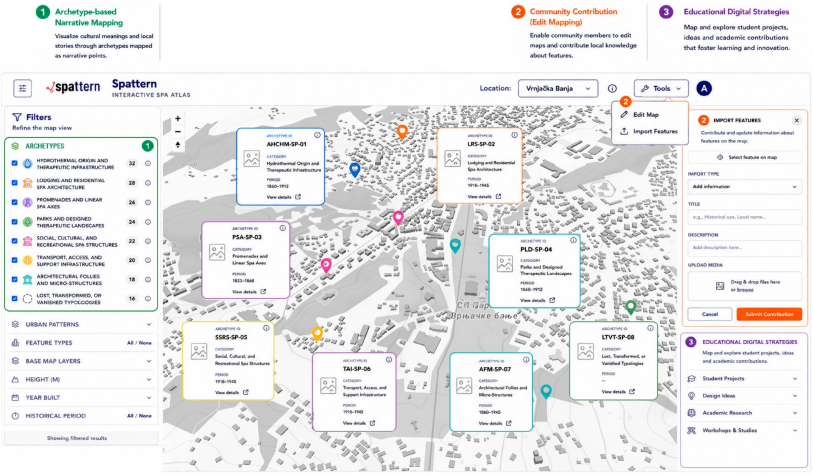


Figure 11. Platform interface highlighting archetype-based narrative mapping, community contribution and educational digital strategies supporting HUL Step 2—Reaching Consensus. Source: Authors.

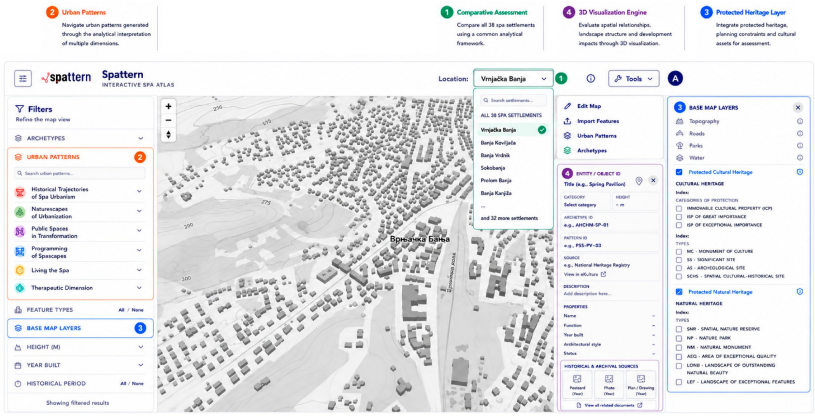


Figure 12. Platform interface highlighting urban patterns, comparative assessment, protected heritage layers and the 3D visualization environment as an analytical basis for HUL Step 3—Assessing Vulnerability. Source: Authors.

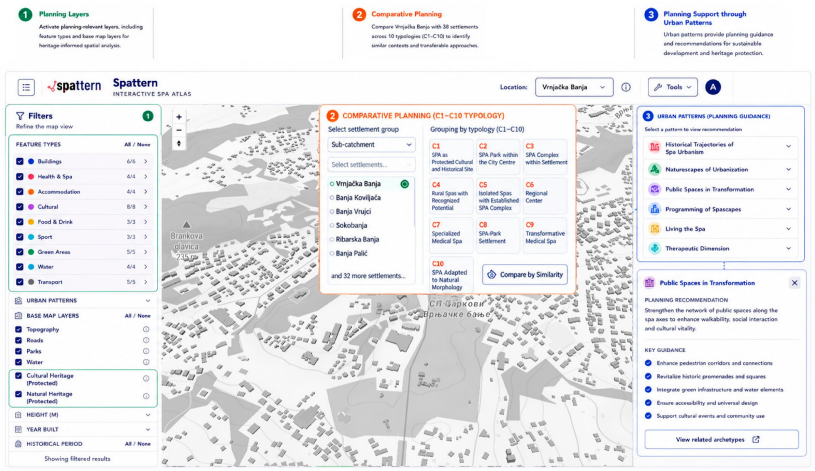


Figure 13. Platform interface highlighting planning layers, comparative planning and planning support through urban patterns supporting HUL Step 4—Integrating into Urban Development. Source: Authors.

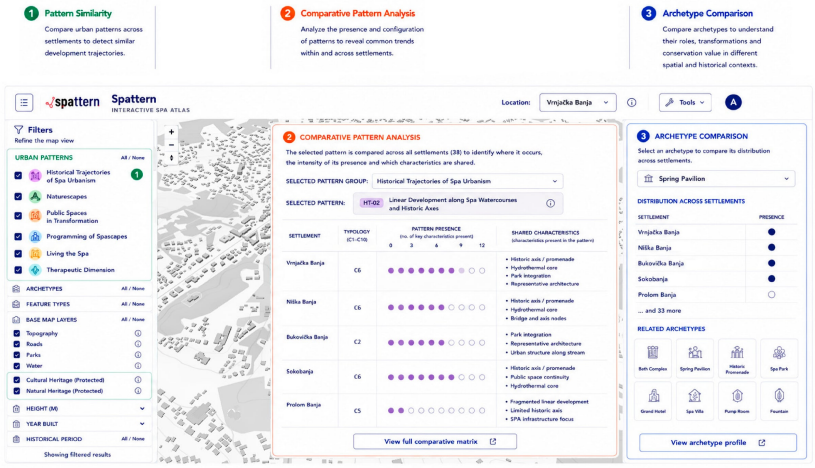


Figure 14. Platform interface highlighting comparative analytical functionalities supporting HUL Step 5—Prioritizing Actions. Source: Authors.

Table 6. Multi-level correspondence between the HUL implementation framework and the SPATTERN platform blueprint.

HUL Step	Conceptual Correspondence	Informational Correspondence	Functional Correspondence
Step 1	Heritage is conceptualized as an interconnected system of natural, cultural, spatial and historical attributes organized through the Compendium and Decoder, with temporal transformation incorporated as an integral dimension of heritage interpretation	Heterogeneous datasets are harmonized into a unified semantic structure through archetype and pattern factsheets, historical periods, entity metadata and linked archival resources, while temporal attribution organizes entities according to successive phases of settlement development	Multi-layer filters, semantic layers, entity/object IDs, historical references and spatial visualization enable integrated exploration of heritage information; the Historical Timeline additionally enables chronological navigation and reconstruction of spatial transformation
Step 2	Heritage values and attributes are interpreted through the inclusion of multiple stakeholder perspectives, local narratives and participatory contributions, extending expert-based knowledge toward an informational basis for shared understanding of heritage	Stakeholder-informed knowledge, archetype narratives, community submissions and educational repositories are structured as complementary components of the platform knowledge base	Archetype-based narrative mapping, community contribution (Import Features workflow) and Educational Digital Strategies support the incorporation of participatory and community-generated knowledge into the shared digital environment; however, the current blueprint does not include structured stakeholder deliberation, procedures for negotiating conflicting heritage values, or mechanisms for recording collectively agreed priorities
Step 3	Heritage vulnerability is approached as a relational condition requiring the combined interpretation of heritage attributes, spatial configurations and development conditions	Analytical dimensions, urban patterns, settlement typologies, protected heritage datasets and three-dimensional spatial data provide a structured information base from which vulnerabilities may be examined comparatively across settlements	Comparative Assessment, Urban Patterns, Protected Heritage Layer and 3D Visualization Engine provide analytical prerequisites for vulnerability assessment; however, the current blueprint does not include dedicated vulnerability indicators, risk-ranking procedures or a formal vulnerability-assessment workflow
Step 4	Analytical knowledge is translated into planning-support logic through transferable urban patterns and planning-oriented interpretation	Planning layers combine feature datasets, protected heritage, typological classification and pattern knowledge within a unified planning environment	Planning layers, settlement comparison and pattern-based planning guidance connect heritage knowledge with planning workflows
Step 5	Potential conservation and development priorities can be informed by comparative interpretation of recurring urban patterns and archetypes rather than isolated heritage objects	Comparative pattern matrices and archetype relationships organize transferable conservation knowledge across settlements	Comparative Pattern Analysis and Archetype Comparison identify common development trajectories and provide comparative evidence relevant to conservation and development priorities, without formally ranking or selecting actions
Step 6	Heritage management is conceptualized as a multi-actor process requiring coordination among stakeholders with different institutional, professional and sectoral perspectives	Stakeholder groups, sectoral expectations and differentiated user mindsets structure the informational basis for connecting different perspectives within a shared platform environment	Stakeholder-informed user profiling and differentiated user logic provide a common informational environment that can support future coordination; however, formal partnership arrangements, collaborative workflows, institutional responsibilities and local management protocols are not operationalized within the current blueprint

4. Results

The results are presented through the six HUL implementation steps (Sections 4.1–4.6). For each step, the section describes the platform components through which the corresponding digital knowledge requirement (Table 1) is addressed, the knowledge outputs of the SPATTERN project on which these components are based, and the degree to which the requirement is operationalized in the current version of the platform. Where the blueprint does not yet fully operationalize a requirement, this is stated explicitly rather than assumed; the resulting correspondence profiles (direct, supportive or partial, as defined in Section 3.3.3) are synthesized and discussed in Section 5.1. The figures in this section show the interface of the SPATTERN platform in its current beta version. Where data entry is not yet complete, placeholder content (e.g., example titles and identifiers) is displayed; base-map labels follow the language of the underlying OpenStreetMap data.

4.1. Step 1: Mapping Resources

The first stage of the SPATTERN platform implementation establishes a structured digital representation of the knowledge generated during the contextual analysis (Compendium) and typomorphological analysis (Decoder). The platform is built upon OpenStreetMap as the underlying spatial framework, which was systematically updated through field verification using the Edit Map functionality to incorporate changes identified during on-site surveys. Building heights are further complemented using the Global Building Atlas dataset [96], providing the three-dimensional geometric basis required for subsequent spatial analyses. The implementation consists of three complementary components: multi-layer documentation, spatial integration, and historical reconstruction and semantic organization (Figure 9).

