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Mapping Digital Solutions for Multi-Scale Built Environment Observation: A Cluster-Based Systematic Review

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INTRODUCTION

Review question / Objective This systematic literature review investigates how digital tools and methods are applied for the observation of the built environment across three interrelated domains — Urban Planning and Development (UPD), Architecture, Engineering and Construction (AEC), and Cultural Heritage (CH). The review aims to decode methodological clusters that define the current landscape of digital solutions and to interpret their interdependencies within a multi-scale workflow, spanning object-, building-, neighborhood-, and city-level applications. The overarching objective is to move beyond fragmented or technology-specific accounts of digital transformation and to develop an integrative methodological understanding that connects diverse disciplinary perspectives.

Three complementary research questions (RQs) guide the review:

RQ1: What are the methodological clusters emerging from the intersection of digital advancements and the built environment, and how can they be visualized and interpreted?

RQ2: What are the key features and attributes of identified solutions, and how do they group into functional categories?

RQ3: What are the comparative roles and interdependencies of these clusters, and how do they inform potential for future research?

Rationale The increasing integration of digital technologies into architecture, planning, and heritage practices has transformed the way the built environment is observed, analyzed, and managed. Over the past decade, the proliferation of digital tools (ranging from BIM-based modeling and GIS analytics to real-time sensors, 3D visualization, and digital-twin platforms) has enabled multidimensional insight into spatial, environmental, and socio-technical systems.

Despite this rapid advancement, the methodological foundations that connect these tools across disciplinary and operational contexts remain fragmented. Existing literature is dispersed across isolated domains such as urban analytics, construction informatics, and cultural-heritage digitization, which often employ different terminologies, scales, and validation approaches.

Prior systematic reviews in related fields have primarily focused on sectoral or technology-specific questions, for example, BIM adoption in construction, smart-city infrastructures, or HBIM applications in heritage preservation. While informative, these studies seldom transcend disciplinary boundaries or examine cross-domain methodological interplay. Moreover, bibliometric reviews that map research trends tend to remain limited to co-authorship or keyword frequencies without interpretive synthesis. Consequently, a comprehensive, integrative framework capturing how digital methods co-evolve across AEC, UPD, and CH domains is still absent. The review therefore situates itself at the intersection of these three knowledge domains, emphasizing the methodological interoperability of digital tools and their potential to act as components within unified observation systems.

Condition being studied This systematic review addresses the state and evolution of digital methods and tools applied to the observation, analysis, and management of the built environment. The "condition" being studied is methodological condition, namely, the fragmentation and lack of interoperability among digital solutions used across AEC, UPD, and CH domains. Specifically, it investigates how digital approaches (ranging from spatial analytics and computational modeling to visualization and real-time monitoring) can be interpreted as interdependent components of an integrated digital workflow. In this sense, the "condition being studied" refers to the present methodological maturity, interdependence, and interoperability of digital methods in built-environment research and practice. The review ultimately seeks to provide a comprehensive diagnosis of this condition, identifying its structure, gaps, and developmental potential, thereby informing the design of future interoperable digital platforms and research frameworks for urban and heritage contexts.

METHODS

Search strategy The search strategy followed the PRISMA 2020 guidelines and combined both structured keyword formulation and iterative refinement to ensure comprehensive yet targeted coverage of the literature addressing digital methods for built-environment observation.

1. Databases and search period
The primary data source was the Scopus database, selected for its broad interdisciplinary coverage across AEC, UPD, and CH research domains. To verify database consistency and cross-index completeness, supplementary searches were performed in Web of Science and IEEE Xplore. The final Scopus search was conducted on 16 April 2025. The selected period (2013 – 2025) captures the consolidation decade of digital transformation in the built environment, from the diffusion of BIM and GIS tools to the emergence of digital-twin platforms and real-time data analytics.

2. Search terms and Boolean query structure
The search string was developed through a three-stage process: (1) Identification of thematic pillars based on preliminary screening and scoping documents, (2) Combination of controlled vocabulary and free-text terms representing both methodological and domain dimensions, and (3) Testing and refinement of the Boolean syntax to balance precision.

The final Boolean query applied in Scopus was built around two conceptual dimensions:
Built-environment context: ("built environment" OR "urban form" OR "urban morphology" OR "urban planning" OR "architectural design" OR "cultural heritage" OR "heritage conservation")
AND
Digital methods and tools: ("digital methods" OR "digital tools" OR "data visualization" OR "digital twin" OR "computational design" OR "BIM" OR "GIS" OR "machine learning" OR "spatial analysis")

These two dimensions were combined using AND, resulting in a comprehensive yet focused dataset that reflects cross-domain applications of digital technology in spatial research and practice.

3. Filters and inclusion limits
To maintain relevance and reproducibility, the following filters were applied:
Language: English only;
Subject areas: g "Social Sciences", "Computer Science", "Engineering", "Environmental Science", "Earth and Planetary Sciences", "Arts and Humanities", "Agricultural and Biological Sciences", "Decision Sciences", "Multidisciplinary";

4. Refinement and validation
The search strategy underwent iterative refinement by a multidisciplinary team of three researchers to ensure conceptual inclusiveness across AEC, UPD, and CH contexts. Adjustments to keyword combinations and Boolean connectors were implemented until no new relevant records appeared in test queries.

The final dataset contained 5261 records initially retrieved from Scopus. After duplicate removal and title/abstract screening, 2124 records were retained for further eligibility evaluation. Following full-text assessment against inclusion and exclusion criteria, 507 records were shortlisted, of which 29 were ultimately included for synthesis as solution-oriented studies demonstrating concrete digital methodologies or tools.

5. Screening and reproducibility
Screening was conducted in three stages: (1) title and keyword relevance, (2) abstract relevance, and (3) full-text eligibility. Each stage was performed independently by three reviewers, with results cross-checked to ensure consistency. Inter-reviewer reliability was verified through Cohen's $\kappa = 0.86$, indicating high agreement. All retrieved metadata (authors, titles, keywords, source journals, and DOIs) were exported to CSV format and processed in VOSviewer 1.6.20 for co-occurrence analysis and clustering. The same dataset was subsequently used for qualitative interpretation and coding in a collaborative spreadsheet environment.

Participant or population This review does not involve human or clinical participants. The population addressed consists of scientific studies and research outputs focusing on the use of digital tools and methods for the observation and analysis of the built environment. Thus, the "population" under study comprises the body of peer-reviewed literature published between 2013 and 2025 that documents empirically grounded digital methodologies.

Intervention This review does not evaluate a clinical or behavioral intervention in the conventional sense; therefore, the concept of "intervention" is not directly applicable to this type of study. However, within the scope of this systematic review, the term can be analogically understood as referring to digital methodological approaches and computational frameworks applied to the observation and analysis of the built environment.

Comparator This systematic review does not include a clinical or experimental comparator in the conventional sense; therefore, the concept of "control" is not directly applicable to this type of study. Nevertheless, a conceptual comparator can be identified in relation to traditional and single-domain approaches to built-environment research and practice that rely on fragmented, discipline-specific, or analogue methodologies.

Study designs to be included Solution-oriented empirical and methodological studies.

Eligibility criteria The eligibility criteria were defined through a two-level inclusion framework integrating topical, disciplinary, and methodological dimensions, and validated through Key Performance Indicators (KPIs) that ensured solution-oriented focus and methodological rigor.

Inclusion criteria
1. Topical relevance – Studies must directly address the application of digital tools and methods for observing, representing, or analyzing the built environment. Eligible works include methodological developments, integrative frameworks, or comparative studies of digital approaches in spatial analysis.
2. Research setting – Papers must be positioned within the professional domains of Architecture, Engineering and Construction (AEC), Urban Planning and Design (UPD), or Cultural Heritage (CH), including interdisciplinary and multidisciplinary contexts related to these domains.
3. Methodological rigor – Studies must present a clearly defined research design, data collection techniques, and analytical procedures, ensuring reliability, validity, and transparency in the methodological process.
4. Solution-oriented contribution – Only studies demonstrating concrete digital implementations (applications, platforms, engines, or protocols) are included. Papers must show verifiable outcomes (e.g., case studies, prototypes, or simulations) and allow replication or transferability of methods across AEC, UPD, and CH domains.
5. KPI-based quality validation – Each study was assessed against four KPIs:
5.1. Functionality – Demonstrated operation of a digital tool or platform in a real or simulated context.
5.2. Scalability – Potential for adaptation beyond the original context.
5.3. Interoperability – Integration with other digital systems or datasets.