Multi-layer documentation represents the process through which heterogeneous research materials are transformed into structured thematic layers and metadata that can be explored through the filters. The layer hierarchy directly reflects the analytical framework developed during the previous research stages. Filters such as archetypes, urban patterns, feature types, historical periods, and base map layers originate from the contextual analysis and typomorphological interpretation rather than from predefined GIS classifications. Historical periods were derived through a chronological synthesis of spa development trajectories across the analysed cases (12 role models of spa settlements). The resulting timeline maps recurrent phases of urbanization (from premodern origins and early institutionalization, through expansion, interruption and decline, to contemporary revitalization) and functions as a consistency check by demonstrating that comparable developmental configurations recur across different historical periods and spa settlements. Consequently, each filter constitutes a standardized digital representation of previously interpreted knowledge, allowing users to isolate specific analytical dimensions while preserving their original semantic meaning.

Spatial integration translates these structured datasets into a coherent geospatial environment where individual entities, urban patterns and archetypes become spatially referenced objects. Every mapped feature is assigned a unique identifier and linked to the corresponding typological category, enabling spatial editing, feature import and continuous enrichment of the database. Instead of storing isolated geometries, the platform establishes explicit relationships between spatial objects and the analytical concepts derived from the rulebook for patterns decoding, ensuring that each element simultaneously functions as a geographic feature and as a carrier of contextual knowledge. This creates an interoperable spatial model suitable for comparative analysis and subsequent computational processing.

Historical reconstruction and semantic organization provide the interpretative layer that connects every mapped entity with its documentary evidence and historical context. Each object is associated with descriptive metadata, historical period, typological classification, functional attributes and references to archival materials such as postcards, photographs, plans, drawings and documentary sources. These information layers originate from the archetype and urban pattern factsheets presented in the methodological framework, where documentary evidence, morphological interpretation, temporal attributes and semantic relationships are systematically structured. The platform therefore does not generate these attributes independently but operationalizes the knowledge previously encoded through the factsheet methodology into a searchable and referenced digital environment. The temporal attributes assigned to individual entities additionally enable this structured historical knowledge to be explored through the Historical Timeline, extending historical reconstruction from object-level metadata to an interactive representation of settlement transformation over time. As a result, historical narratives become computationally accessible while maintaining traceability to their original documentary sources.

The Historical Timeline operationalizes the chronological framework developed during the contextual analysis through eight historically defined periods: Initial Phase—Premodern Origins (until 1833); Proto-Modernization—Dynastic and State Initiatives (1833–1868); Consolidation of Urban Identity (1868–1912); Interruption Due to War (1912–1918); Interwar Golden Age (1918–1945); Socialist Transformation and State-Driven Development (1945–1980s); Decline and Stagnation During Transition (1980–2000); and Contemporary Revitalization and Sustainable Transition (2000–present). The period boundaries are approximate: the 1980s are treated as a transitional decade between the sixth and seventh periods, and the fifth period extends to 1945 to include the Second World War years. The chronological boundaries reflect major shifts in the historical, political, and socio-economic conditions shaping the development of spa settlements in Serbia. In particular, the transition around 2000 marks the end of a prolonged period of political and economic instability during the 1990s and the beginning of post-socialist restructuring, accompanied by changing investment conditions, tourism development, and renewed interest in the revitalization of spa environments. The designation "2000–present" therefore identifies the most recent phase within the historical development framework, rather than implying continuous or real-time monitoring of contemporary transformations. The timeline functions as an interpretative instrument for exploring historically documented spatial change, with the period boundaries representing broader developmental transitions rather than uniform turning points across all settlements.

Rather than navigating through individual years, users can explore spatial development through these successive phases, which provide a common temporal reference system for interpreting transformations across the analysed settlements. Because mapped objects are associated with their corresponding historical affiliation in the underlying database, the timeline dynamically controls the visibility of spatial entities and thematic layers, enabling changing relationships between natural resources, urban morphology, and heritage attributes to be explored across successive stages of development (Figure 10).

4.2. Step 2: Reaching Consensus

The second implementation stage extends the platform beyond institutional datasets by incorporating participatory and community-generated knowledge into the digital heritage environment. While the previous steps established a structured representation of documented heritage resources and analytical interpretations, this stage introduces mechanisms through which local narratives, community contributions, and educational outputs become part of the continuously evolving knowledge base (Figure 11). These functionalities provide an informational basis for stakeholder consultation by making different forms of heritage knowledge and interpretation accessible within a shared spatial environment. However, they should be understood as enabling conditions for consensus-building rather than as mechanisms through which consensus is formally established. The implementation is organized around three complementary components: archetype-based narrative mapping, community contribution, and educational digital strategies.

Archetype-based narrative mapping provides the primary mechanism for representing intangible heritage values and local cultural narratives within the spatial environment. Unlike urban patterns, which describe recurrent spatial configurations at the settlement scale, archetypes represent generalized types of spatial entities associated with characteristic architectural typologies, public spaces, landscape elements and historical structures, whose instances are mapped in individual settlements. These archetypes are organized into eight thematic groups: Hydrothermal Origin and Therapeutic Infrastructure, Lodging and Residential Spa Architecture, Promenades and Linear Spa Axes, Parks and Designed Therapeutic Landscapes, Social, Cultural and Recreational Spa Structures, Transport, Access and

Support Infrastructure, Architectural Follies and Micro-Structures, and Lost, Transformed or Vanished Typologies. Each mapped archetype is linked to the standardized factsheets previously developed in the Decoder, allowing narrative interpretation, historical documentation, and temporal information to be transferred into a spatially referenced digital environment. Consequently, narrative mapping does not create new heritage information but spatially operationalizes the semantic knowledge encoded through the archetype framework.

Community contribution enables the controlled enrichment of the database through the Import Features functionality. The same Import Features functionality is used by the research team for database maintenance in Step 1 (spatial integration); here it is open to community users under controlled conditions. This module allows users to contribute additional information, descriptive narratives, photographs, documentary records, or other locally relevant materials associated with existing spatial entities or newly identified features. Rather than modifying the analytical framework itself, community contributions complement the existing knowledge base by extending the available documentary evidence and strengthening local representation. In this way, institutional heritage inventories are progressively supplemented with community-generated knowledge while preserving the standardized semantic structure established during the methodological phase.

Educational digital strategies establish the platform as an environment for continuous academic engagement and knowledge transfer. Besides documenting existing heritage resources, the platform accommodates student projects, design proposals, academic research, workshops, and other educational outputs that address the future development of spa settlements. These contributions are organized as dedicated thematic layers that coexist with the analytical and heritage datasets, enabling educational work to become part of the broader digital knowledge ecosystem. Consequently, the platform supports not only documentation and interpretation of existing conditions but also the communication of future design ideas and research initiatives, reinforcing the role of academic institutions within participatory heritage management.

Taken together, these three components establish a participatory knowledge environment that can support, but does not independently accomplish, the consensus-building objective of the second HUL implementation step. While archetype-based narrative mapping provides a common interpretative reference and community and educational contributions broaden the range of represented perspectives, the current blueprint does not include structured stakeholder deliberation, procedures for negotiating conflicting heritage values, or mechanisms for recording collectively agreed priorities. Its correspondence with Step 2 is therefore primarily informational and preparatory rather than fully operational. Establishing consensus would require complementary participatory processes and institutional arrangements through which stakeholders can collectively evaluate heritage significance, reconcile different interpretations, and agree on shared objectives. Developing and validating such mechanisms remains an important direction for the further operationalization of the proposed framework.

4.3. Step 3: Assessing Vulnerability

The third HUL implementation step concerns the assessment of the vulnerability of heritage attributes to different forms of change and development pressure. Within the SPATTERN blueprint, this requirement is addressed partially rather than through a dedicated vulnerability-assessment procedure. The platform does not currently incorporate explicit vulnerability indicators, risk-ranking procedures, or a formal model for evaluating the susceptibility of heritage attributes to specific pressures. Instead, it provides an integrated analytical environment through which spatial configurations, urban patterns, protected heritage assets, and differences among settlements can be examined comparatively. In

this sense, the existing platform components establish an analytical basis for vulnerability assessment, while its explicit operationalization remains an identified area for further development (Figure 12).

Four existing components are particularly relevant to this analytical basis: urban patterns, comparative assessment, protected heritage layers, and the 3D visualization engine. Rather than constituting vulnerability-assessment tools in themselves, these components provide complementary forms of evidence through which potentially sensitive spatial relationships, heritage attributes, and conditions of transformation can be identified and interpreted.

Urban patterns constitute the principal analytical framework of this step. Their organization follows the methodological structure developed through the typomorphological study, in which the evolution of spa settlements was interpreted through three dimensions of urbanization: Material Transformation, Territorial Regulation, and Everyday Life. These dimensions are further structured into six analytical themes: Historical Trajectories of Spa Urbanism, Naturescapes of Urbanization, Public Spaces in Transformation, Programming of Spascapes, Living the Spa, and Therapeutic Dimension. Within each theme, individual urban patterns were identified, formally described through standardized factsheets, and subsequently affiliated with the complete corpus of 38 spa settlements. Comparative assessment provides a unified analytical environment for all analysed spa settlements included in the research. Each settlement is represented through an identical data structure, analytical hierarchy, and visualization logic, allowing direct comparison without requiring additional data harmonization. The location selector therefore functions not merely as a navigation tool but as the entry point to a standardized comparative framework in which every settlement can be examined through the same analytical dimensions, typological classifications, and digital representations. Protected heritage layers integrate officially designated cultural and natural heritage resources into the analytical environment. These layers are derived from the national heritage registers of Serbia and include both cultural and natural protection datasets that were collected, classified, and harmonized for all 38 spa settlements. Cultural heritage information distinguishes categories of legal protection and heritage types, while natural heritage layers incorporate nationally recognized protected landscapes and ecological assets. The layers therefore support the identification of heritage elements potentially relevant to vulnerability assessment, while the evaluation of their actual degree of vulnerability requires additional indicators concerning exposure, sensitivity, and specific development or environmental pressures that are not yet incorporated into the current blueprint. Although the data architecture includes a dataset on natural risk and ecological conditions (Appendix B), it serves as contextual information and is not yet processed into vulnerability or risk indicators.