5.4. Replicability and Transparency – Reproducibility of workflows and openness of methodological documentation

Exclusion criteria
1. Papers that are purely conceptual or theoretical, without implemented or tested digital methods.
2. Studies outside the AEC, UPD, or CH scope (e.g., unrelated computer science or social science works).
3. Publications lacking methodological transparency or insufficient detail for replication.
4. Non–peer-reviewed or non-indexed documents, works not in English, or published outside the 2013–2025 time frame.

Information sources The Scopus database was selected as the main source of bibliographic data due to its wide disciplinary range, extensive indexing of both journal and conference publications, and suitability for bibliometric and content-based analyses. Scopus provided comprehensive access to peer-reviewed studies combining digital technologies, spatial analysis, and methodological innovation.

To confirm data reliability and consistency, supplementary cross-checking searches were conducted in Web of Science (WoS) and IEEE Xplore. These secondary sources were used to verify the coverage of key papers, identify potential omissions, and validate the integrity of retrieved metadata.

The search period extended from January 2013 to April 2025, covering the decade of significant digital transformation in built-environment research. The final search update was performed on 16 April 2025.

Main outcome(s) The main outcome of this systematic review is the identification and interpretation of four methodological clusters that collectively represent the digital transformation of the built-environment observation process. These clusters were derived from a combined bibliometric and qualitative synthesis of 29 solution-oriented studies and visualize the structure, interdependence, and functional complementarity of digital methods applied across AEC, UPD, and CH domains.

1. Data Integration and User-Centric Analysis – focuses on multi-source data fusion, interoperability, and participatory analytics, enabling user-centered exploration and decision support.
2. Advanced 3D Spatial Analysis and Processing – includes workflows using BIM, GIS, and computational modeling for morphological, structural, and environmental analysis at various spatial scales.
3. Real-Time Interaction and Digital-Twin Support – encompasses dynamic feedback systems, simulation, and IoT-based sensing that integrate physical and digital environments for monitoring and adaptive management.
4. 3D Visualization and Communication – covers digital storytelling, visualization, AR/VR, and other immersive or interactive forms of spatial communication.

Quality assessment / Risk of bias analysis Quality assessment in this review followed a multi-layered validation procedure combining methodological screening, KPI-based evaluation, and inter-coder reliability testing to ensure transparency, consistency, and robustness of the included studies. The review did not apply traditional bias assessment tools used in clinical or experimental research. Instead, risk of bias was addressed through the design of the selection and evaluation process itself, ensuring that only studies meeting explicit methodological and empirical standards were included.

The procedure consisted of three stages:

1. Relevance screening – initial filtering of titles and abstracts against topical and disciplinary criteria (AEC, UPD, CH).
2. Full-text assessment – evaluation of methodological transparency, data availability, and analytical procedures.
3. Quality validation using Key Performance Indicators (KPIs).

Only papers meeting satisfactory levels across all four KPIs were retained as solution-oriented studies (29 in total). Studies with conceptual or unverified approaches were excluded. To ensure reliability, three researchers conducted the evaluation process. Inter-rater agreement was statistically verified using Cohen's $\kappa = 0.86$, indicating high consistency and minimal subjective bias.

Strategy of data synthesis Data synthesis was designed as a two-tier analytical process combining quantitative bibliometric analysis and qualitative content interpretation to ensure both structural and interpretive understanding of the methodological landscape. The integration of these approaches enabled the review to identify, visualize, and interpret methodological clusters and their interrelations across the AEC, UPD, and CH domains. 1. Quantitative synthesis (Bibliometric co-occurrence analysis)

The quantitative stage was conducted using VOSviewer (version 1.6.20), applying co-occurrence mapping based on author keywords, titles, and abstracts extracted from the Scopus dataset. Each bibliographic record was analyzed for keyword frequency (OCC – Occurrence Count) and Total Link Strength (TLS), representing conceptual proximity among studies.

VOSviewer's LinLog layout algorithm was used to visualize the semantic distances between keywords and generate network clusters, which form the structural foundation for identifying thematic domains of digital methods. The output of this phase produced a weighted network map, from which four primary clusters were extracted based on conceptual density and internal link strength.

2. Qualitative synthesis (Feature-based content analysis)

The second stage involved a manual qualitative coding process, where each of the 29 included solution-oriented studies was examined in depth to identify analytical features—specific methodological characteristics, tools, or workflows. A total of 30 analytical features were defined and grouped into five comparative dimensions, enabling consistent cross-study evaluation.

Qualitative synthesis validated and contextualized the bibliometric clusters by examining their methodological function, application scale, and interoperability potential.

3. Comparative and interdependency analysis

Following the two primary analytical layers, a comparative synthesis was conducted to interpret how the identified clusters interrelate as parts of a broader digital workflow. This stage resulted in the recognition of four interdependent methodological clusters. These clusters were further analyzed through an interdependency matrix, revealing the sequential and reciprocal relations that structure the digital transformation of built-environment research.

4. Integration and visualization

The results of both analyses were integrated and visualized through diagrams and tables, ensuring reproducibility and transparency. The synthesis approach thus provided a hybrid evidence base, combining the precision of bibliometric mapping with the interpretive depth of qualitative analysis, compliant with PRISMA 2020 standards.

Subgroup analysis Subgroup analysis in this review was conducted to identify and interpret internal variations among the included solution-oriented studies. This analysis was based on methodological differentiation and functional categorization of digital approaches applied within the built environment. Within and across these four clusters, subgroup analysis explored comparative dimensions that further differentiate methodological orientations:

1. Scale of application (object, building, district, city),
2. Data typology (geometric, semantic, environmental, social),
3. Interoperability capacity (degree of integration between tools and datasets), and
4. User engagement (expert-driven vs participatory or interactive systems).

Sensitivity analysis Sensitivity analysis in this review was designed to test the robustness and stability of the results emerging from both the bibliometric and qualitative stages of synthesis. Although the study does not include statistical sensitivity testing as in quantitative meta-analyses, it applies methodological sensitivity checks to ensure that the identified clusters and interpretations are not dependent on arbitrary analytical choices.

Three complementary procedures were applied:

1. Validation of inclusion and exclusion thresholds – The robustness of the final dataset (29 studies) was verified by varying inclusion parameters during the selection process. Trial runs were performed with slightly broader and narrower sets of criteria (e.g., inclusion of additional borderline papers or exclusion of lower-rigor studies). The resulting co-occurrence structures remained stable, confirming the consistency of cluster formation.

2. Parameter variation in bibliometric mapping – Sensitivity was tested by adjusting VOSviewer parameters such as minimum keyword occurrence, counting method (binary vs full), and layout algorithm (LinLog vs Fractionalization). Despite these changes, the core structure of the four methodological clusters and their relative proximity remained consistent, demonstrating the reliability of the co-occurrence patterns.

3. Cross-validation of qualitative coding – In the qualitative stage, feature identification and cluster interpretation were independently performed by three reviewers. Discrepancies were discussed until consensus was achieved. Cohen's κ = 0.86

indicated high inter-coder agreement, suggesting minimal interpretive bias.

Additional checks involved comparing the OCC and TLS metrics across VOSviewer outputs to confirm internal stability of network linkages. Minor variations in node density or color assignment did not alter cluster composition or the interpretive logic of the synthesis.

Overall, the sensitivity analysis demonstrated that both the quantitative structure (cluster configuration) and qualitative interpretation (methodological typology) are robust to parameter changes and reviewer subjectivity. This confirms that the observed four-cluster framework represents an inherent structural property of the literature rather than an artifact of the analytical procedure.

Country(ies) involved Conducted in Serbia by researchers from the University of Belgrade — Faculty of Architecture, Faculty of Organizational Sciences, and Faculty of Philosophy.

Keywords digital tools; built environment observation; systematic literature review; co-occurrence analysis; digital platforms; workflow integration.

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