Finally, the 3D visualization engine supports the spatial interpretation of these relationships by integrating topography, terrain morphology, building volumes, hydrographic elements, and landscape structure within a common model. Each mapped entity is associated with an Entity/Object ID linking its geometric representation to descriptive metadata and semantic attributes derived from the structured knowledge base. This enables heritage assets and urban patterns to be examined within their broader morphological and environmental context and provides a spatial basis for recognizing relationships that may not be apparent through conventional two-dimensional mapping. Nevertheless, visualization and contextual interpretation should be distinguished from vulnerability assessment itself. The current 3D environment supports the reading of potentially relevant spatial conditions but does not yet evaluate their susceptibility to particular hazards or development pressures.

4.4. Step 4: Integrating into Urban Development

The fourth implementation stage translates the structured heritage knowledge into a planning-support environment. While the previous steps focused on documenting, interpreting, and enriching heritage information, this stage operationalizes these results within planning workflows by integrating analytical layers, comparative planning capabilities, and planning guidance derived from typomorphological interpretation (Figure 13). The implementation is organized around three complementary components: planning layers, comparative planning, and planning support through urban patterns.

Planning layers establish the spatial framework through which heritage information becomes directly applicable to planning practice. The platform combines two complementary groups of planning-relevant datasets. The first consists of feature types, which classify the built and natural environment into thematic categories including buildings, health and spa facilities, accommodation, cultural facilities, food and drink, sports infrastructure, green areas, water elements, and transport. The second group comprises base map layers, integrating topography, roads, parks, hydrographic features, and officially designated cultural and natural heritage resources. Together, these layers create a unified planning environment in which urban structure, environmental context, functional organization, and regulatory protection can be examined simultaneously, enabling planners to evaluate development proposals within their broader territorial and heritage context.

Comparative planning extends the analytical framework from individual settlements to the entire network of 38 spa settlements. Because every settlement is represented through an identical database structure and analytical framework, planning strategies can be compared across different spatial contexts without additional data harmonization. The platform further supports comparison through the previously established settlement typology (C1–C10), allowing planners to identify settlements sharing similar morphological characteristics, developmental trajectories, and planning conditions. Rather than comparing isolated indicators, this functionality enables the transfer of planning experience between typologically related settlements and supports the identification of contextually appropriate development approaches.

Planning support through urban patterns transforms typomorphological interpretation into operational planning guidance. Each urban pattern previously identified through the Decoder is associated with a corresponding set of planning recommendations derived from its spatial characteristics, functional role, historical significance, and observed transformation processes. The recommendations were formulated by the research team on the basis of the expert input collected at the expert workshop (Section 3.1.4; Appendix A). Consequently, urban patterns become planning knowledge objects rather than descriptive analytical categories alone. Selecting a pattern provides access to recommendations that relate morphological interpretation to potential planning interventions while maintaining direct links to associated archetypes and documentary evidence. In this way, planning guidance remains explicitly connected to the analytical knowledge generated during the previous methodological stages.

4.5. Step 5: Prioritizing Actions

Rather than introducing additional datasets, Step 5 draws on and synthesizes the previously established analytical framework to enable comparison of recurring spatial configurations, identification of shared development trajectories, and recognition of transferable conservation approaches across the entire corpus of spa settlements (Figure 14). Within the current SPATTERN blueprint, these functionalities provide an analytical basis for prioritization rather than a formal mechanism for ranking or selecting conservation

and development actions. The implementation is organized around three complementary components: pattern similarity, comparative pattern analysis, and archetype comparison.

Pattern similarity enables the comparison of urban patterns across all settlements included in the platform. Since every pattern has previously been defined through a standardized factsheet and affiliated with the 38 spa settlements, the platform is designed to identify where similar spatial configurations occur regardless of their geographical location. Instead of comparing settlements only as individual case studies, this functionality allows users to recognize common developmental trajectories through recurring urban patterns that appear in different territorial and historical contexts. The similarity comparison is descriptive: it identifies settlements in which the same pattern occurs with shared characteristics and does not compute a statistical similarity index. Such comparative recognition provides evidence for identifying recurrent conditions and potentially transferable responses but does not itself establish priorities among alternative actions.

Comparative pattern analysis represents the principal analytical component of this step. After selecting an urban pattern, the platform generates a comparative matrix showing its distribution across the complete corpus of spa settlements. For each settlement, the analysis presents its typological affiliation (C1–C10), the presence of the selected pattern, expressed as the number of its key characteristics identified in that settlement (on a scale of 0 to 12), and the set of characteristics associated with its occurrence. This score is a descriptive count rather than a statistical similarity or weighting measure; the matrix provides an analytical overview of how individual patterns recur or combine across different settlement types. This enables the identification of shared spatial characteristics and recurring developmental tendencies provide an evidence base for considering conservation and development priorities, while maintaining direct traceability to the typomorphological interpretation developed during the Decoder. The platform therefore supports prioritization through comparative evidence, while the actual weighting, ranking, and selection of actions remain dependent on planning objectives, stakeholder deliberation, and decision-making procedures external to the current blueprint.

Archetype comparison complements the settlement-scale analysis by focusing on individual types of spatial elements. While urban patterns describe broader spatial configurations, archetypes represent recurring types of spatial elements that collectively constitute these configurations. The comparison module allows users to examine the distribution of a selected archetype across the 38 spa settlements and to identify its associated archetypes within similar spatial contexts. This functionality supports interpretation of how individual heritage elements contribute to broader urban patterns and provides contextual evidence relevant to considering their roles, transformations and conservation value in different spatial and historical contexts. The comparison is descriptive: the interface presents the distribution and related archetypes, but it does not assign conservation significance or priority scores to individual archetypes.

4.6. Step 6: Establishing Partnerships and Local Management Frameworks

The sixth HUL implementation step concerns the establishment of partnerships, local management frameworks, and coordination mechanisms among the actors involved in heritage conservation and urban development. Within the SPATTERN blueprint, this requirement is addressed primarily through the user and institutional logic of the platform rather than through a dedicated governance module. The expert questionnaire conducted across the 38 spa settlements identified the needs and perspectives of multiple stakeholder groups, which were subsequently translated into six functional user profiles with differentiated requirements for accessing, interpreting, and using platform knowledge. In this way, the platform provides a shared digital environment in which heritage, planning, envi-

ronmental, tourism, research, and local-development perspectives can operate through a common knowledge structure.

This logic is further supported by the platform architecture, which combines differentiated user access with connections to external data sources and institutional information systems. These components establish a technical basis for information exchange and coordination across different actors and knowledge domains. However, the current blueprint does not formalize institutional responsibilities, partnership arrangements, collaborative decision-making procedures, or local management protocols. The correspondence with HUL Step 6 is therefore partial. SPATTERN provides a common information infrastructure relevant for supporting future partnerships and coordinated local management, while the organizational and governance mechanisms through which such partnerships would operate remain outside the current scope of the platform.

5. Discussion

5.1. Evaluating the Operational Alignment Between the HUL Framework and the SPATTERN Blueprint

A central question addressed by this study concerns whether the digital blueprint extends beyond the visualization of heritage information and provides an operational interpretation of the implementation logic embedded within the UNESCO HUL Recommendation. The alignment analysis indicates the correspondence extends across the six implementation steps, although with different degrees and forms of operational alignment, ranging from directly implemented platform functionalities to supportive analytical capacities and partially addressed requirements. Rather than introducing independent digital tools for individual HUL steps, the proposed blueprint translates the requirements of the HUL implementation framework into an interconnected digital workflow, while also revealing where the current platform architecture does not yet fully operationalize particular requirements.

This operational correspondence is summarized in Table 5, which synthesizes the implementation pathway of each HUL step by relating digital knowledge requirements to the methodological origin of the underlying datasets, the corresponding implementation components of the platform, and the digital tools through which these components become operational. Considered together, these elements illustrate that the implemented platform functionalities originate from previously established methodological constructs, rather than representing an isolated software feature. The resulting implementation therefore preserves the analytical logic developed throughout the Compendium and Decoder and embeds it within a unified digital environment. At the same time, the crosswalk identifies requirements for which the current blueprint provides an analytical or informational basis without yet incorporating a dedicated operational mechanism, most notably consensus-building, vulnerability assessment and partnership-based local management. These cases are retained as partial correspondences and development gaps rather than being assigned artificial functional equivalence. Action prioritization is addressed through supportive analytical capacities that inform, but do not establish, priorities.

However, documenting implementation alone does not explain the nature of the correspondence between the HUL framework and the SPATTERN blueprint. For this reason, Table 6 examines the alignment at three complementary implementation levels: conceptual, informational and functional. This distinction makes it possible to evaluate whether each HUL implementation step is reflected only through interface functionalities or whether its underlying knowledge organization is consistently maintained across the complete digital architecture.

The comparison suggests that the strongest contribution of the proposed blueprint lies precisely in this continuity between analytical knowledge production and digital implementation. Conceptual structures established through the analytical framework are systematically transformed into interoperable information structures and translated into platform functionalities to different degrees, depending on the requirements of each HUL implementation step. Consequently, the digital environment does not function merely as a repository or visualization interface but as an implementation framework in which analytical interpretation, semantic organization and operational support remain explicitly connected. At the same time, the comparison demonstrates that digital operationalization is not uniform. While several HUL requirements are directly supported through dedicated platform functionalities, others are addressed through analytical and informational capacities that establish a basis for further development. In particular, consensus-building (Step 2), vulnerability assessment (Step 3) and partnership-based local management (Step 6) remain only partially operationalized within the current blueprint, while action prioritization (Step 5) is supported only through comparative analytical evidence.

The distinction between informational support and operational assessment is particularly relevant to HUL Steps 3 and 5. In Step 3, the integration of protected heritage datasets, urban patterns, settlement comparisons, and differentiated user perspectives establishes a structured evidence base for examining potentially vulnerable heritage conditions. However, these components do not independently determine vulnerability, as no explicit indicators, weighting criteria, or assessment procedures have yet been implemented. Similarly, in Step 5, Comparative Pattern Analysis and Archetype Comparison enable the identification of recurring spatial conditions and potentially transferable conservation approaches, but do not establish priorities among alternative conservation and development actions. Such prioritization would require explicit evaluation criteria, stakeholder-defined objectives, and procedures for comparing and selecting interventions. The current blueprint therefore supports the analytical preparation of vulnerability assessment and action prioritization, while their formal evaluation and decision-making mechanisms remain outside its present functional scope.

5.2. Methodological Contribution and Implications for Heritage-Sensitive UDPs

The methodological roadmap presented in Figure 15 synthesizes the knowledge transformation process proposed in this study. The proposed methodology conceptualizes platform development as the final stage of a structured knowledge process in which analytical knowledge is progressively translated into interoperable digital structures. The roadmap demonstrates that the implementation of heritage-sensitive UDPs depends not only on technical system design but also on the systematic organization of knowledge throughout successive methodological phases. The roadmap illustrates four consecutive stages of a knowledge-translation process. The first three stages describe the procedure applied in developing the SPATTERN blueprint, while the fourth presents the HUL-oriented functionalities that the resulting knowledge structure is intended to support; the degree to which each is currently implemented is documented in Section 5.1 (Tables 5 and 6). The second stage transformed these heterogeneous knowledge sources into transferable analytical structures through comparative typomorphological interpretation and the specification of urban patterns and archetypes. The third stage consolidated these outputs into a coherent knowledge model integrating analytical dimensions, settlement typologies, patterns, archetypes, historical periods, heritage datasets, and user profiles, was discussed with experts at the workshop (Section 3.1.4) and subsequently formalised during digital structuring (Section 3.2). Finally, these structured knowledge components are operationalized through platform functionalities aligned with the six implementation steps of the HUL

Recommendation. In SPATTERN this operationalization is addressed directly for some steps and through supportive analytical capacities or only partially for others (Section 5.1, Tables 5 and 6); functionalities that are intended but not yet implemented are marked with dashed lines in Figure 15.



Figure 15. Methodological roadmap for translating heritage knowledge into a heritage-sensitive UDP. Stages 01–03 correspond to the procedure applied in the SPATTERN blueprint; stage 04 presents the intended HUL-oriented functionalities for each implementation step as a reference for platform development. The extent to which SPATTERN currently implements them is shown in Tables 5 and 6: Steps 1 and 4 are addressed directly, Step 5 through supportive analytical capacities, and Steps 2, 3 and 6 only partially. Dashed boxes in stage 04 indicate intended functionalities that are not yet implemented in the current blueprint. Source: Authors.

One of the principal methodological contributions lies in the explicit differentiation between (1) knowledge acquisition, (2) knowledge extraction, (3) knowledge structuring, and (4) knowledge operationalization. Each phase produces a clearly defined analytical output that serves as the methodological input for the subsequent phase. This sequential organization establishes complete traceability between the original evidence, the analytical interpretation, the structured knowledge model, and the final platform functionalities. Consequently, every digital component implemented within the platform can be directly linked to the methodological procedures through which it was generated. An additional contribution is the introduction of an intermediate expert consultation stage positioned between knowledge structuring and platform operationalization. The expert workshop provided an opportunity to evaluate the coherence of the analytical framework, discuss the applicability of the proposed patterns and archetypes, and review the preliminary platform requirements. The workshop was designed as an expert-informed assessment rather than a comprehensive validation (Section 3.1.4, Appendix A). Incorporating expert feedback at this stage supported the consistency of the knowledge model and helped keep the subsequent platform design remained grounded in planning practice and heritage management experience. From a broader methodological perspective, the proposed roadmap offers a transferable procedure for developing heritage-sensitive UDPs, although its transferability beyond Serbian spa settlements remains to be tested (Section 5.3). Consequently, the contribution extends beyond the development of the SPATTERN platform itself by proposing a reproducible methodological pathway for translating heritage knowledge into operational digital frameworks.

5.3. Limitations and Future Developments

Although the study demonstrates the feasibility of translating typomorphological knowledge into a structured digital environment, the current implementation should be understood as a research blueprint rather than a fully operational planning information system. Three limitations therefore define the scope of the present work while simultaneously identifying directions for future development. First, the analytical framework was developed using evidence from 38 spa settlements in Serbia, with detailed typomorphological interpretation conducted for 12 role model settlements. Although the resulting analytical dimensions, urban patterns, and archetypes were intentionally formulated as transferable knowledge structures, their applicability beyond Serbian spa settlements remains to be examined in different geographical, institutional, and cultural contexts. Future research should therefore evaluate the transferability of the proposed knowledge model across other spa regions and additional categories of historic settlements.

Second, the expert workshop provided an important expert assessment of the conceptual organization and analytical dimensions underlying the proposed blueprint. However, the workshop was conducted prior to the implementation and testing of the complete platform; participants were presented with the blueprint and an early beta version of the interface for illustrative purposes only. Also, the planning recommendations linked to urban patterns draw on expert input but have not yet been evaluated through application in planning processes. Consequently, the present study demonstrates the methodological process through which heritage knowledge is structured and operationalized, while the evaluation of the platform itself including usability, user interaction, decision-support performance, and practical application in planning processes, constitutes the next stage of the research. This distinction reflects the primary objective of the present study, which focuses on establishing a transparent and reproducible methodological framework for knowledge operationalization rather than assessing software performance. While the correspondence between SPATTERN functionalities and the six HUL implementation steps demonstrates

conceptual and methodological alignment, it should not be interpreted as evidence of the platform's effectiveness in actual planning and heritage management processes. Such effectiveness requires further testing with institutional stakeholders through practical planning applications, including the assessment of usability, decision-support relevance, and integration into existing planning and management workflows.

Third, specific limitations concern the absence of dedicated consensus-building mechanisms (Step 2), vulnerability-assessment procedures (Step 3), action-prioritization procedures (Step 5), and formalized partnership and local management frameworks (Step 6). Future development should therefore examine how the existing heritage, environmental, spatial, and comparative datasets could be complemented by explicit vulnerability indicators, criteria for assessing development impacts, and transparent multi-criteria evaluation procedures. For action prioritization, these would additionally require stakeholder-defined conservation and development objectives, criteria weighting, and mechanisms for comparing alternative interventions. For consensus-building and partnerships, development would require complementary participatory processes and institutional arrangements for stakeholder deliberation, negotiation of conflicting values, recording of agreed priorities and allocation of institutional responsibilities, designed and tested with local institutions. Their development and validation through practical planning and heritage-management applications would be necessary before the platform could be considered an operational assessment, prioritization and coordination system.

The proposed framework nevertheless creates multiple opportunities for future development. The established knowledge model provides a foundation for integrating advanced analytical capabilities, including automated pattern recognition, AI-assisted semantic interpretation, scenario-based simulation and predictive scenario modelling, and interoperability with CityGML, digital twins, and other urban information infrastructures. In parallel, future research should investigate the practical application of the platform through stakeholder testing and real planning processes, thereby evaluating how the proposed methodological framework supports evidence-based heritage management and implementation of the HUL approach.

6. Concluding Remarks

This study set out to examine how the implementation logic of the HUL approach can be translated into the conceptual, informational, and functional organization of a heritage-sensitive UDP. Using the SPATTERN platform blueprint and Serbian spa settlements as an observatory case, the research demonstrates that such translation is feasible when platform development begins not with technological capabilities, but with an explicit definition of the knowledge that the platform is expected to represent, relate, and operationalize. The principal outcome is therefore not a claim that HUL can be reduced to a digital model, but the identification of a structured pathway through which its implementation logic can inform the design of digital infrastructure.

In response to RQ1, the study indicates that no single analytical tool is sufficient to translate HUL into digital knowledge requirements. What is required instead is a coordinated analytical framework. In the SPATTERN case, this framework is organized through six analytical dimensions (SLNR, AHCHM, SMO, FHS, PSS and UTC), a typological framework of urban patterns, archetypes and settlement categories (C1–C10), and six user profiles, which together translate the HUL knowledge requirements into data structures and platform functionalities. It combines multi-layer documentation, spatial and historical interpretation, morphological analysis, community and user knowledge, comparative analysis and planning information. The analysis also identifies capacities that the HUL implementation logic requires but that remain outside the current blueprint: structured consensus-building,

value and vulnerability assessment, and partnership-based local management. Temporal monitoring, treated here as a cross-cutting capacity rather than a separate HUL step (Section 2.2), is supported only through the historical timeline and not through continuous or real-time observation. The practical implication is that the development of heritage-sensitive UDPs should begin with the formulation of knowledge requirements derived from heritage objectives, rather than with the selection of available technologies or datasets. This reverses the conventional technology-driven sequence: analytical requirements define the necessary data and relationships, which subsequently determine appropriate digital methods, platform components, and functionalities.

In response to RQ2, the findings show that heterogeneous heritage knowledge becomes platform-compatible when it is progressively transformed through a traceable sequence from empirical evidence to analytical categories, relational structures, user requirements, datasets, and functional modules. The SPATTERN case suggests that the critical operation is therefore not simply data integration, but the construction of an intermediate knowledge architecture structured to retain relationships between natural systems, urban morphology, heritage values, socio-cultural practices, and patterns of use while translating them into digital features. For future platform development, this implies that interoperability should be addressed not only at the technical level of data formats and standards, but also at the semantic level. The meaning, provenance, scale, and analytical role of heritage information need to remain traceable as knowledge moves from research to database and from database to platform functionality.

In response to RQ3, the HUL–SPATTERN crosswalk demonstrates that correspondence between a normative heritage framework and a UDP should be understood as a multi-level relationship rather than a binary condition of compliance. The strongest basis for alignment occurs when a HUL requirement can be followed consistently from a conceptual principle, through an explicit information structure, to a corresponding platform function. Where this chain remains incomplete, the gap itself becomes operationally useful because it identifies what must be developed further. In particular, the partial correspondence identified for consensus-building, vulnerability assessment and partnership-based local management, and the supportive-only correspondence for action prioritization, demonstrate that the availability of structured heritage knowledge and comparative analytical tools should not be equated with the existence of formal assessment, deliberation or decision-making procedures. In this respect, the crosswalk can function beyond the present case as a design and evaluation instrument. Applied iteratively during platform development, it can reveal whether heritage objectives remain embedded as digital systems evolve, rather than being progressively displaced by technological or data-driven priorities.

Taken together, the three answers suggest a broader methodological principle for the development of heritage-sensitive UDPs—heritage sensitivity should be encoded in the architecture of knowledge before it is encoded in the architecture of software. For SPATTERN, the immediate next step is therefore to move from blueprint-level correspondence toward implementation-level validation. This requires testing the proposed knowledge architecture through the fully operational platform, evaluating its use within actual planning and heritage-management tasks, and examining whether the identified conceptual–informational–functional chains remain intact in practice. Application to other heritage-sensitive settlement types would provide a further test of which elements of the framework are context-dependent and which can operate as transferable components of a more general heritage-sensitive UDP model. These steps would shift validation from the internal coherence demonstrated in the present study toward evidence of adaptability and decision-support capacity in real-world contexts. This direction is consistent with the distinction drawn in Section 5.3 between the methodological framework presented here and

the subsequent need to test the completed platform itself. Ultimately, the relevance of digital infrastructures for urban heritage does not depend on their capacity to accumulate ever larger quantities of data, but on their capacity to maintain relationships between evidence, values, spatial processes and decisions. The HUL framework provides the principles through which these relationships can be understood. The contribution of the SPATTERN knowledge-translation framework lies in positioning knowledge translation between these two domains as an explicit and reproducible design process. In doing so, the study points toward UDPs that do not merely contain heritage data, but are inherently structured to process with the relational and evolving character of urban heritage.

Supplementary Materials: Supplementary Materials S1 provides the expert questionnaire research design and aggregated results, including the questionnaire structure, respondent framework, and results across the 38 spa settlements included in the study. Supplementary Materials S2 presents the SPATTERN platform blueprint, documenting its conceptual organization, data architecture, analytical dimensions, functional modules, and user profiles. These materials can be accessed at the provided links: https://doi.org/10.5281/zenodo.22725954 (accessed on 1 September 2026) (Supplementary Materials S1), and https://doi.org/10.5281/zenodo.22726080 (accessed on 1 September 2026) (Supplementary Materials S2).

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Institutional Review Board Statement: This research was conducted in accordance with the Code of Conduct for Scientific Research (21 February 2018, National Council for Scientific and Technological Development, Serbia) and the Code of Professional Ethics at the University of Belgrade (10 July 2016, Gazette of the University of Belgrade, No. 193). The research was approved by the Ethical Committee of the University of Belgrade—Faculty of Architecture (Decision No. 02-1592/2, 10 October 2020).

Informed Consent Statement: Informed consent was obtained from all participants involved in the study, including respondents who participated in the expert questionnaire and experts who took part in the workshop.

Data Availability Statement: The data supporting the findings of this study are presented within the article, its Appendices, and the Supplementary Materials. Appendix A provides a structured synthesis of the expert workshop findings, including the consolidated Mentimeter results and their methodological and functional implications for the SPATTERN platform blueprint. Appendix B presents an overview of the primary and secondary datasets used in developing the platform blueprint, including their origin, source, data type, and analytical purpose. The Supplementary Materials include the design and aggregated results of the expert questionnaire, as well as the SPATTERN platform blueprint. The study also draws on project-generated analytical materials and data obtained from publicly available and institutional sources, as specified in the manuscript. No copyrighted or otherwise restricted source materials have been reproduced or shared as part of the study.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AHCHM	Architectural Heritage and Cultural–Historical Monuments
BIM	Building Information Modeling
CityGML	City Geography Markup Language
DEM	Digital Elevation Model
FHS	Functional Hierarchy of Space
GIS	Geographic Information System
HBIM	Historic Building Information Modeling
HGIS	Historical Geographic Information System
HUL	Historic Urban Landscape
LULC	Land Use/Land Cover
NGO	Non-Governmental Organization
OSM	OpenStreetMap
POI	Point of Interest
PSS	Public Space System
SLNR	Spatial Links with Natural Resources
SMO	Specificities of Matrix and Organization
UDP	Urban Data Platform
UTC	Urban Tissue Character
WebGIS	Web Geographic Information System
WP	Work Package

Appendix A

The expert workshop, involving 22 participants representing 10 spa settlements, was structured around three interconnected phases: (1) Relational Recognition, (2) Planning Translation, and (3) Scenario Orientation. Together, these phases provided a structured framework for examining the applicability of the proposed relational approach to spa settlements, its relevance to planning practice, and its potential contribution to future development strategies. The assessment combined structured responses collected through Mentimeter with a moderated expert discussion. For analytical clarity, the questionnaire items were consolidated into thematic analytical categories corresponding to the three phases. Table A1 summarizes the principal findings and their implications for the SPATTERN analytical framework, while Table A2 documents the expert feedback and its implications for the SPATTERN blueprint. The workshop findings are interpreted as an expert-informed assessment of the applicability and practical relevance of the proposed framework, rather than as comprehensive empirical validation of the methodology or the operational performance of the digital platform.

Table A1. Consolidated Mentimeter findings and implications for the SPATTERN analytical framework.

Phase/Analytical Item	Evaluation Focus	Evidence from Mentimeter	Interpretation	Implications for SPATTERN Digital Blueprint
I. Relational Recognition: Resource–space relations	Thermal resources, public spaces and landscape relationships	Thermal resources forming the spa centre: 9 selections; connection to parks: 7. Parks as dominant public spaces: 11. Landscape integration through parks: 7	Resource-based spatial organization coexists with park-oriented and landscape-integrated configurations	Reinforces SLNR and PSS analytical dimensions and their representation through georeferenced analytical layers and spatial mapping

Table A1. *Cont.*

Phase/Analytical Item	Evaluation Focus	Evidence from Mentimeter	Interpretation	Implications for SPATTERN Digital Blueprint
I. Relational Recognition: Functional and heritage integration	Accommodation, everyday life, heritage and contemporary development	Direct accommodation–spa integration: 8 selections; complementary tourism and everyday life: 9; heritage only partially preserved: 11	Functional integration appears more established than the integration of heritage into contemporary development	Supports distinguishing FHS from AHCHM and UTC within the multidimensional platform structure, enabling separate and comparative examination
I. Relational Recognition: Institutional and infrastructural conditions	Planning regulation and infrastructure as spatial development conditions	Weak or unclear planning influence: 11 selections; infrastructure identified as a major development problem: 11	Spatial development is conditioned by institutional and infrastructural limitations	Reinforces integration of planning documentation and contextual infrastructure information into the structured settlement database and thematic analytical layers
I. Relational Recognition: Spatial dimensions and development generators	Material transformation, territorial regulation, everyday life and dominant generators	Material transformation: 2.7–2.8/5; territorial regulation: 2.3–2.4/5; everyday life: 2.7–3.1/5. Natural resources: 10 selections; medical-therapeutic systems: 9	Differences between spatial organization, regulation and everyday use support multidimensional interpretation; multiple generators coexist	Supports translation from three contextual dimensions to six preliminary platform analytical dimensions and differentiated requirements across settlement typologies
II. Planning Translation: Recognition in planning documents	Recognition of relational spatial characteristics in planning practice	Systematic recognition: 0; partial recognition: 6; limited or absent recognition: 4	Relational spatial characteristics are not consistently articulated in existing planning documents	Supports bringing together planning documents, spatial information and analytical interpretations within a shared georeferenced knowledge environment
II. Planning Translation: Critical spatial challenges	Principal development constraints and spatial conflicts	Infrastructure limitations: 10 selections; uncoordinated heritage–new development: 8; unclear spa-centre structure and tourism–everyday-life conflicts: 2 each	Infrastructure and heritage–new development relationships emerge as prominent planning concerns	Highlights AHCHM, SMO, FHS and contextual layers for interpreting conflicts, without constituting an operational vulnerability-assessment mechanism
II. Planning Translation: Planning tools and intervention priorities	Relevance of analytical tools and intervention types	Nature–urban integration: 4.5/5; heritage protection and activation: 4.2/5; urban-pattern analysis: 3.8/5. New programmes: 4.2/5; access improvements: 3.9/5	Respondents prioritized integrated environmental and heritage-sensitive approaches alongside programme and access improvements	Supports analytical filters, thematic layers, pattern-based interpretation and comparative spatial exploration, without automated intervention prioritization

Table A1. *Cont.*

Phase/Analytical Item	Evaluation Focus	Evidence from Mentimeter	Interpretation	Implications for SPATTERN Digital Blueprint
III. Scenario Orientation: Preferred development trajectories	Future development directions	Access and circulation: 4.4/5; public-space reorganization: 3.9/5; new programmes: 3.7/5; nature integration: 3.4/5	Preferred directions combine connectivity, public-space restructuring and functional diversification	Supports spatial comparison and analytical layers for interpreting alternative directions, rather than automated scenario generation
III. Scenario Orientation: Priority actions and future visions	Concrete interventions and future development perspectives	Open responses emphasized transport and infrastructure, pedestrian connections, parking, public-space renewal and heritage protection. Sustainability: 3 mentions	Immediate infrastructure and public-space needs coexist with sustainability-oriented aspirations	Supports spatially referenced narratives, contextual information and educational or research thematic contributions for communicating development perspectives

Notes: The numbers in "Evidence from Mentimeter" are observed counts of selections, not counts out of a uniform respondent total. Participation varied by question: Phase I Q1–Q8 had 11–15 respondents per item (with one additional single-response display for the regulation item); Phase I dimension ratings were displayed for two separate response sets (15 and 9 participants), and the development-generator item had 14 respondents. Phase II planning recognition had 10 respondents, spatial challenges 12, tool ratings 11, and intervention ratings 10. Phase III development-direction ratings had 14 respondents; the open intervention question showed 13 participants and the future-keyword question 9. Some questions permitted multiple selections, so selection totals may exceed the number of respondents. Scores are displayed means on a five-point scale and are not response counts.

Table A2. Expert feedback and methodological implications for the SPATTERN blueprint.

Aspect	Expert Feedback	Implications for Methodological and Digital Structuring
Relational interpretation of spa settlements	Responses identified multiple spatial configurations linking thermal resources, public spaces, natural landscapes and spa functions	Reinforces relational interpretation and its translation into interconnected dimensions, particularly SLNR, SMO, FHS and PSS
Differentiation of analytical dimensions	Assessments of material transformation, territorial regulation and everyday life showed different perceived levels of development	Supports distinct interpretative perspectives and translation into six complementary platform dimensions rather than one composite assessment
Pattern interpretation and settlement diversity	Natural-resource and medical-therapeutic generators were prominent alongside tourism, landscape, heritage and accessibility-related generators	Supports the typology–dimension approach, interpreting categories through combinations of dimensions rather than a single characteristic
Heritage and contemporary transformation	Heritage was predominantly described as partially preserved; uncoordinated heritage–new development was identified as a major challenge	Reinforces AHCHM and UTC, archetype-based documentation and historical/contextual layers for examining continuity and transformation
Planning-oriented knowledge integration	Participants reported limited systematic recognition of spatial relationships in planning documents and substantial infrastructure constraints	Supports integration of planning documentation, settlement profiles and analytical layers into a georeferenced knowledge structure; does not establish planning-compliance or infrastructure-performance evaluation

Table A2. *Cont.*

Aspect	Expert Feedback	Implications for Methodological and Digital Structuring
Planning guidance for urban patterns	Respondents prioritized nature–urban integration, heritage protection and activation, new programmes and access improvements as intervention directions	Informed the formulation of planning recommendations associated with urban patterns; the recommendations remain expert-informed and have not been validated in planning practice
Analytical exploration and comparison	Respondents rated nature–urban integration, heritage protection and urban-pattern analysis as relevant planning tools	Supports thematic filtering, analytical mapping and comparative exploration of settlement characteristics and archetypes
Development-oriented knowledge exchange	Participants emphasized accessibility, public-space improvements, programmatic activation and sustainability-oriented development	Reinforces educational thematic layers and spatially referenced contributions for communicating research and development perspectives, without validated scenario-generation or collective prioritization

Appendix B

The following table provides a structured overview of the datasets incorporated into the SPATTERN platform data architecture. The datasets are classified according to their origin, source, data type, and intended analytical purpose, distinguishing between secondary data obtained from existing institutional and open-access sources (S) and primary or project-generated data produced through the SPATTERN research process (P). This classification reflects the heterogeneous knowledge base underlying the platform and provides a reference for the data structures discussed in the methodological framework.

Table A3. Datasets integrated within the SPATTERN platform data architecture.

Dataset	Origin	Source	Data Type	Purpose/Description
Building Footprints Data	S	OpenStreetMap, Republic Geodetic Authority	Vector (Polygon)	Geometric background, structural base
Topographic Data	S	OpenStreetMap, Republic Geodetic Authority	Raster/Vector (DEM, contour lines)	Elevation, slope, terrain modeling
Street Network Data	S	Republic Geodetic Authority	Vector (Line)	Connectivity, accessibility, matrix
Parcel Boundaries Data	S	OpenStreetMap, Republic Geodetic Authority	Vector (Polygon)	Land division, ownership units
LULC Data (current)	S	OpenStreetMap, Republic Geodetic Authority	Raster/Vector	Land cover/use classification
Urban Plans & Regulation Data	S	Official Documents from Local Governance Websites	Vector (Polygon)	Planning constraints and zoning
Urban Tissue Typologies Data	P	WP2, WP3	Vector/Attribute Table	Morphological classification
Building Heights Data	S	Global Building Atlas, OpenStreetMap	Attribute/3D Vector	Volumetric characteristics
Cultural Heritage Data	S	Institute for the protection of cultural monuments of Serbia	Point/Polygon + Attribute	Protected sites, monuments, assets

Table A3. *Cont.*

Dataset	Origin	Source	Data Type	Purpose/Description
Natural Heritage Data	S	Nature Conservation Institute, Republic Geodetic Authority	Point/Polygon + Attribute	Protected natural zones, landscapes
Natural Risk & Ecological Data	S	OpenStreetMap, Republic Geodetic Authority	Raster/Vector	Contextual environmental sensitivity layer (not used for vulnerability assessment in the current blueprint)
POI Data (Monuments, Trails, Facilities)	S	OpenStreetMap, Republic Geodetic Authority	Point/Line	Tourist & functional points of interest
Historical Data	P	WP1, WP2, WP3	Images, Maps, Documents	Time-based narrative, archival context
Photo Documentation Data	P	WP1, WP2, WP3	Image (JPEG, PNG)	Visual support for storytelling
Cultural Routes Data	P	WP2, WP3	Vector (Line) + Metadata	Tourist and thematic routes
Spa Infrastructure Data	P	WP2, WP3	Point/Polygon + Attribute	Facilities related to spa/wellness activities
Sustainability Commitments Data	P	WP2, WP3	Attribute Table/Indicator Matrix	Commitments to sustainability
Landscape Type Data	P	WP2, WP3	Polygon	Characterization of landscape typologies
Public Spaces System Data	P	WP2, WP3	Polygon/Attribute	Open space typologies and hierarchy
Settlement Matrix Typologies Data	P	WP2, WP3	Tabular + Spatial Index	Pattern categorization for comparison
Pattern Evolution Data	P	WP2, WP3	Vector/Image Series	Temporal change in urban patterns

Note: S = Secondary data; P = Primary/project-generated data.

References

1. van der Graaf, S.; Ballon, P. Navigating platform urbanism. *Technol. Forecast. Soc. Change* **2019**, *142*, 364–372. [CrossRef]
2. Sadowski, J. Cyberspace and cityscapes: On the emergence of platform urbanism. *Urban Geogr.* **2020**, *41*, 448–452. [CrossRef]
3. Caprotti, F.; Chang, I.C.C.; Joss, S. Beyond the smart city: A typology of platform urbanism. *Urban Transform.* **2022**, *4*, 4. [CrossRef] [PubMed]
4. Barns, S. Re-engineering the city: Platform ecosystems and the capture of urban big data. *Front. Sustain. Cities* **2020**, *2*, 32. [CrossRef]
5. Bauriedl, S.; Strüver, A. Platform urbanism: Technocapitalist production of private and public spaces. *Urban Plan.* **2020**, *5*, 267–276. [CrossRef]
6. Psyllidis, A.; Bozzon, A.; Bocconi, S.; Titos Bolivar, C. A platform for urban analytics and semantic data integration in city planning. In Proceedings of the International Conference on Computer-Aided Architectural Design Futures, São Paulo, Brazil, 8–10 July 2015; pp. 21–36.
7. Vítor, G.; Rito, P.; Sargento, S.; Pinto, F. A scalable approach for smart city data platform: Support of real-time processing and data sharing. *Comput. Netw.* **2022**, *213*, 109027. [CrossRef]
8. Anttiroiko, A.-V. Digital urban planning platforms: The interplay of digital and local embeddedness in urban planning. *Int. J. E-Plan. Res. (IJEPR)* **2021**, *10*, 35–49.
9. Bagheri, S.; Brandt, T.; Sheombar, H.S.; Van Oosterhout, M. Value Creation through Urban Data Platforms: A Conceptual Framework. In Proceedings of the HICSS, Kauai, HI, USA, 5–8 January 2021; pp. 1–10.

10. van Oosterhout, M.; Holst, J.; Sheombar, H.; van Heck, E. *Research Study on Urban Data Platforms in Europe*; Forschungsbericht; Erasmus Centre for Data Analytics: Rotterdam, The Netherlands, 2020.
11. Kourtit, K. Cultural heritage, smart cities and digital data analytics. *East. J. Eur. Stud.* **2019**, *10*, 151–159.
12. Amato, F.; Moscato, V.; Picariello, A.; Colace, F.; Santo, M.D.; Schreiber, F.A.; Tanca, L. Big data meets digital cultural heritage: Design and implementation of scrabs, a smart context-aware browsing assistant for cultural environments. *J. Comput. Cult. Herit. (JOCCH)* **2017**, *10*, 1–23.
13. Djokić, V.; Djordjević, A.; Milovanović, A. Big data and urban form: A systematic review. *J. Big Data* **2025**, *12*, 17. [CrossRef]
14. Lasorella, M.; Rondinelli, M.F.L.; Guida, A.; Fatiguso, F. Integrated Digital Environments for the Knowledge and Management of Low-Accessible Cultural Heritage: A Multiscale Web-Based Framework. *Heritage* **2026**, *9*, 133. [CrossRef]
15. Kourtit, K.; Nijkamp, P.; Romão, J. Cultural heritage appraisal by visitors to global cities: The use of social media and urban analytics in urban buzz research. *Sustainability* **2019**, *11*, 3470. [CrossRef]
16. Ducatteeuw, V.; Danniau, F.; Verbruggen, C. Mapping ghent's cultural heritage: A place-based approach with web GIS. *Int. J. Digit. Humanit.* **2025**, *7*, 91–113. [CrossRef]
17. Karayazi, S.S.; Dane, G.; de Vries, B. Utilizing urban geospatial data to understand heritage attractiveness in Amsterdam. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 198. [CrossRef]
18. Moise, C.; Dana Negula, I.; Mihalache, C.E.; Lazar, A.M.; Dedulescu, A.L.; Rustoiu, G.T.; Inel, I.C.; Badea, A. Remote sensing for cultural heritage assessment and monitoring: The case study of Alba Iulia. *Sustainability* **2021**, *13*, 1406. [CrossRef]
19. Colucci, E.; Kokla, M.; Noardo, F. Ontology-based data mapping to support planning in historical urban centres. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2021**, *43*, 39–45. [CrossRef]
20. Ranjgar, B.; Sadeghi-Niaraki, A.; Shakeri, M.; Choi, S.-M. An ontological data model for points of interest (POI) in a cultural heritage site. *Herit. Sci.* **2022**, *10*, 13. [CrossRef]
21. Artopoulos, G.; Fokaides, P.; Lysandrou, V.; Deligiorgi, M.; Sabatakos, P.; Agapiou, A. Data-driven multi-scale study of historic urban environments by accessing earth observation and non-destructive testing information via an HBIM-supported platform. *Int. J. Archit. Herit.* **2024**, *18*, 920–939. [CrossRef]
22. Matrone, F.; Colucci, E.; Iacono, E.; Ventura, G.M. The HBIM-GIS Main10ance platform to enhance the maintenance and conservation of historical built heritage. *Sensors* **2023**, *23*, 8112. [CrossRef] [PubMed]
23. Mazzetto, S. A review of urban digital twins integration, challenges, and future directions in smart city development. *Sustainability* **2024**, *16*, 8337. [CrossRef]
24. Ketzler, B.; Naserentin, V.; Latino, F.; Zangelidis, C.; Thuvander, L.; Logg, A. Digital twins for cities: A state of the art review. *Built Environ.* **2020**, *46*, 547–573. [CrossRef]
25. Fattore, C.; Buldo, M.; Priore, A.; Porcari, S.; Porcari, V.D.; De Fino, M. A comprehensive overview of heritage bim frameworks: Platforms and technologies integrating multi-scale analyses, data repositories, and sensor systems. *Heritage* **2025**, *8*, 247. [CrossRef]
26. Carlisle, P.K.; Avramides, I.; Dalgity, A.; Myers, D. The Arches Heritage Inventory and Management System: A standards-based approach to the management of cultural heritage information. In Proceedings of the CIDOC (International Committee for Documentation of the International Council of Museums) Conference: Access and Understanding–Networking in the Digital Era, Dresden, Germany, 6–11 September 2014; pp. 6–11.
27. Liu, F.; Hindmarch, J.; Hess, M. A review of the cultural heritage linked open data ontologies and models. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *XLVIII-M-2-2023*, 943–950. [CrossRef]
28. Ginzarly, M. Social media data for the conservation of historic urban landscapes: Prospects and challenges. In Proceedings of the International Conference on Human-Computer Interaction, Virtual, 24–29 July 2021; pp. 209–223.
29. Bai, N.; Ducci, M.; Mirzikashvili, R.; Nourian, P.; Roders, A.P. Mapping urban heritage images with social media data and artificial intelligence, a case study in Testaccio, Rome. In Proceedings of the 29th CIPA Symposium on Documenting, Understanding, Preserving Cultural Heritage. Humanities and Digital Technologies for Shaping the Future, Florence, Italy, 25–30 June 2023; pp. 139–146.
30. Milovanović, A.; Šošević, U.; Cvetković, N.; Pešić, M.; Janković, S.; Krstić, V.; Ristić Trajković, J.; Milojević, M.; Nikezić, A.; Simić, D. Mapping Digital Solutions for Multi-Scale Built Environment Observation: A Cluster-Based Systematic Review. *Smart Cities* **2025**, *8*, 196. [CrossRef]
31. Rey-Pérez, J.; Pereira Roders, A. Historic urban landscape: A systematic review, eight years after the adoption of the HUL approach. *J. Cult. Herit. Manag. Sustain. Dev.* **2020**, *10*, 233–258.
32. Šćekić, J.; Nikolić, M.; Milovanović, A. The Notion of Value in the Global Academic Discourse: Identification and Representation in the Main Approaches to Cultural Heritage Preservation. *Architecture* **2026**, *6*, 20. [CrossRef]
33. Barns, S. Smart cities and urban data platforms: Designing interfaces for smart governance. *City Cult. Soc.* **2018**, *12*, 5–12. [CrossRef]
34. Kitchin, R.; McArdle, G. Urban data and city dashboards: Six key issues. *SocArXiv* **2016**. [CrossRef]
35. Kitchin, R. Data-driven urbanism. In *Data and the City*; Routledge: London, UK, 2017; pp. 44–56.

36. Pradhan, S.; Dubey, A.; Khare, S.; Nannapaneni, S.; Gokhale, A.; Mahadevan, S.; Schmidt, D.C.; Lehofer, M. Chariot: Goal-driven orchestration middleware for resilient iot systems. *ACM Trans. Cyber-Phys. Syst.* **2018**, *2*, 1–37.
37. Jeddoub, I.; Nys, G.-A.; Hajji, R.; Billen, R. Digital Twins for cities: Analyzing the gap between concepts and current implementations with a specific focus on data integration. *Int. J. Appl. Earth Obs. Geoinf.* **2023**, *122*, 103440. [CrossRef]
38. Dore, C.; Murphy, M. Integration of HBIM and 3D GIS for digital heritage modelling. In Proceedings of the Digital Documentation International Conference, Edinburgh, Scotland, 22–23 October 2012.
39. Di Stefano, F.; Malinverni, E.S. Extension of the CityGML Schema for a New Model of Accessible Urban Environment. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2025**, *48*, 375–382. [CrossRef]
40. Ricca, S.; Luo, X. The Implementation of the UNESCO Historic Urban Landscape Recommendation. In Proceedings of the International Expert Meeting, Shanghai, China, 26–28 March 2018; pp. 26–28.
41. Bandarin, F.; Van Oers, R. *The Historic Urban Landscape: Managing Heritage in an Urban Century*; John Wiley & Sons: Hoboken, NJ, USA, 2012.
42. Ginzarly, M.; Houbart, C.; Teller, J. The Historic Urban Landscape approach to urban management: A systematic review. *Int. J. Herit. Stud.* **2019**, *25*, 999–1019. [CrossRef]
43. UNESCO. *Urban Heritage for Resilience: Consolidated Results of the Implementation of the 2011 Recommendation on the Historic Urban Landscape*; 3rd Member States Consultation; UNESCO: Paris, France, 2023; 132p.
44. Misilmani, A.H.; El-Bastawissi, I.Y.; Ayad, H.; El Sayary, S. BIM-GIS integration an innovative tool to enhance urban heritage management in the digital era. *Archit. Plan. J. (APJ)* **2024**, *30*, 3. [CrossRef]
45. Tian, Z. Heritage as a driver for resilience: A four-dimensional Historic Urban Landscape (HUL) approach to cultural heritage in urban development. In Proceedings of the ISOCARP World Planning Congress, Siena, Italy, 8–12 October 2024.
46. Oliveira, V. *Urban morphology: An Introduction to the Study of the Physical Form of Cities*; Springer: Berlin/Heidelberg, Germany, 2016.
47. Whitehand, J. Urban morphology and historic urban landscapes. *World Herit. Pap.* **2010**, *27*, 35–44.
48. Oliveira, V.; Porta, S. Quantitative and qualitative analysis in urban morphology: Systematic legacy and latest developments. *Proc. Inst. Civ. Eng.-Urban Des. Plan.* **2025**, *178*, 75–87. [CrossRef]
49. Samuel, J.; Périnaud, C.; Gay, G.; Servigne, S.; Gesquière, G. Representation and visualization of urban fabric through historical documents. In Proceedings of the 14th EUROGRAPHICS Workshop on Graphics and Cultural Heritage, Genoa, Italy, 5–7 October 2016; pp. 157–166.
50. Colucci, E.; Iacono, E.; Matrone, F.; Ventura, G.M. The development of a 2D/3D BIM-GIS web platform for planned maintenance of built and cultural heritage: The MAIN10ANCE project. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 433–439. [CrossRef]
51. Fleischmann, M.; Feliciotti, A.; Romice, O.; Porta, S. Morphological tessellation as a way of partitioning space: Improving consistency in urban morphology at the plot scale. *Comput. Environ. Urban Syst.* **2020**, *80*, 101441. [CrossRef]
52. Oliveira, V.; Medeiros, V. Morpho: Combining morphological measures. *Environ. Plan. B Plan. Des.* **2016**, *43*, 805–825. [CrossRef]
53. Milovanović, A.; Pešić, M.; Janković, S.; Krstić, V.; Ristić Trajković, J.; Milojević, M.; Nikezić, A.; Đokić, V. *Compendium of Spascapes: Personalities, Form and Development*; Faculty of Architecture—University of Belgrade: Belgrade, Serbia, 2025.
54. Milovanović, A.; Pešić, M.; Janković, S.; Krstić, V.; Ristić Trajković, J.; Milojević, M.; Nikezić, A.; Đokić, V. *Decoder of Spascapes: Rulebook for Patterns Definition*; Faculty of Architecture—University of Belgrade: Belgrade, Serbia, 2026.
55. Cvetković, N.; Šošević, U.; Pešić, M.; Milovanović, A.; Simić, D.; Đokić, V. *Blueprint for the SPATTERN Digital Platform: Structuring Data, Users, and Functionalities (Deliverable D4.1)*; Faculty of Architecture—University of Belgrade: Belgrade, Serbia, 2025.
56. Cassatella, C.; Carlone, G. GIS-based visual analysis for planning and designing historic urban landscapes: The case of Turin. In Proceedings of the 2013 Digital Heritage International Congress (DigitalHeritage), Marseille, France, 28 October–1 November 2013; pp. 45–52.
57. Widodo, J.; Wong, Y.C.; Ismail, F. Digital historic urban landscape methodology for heritage impact assessment of Singapore. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *4*, 327–334. [CrossRef]
58. Wang, X.; Han, F.; Bian, X.; Li, Z. Mapping the Past with Present Digital Tools: Historic Urban Landscape Research in Chinese City, Xi'an Walled City Area. *Built Herit.* **2018**, *2*, 42–57. [CrossRef]
59. Bai, X.; Jiao, X.; Sakai, T.; Xu, H. Mapping the past with historical geographic information systems: Layered characteristics of the historic urban landscape of Nanjing, China, since the Ming Dynasty (1368–2024). *Herit. Sci.* **2024**, *12*, 283. [CrossRef]
60. Ramírez Eudave, R.; Ferreira, T.M. Characterisation of the historic urban landscape through the Aristotelian four causes: Towards comprehensive GIS databases. *Remote Sens.* **2021**, *13*, 1879. [CrossRef]
61. Zhao, X.; Marnane, K.; Greenop, K. The role of digital technologies in recording values of human settlements: Testing a practical Historic Urban Landscape approach in China and India. *Digit. Creat.* **2021**, *32*, 253–274. [CrossRef]
62. Van der Hoeven, A. Historic urban landscapes on social media: The contributions of online narrative practices to urban heritage conservation. *City Cult. Soc.* **2019**, *17*, 61–68. [CrossRef]

63. Ginzarly, M.; Roders, A.P.; Teller, J. Mapping historic urban landscape values through social media. *J. Cult. Herit.* **2019**, *36*, 1–11. [CrossRef]
64. van der Hoeven, A. Valuing urban heritage through participatory heritage websites: Citizen perceptions of historic urban landscapes. *Space Cult.* **2020**, *23*, 129–148. [CrossRef]
65. Albuquerque, A.R.; Botelho, M.L.; Crozat, D. Storytelling and online media as narrative practices for engaging with the Historic Urban Landscapes (HUL). In *Landscape as Heritage. International Critical Perspectives*; Routledge: London, UK, 2022; pp. 67–79.
66. Zhou, X.; Tang, Y.; Su, J. Heritage corridor routing method from historic urban landscape and digital footprint perspectives—The case of historical urban area in Nanjing, China. *Landsc. Archit. Front.* **2023**, *11*, 11–37. [CrossRef]
67. Aliakbari, F.; Dinler, M. Application of digital tools in heritage landscapes: A Systematic Literature Review. *Stud. Digit. Herit.* **2025**, *9*, 383–405. [CrossRef]
68. Ripp, M.; Gustafsson, C.; Jones, Z.; Majumdar, S.; Ginzarly, M. Historic urban landscapes and heritage systems as the basis for sustainable urban development. *Land* **2025**, *14*, 1783. [CrossRef]
69. World Heritage Training and Research Institute for the Asia and the Pacific Region; Australia. City of Ballarat; Tongji University (China); Federation University Australia. *The HUL Guidebook: Managing Heritage in Dynamic and Constantly Changing Urban Environments; A Practical Guide to UNESCO's Recommendation on the Historic Urban Landscape*; Federation University Australia: Ballarat, Australia, 2016; 59p.
70. Ramírez Eudave, R.; Ferreira, T.M. On the suitability of a unified GIS-BIM-HBIM framework for cataloguing and assessing vulnerability in Historic Urban Landscapes: A critical review. *Int. J. Geogr. Inf. Sci.* **2021**, *35*, 2047–2077. [CrossRef]
71. UNESCO. *New Life for Historic Cities: The Historic Urban Landscape Approach Explained*; United Nations Educational, Scientific and Cultural Organization (UNESCO): Paris, France, 2013.
72. Yang, C.; Chen, Z.; Han, F.; Du, M. Aligning UNESCO HUL Approach with Digital Transformation: A Spatiotemporal Inventory Framework for Urban Landscape Heritage. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2025**, *48*, 1639–1644. [CrossRef]
73. Elwazani, S.; Khorshidifard, S. The public participation in the implementation of the UNESCO's Historic Urban Landscape approach. *J. Cult. Herit. Manag. Sustain. Dev.* **2024**, *16*, 689–707. [CrossRef]
74. Shin, H.; Kang, H. Educational Strategies for Digital Documentation in Southeast Asian World Heritage Cities: Implementing the HUL Approach. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2025**, *X-M-2-2025*, 309–315. [CrossRef]
75. Ginzarly, M.; Joshi, M.Y.; Teller, J. A multidimensional framework for assessing cultural heritage vulnerability to flood hazards. *Int. J. Herit. Stud.* **2024**, *30*, 1173–1192. [CrossRef]
76. Quesada-Ganuza, L.; Garmendia, L.; Alvarez, I.; Roji, E. Vulnerability assessment and categorization against heat waves for the Bilbao historic area. *Sustain. Cities Soc.* **2023**, *98*, 104805. [CrossRef]
77. Cacciotti, R.; Sardella, A.; Drdácký, M.; Bonazza, A. A Methodology for Vulnerability Assessment of Cultural Heritage in Extreme Climate Changes. *Int. J. Disaster Risk Sci.* **2024**, *15*, 404–420. [CrossRef]
78. Tucci, G.; Fiorini, L.; Meucci, A.; Conti, A. Integrated Geomatic Solutions for the Digital Twin of Florence: Protecting the Arno River and its Historic Urban Landscape from Climate Risks. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2025**, *48*, 1463–1470. [CrossRef]
79. Altuntaş, S.U.; Atalay, H.; Dervisoglu, A. Urban Silhouette Analysis in Historical Peninsula Süleymaniye District Using Digital Twin Technology. *Turk. J. Eng.* **2026**, *10*, 640–648. [CrossRef]
80. Gaffney, C.F.; Croucher, K.; Bates, C.R.; Booker, O.; Dunn, R.; Evans, A.; Ichumbaki, E.B.; Moore, J.; Ogden, J.; Ritchings, J. Digital twins at the city and town scale: Europe and beyond. *Internet Archaeol.* **2025**, 70. [CrossRef]
81. Trillo, C.; Aburamadan, R.; Udeaja, C.; Moustaka, A.; Baffour, K.G.; Makore, B.C.N. Enhancing heritage and traditional architecture conservation through digital technologies. Developing a digital conservation handbook for As-Salt, Jordan. In Proceedings of the International Symposium: New Metropolitan Perspectives, Online, 26–28 May 2020; pp. 211–219.
82. Kaya, D.I. Smart decision making for global heritage cities: Innovative community engagement and management tools for historic urban landscapes. In Proceedings of the AHRA 2018: Smartness? Between Discourse and Practice, Eindhoven, The Netherlands, 15–17 November 2018.
83. Indrajaya, I.; Fisu, A.A.; Hafid, Z.A.; Natsir, R.; Dahlan, A.; Marzaman, L.U. Developing a WebGIS-based spatial information system integrating historical data to map cultural heritage buildings in Palopo. *Reg. J. Pembang. Wil. Dan Perenc. Partisipatif* **2026**, *21*, 470–489. [CrossRef]
84. Villanueva-Merino, A.; López-de-Aguileta-Benito, A.; Izkara, J.L.; Egusquiza, A. Spatial decision making for improvement of the resilience of the historic areas: SHELTER DSS. In Proceedings of the International Conference on Innovation in Urban and Regional Planning, L'Aquila, Italy, 6–8 September 2023; pp. 384–395.
85. Ghandehariun, S.; Faghihi, S. Dynamic Decision-Support for Heritage-Sensitive Urban Regeneration: An AI-Driven Framework Integrating Socio-Cultural Sustainability. *Results Eng.* **2025**, *28*, 108189. [CrossRef]

86. Jaillot, V.; Istasse, M.; Servigne, S.; Gesquière, G.; Rautenberg, M.; Lefort, I. Describing, comparing and analysing digital urban heritage tools: A methodology designed with a multidisciplinary approach. *Digit. Appl. Archaeol. Cult. Herit.* **2020**, *17*, e00135. [CrossRef]
87. Zhang, L. Preserving Cultural Heritage in the Age of Tourism: Stakeholder Collaboration and Digital Solutions for Sustainable Development. *Sustain. Dev.* **2026**, *34*, 6208–6238. [CrossRef]
88. Cunha Ferreira, T.; Rey-Pérez, J.; Pereira Roders, A.; Tarrafa Silva, A.; Coimbra, I.; Breda Vazquez, I. The historic urban landscape approach and the governance of world heritage in urban contexts: Reflections from three European cities. *Land* **2023**, *12*, 1020. [CrossRef]
89. Available online: https://spattern.org/about/ (accessed on 9 September 2026).
90. Milovanović, A.; Pešić, M.; Janković, S.; Milojević, M.; Ristić Trajković, J.; Krstić, V.; Nikezić, A.; Djokić, V. Spascapes as Relational Constructs: A Model-Based Framework for Comparative Spa Settlement Analysis. *Urban Sci.* **2026**, *10*, 311. [CrossRef]
91. UNESCO. Nomination of the Great Spas of Europe for Inclusion on the World Heritage List. Available online: https://www.greatspatownsofeurope.eu/the-great-spa-towns/downloads/the-nomination-document/ (accessed on 9 September 2026).
92. Đokić, V.; Simić, D.; Nikezić, A.; Milojević, M.; Ristić Trajković, J.; Krstić, V.; Šošević, U.; Pešić, M.; Janković, S.; Cvetković, N. *SPATTERN Review of Methodological Approaches*; Faculty of Architecture, University of Belgrade: Belgrade, Serbia, 2024.
93. Đokić, V.; Simić, D.; Nikezić, A.; Milojević, M.; Ristić Trajković, J.; Krstić, V.; Šošević, U.; Pešić, M.; Janković, S.; Cvetković, N. *SPATTERN Database of Spa Settlements in Serbia*; University of Belgrade-Faculty of Architecture: Belgrade, Serbia, 2024.
94. Đokić, V.; Simić, D.; Nikezić, A.; Milojević, M.; Ristić Trajković, J.; Krstić, V.; Šošević, U.; Pešić, M.; Janković, S.; Cvetković, N. *SPATTERN Study: Questionnaire for the State-of-the-Art*; University of Belgrade-Faculty of Architecture: Belgrade, Serbia, 2024.
95. Schmid, C.; Streule, M. *Vocabularies for an Urbanising Planet: Theory Building Through Comparison*; Birkhäuser: Basel, Switzerland, 2023.
96. Zhu, X.X.; Chen, S.; Zhang, F.; Shi, Y.; Wang, Y. GlobalBuildingAtlas: An open global and complete dataset of building polygons, heights and LoD1 3D models. *Earth Syst. Sci. Data* **2025**, *17*, 6647–6668. [CrossRef]

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