CHALLENGES AND LIMITATIONS IN THE APPLICATION OF DIGITAL TOOLS WITHIN BUILT ENVIRONMENT DISCIPLINES: A STRUCTURED LITERATURE REVIEW

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ABSTRACT

The application of digital tools and methods in built environment-related disciplines holds significant potential for advancing knowledge and enhancing practice within architectural, urbanism-related and cultural heritage domains. However, addressing their associated risks and limitations (R&L) is essential for achieving methodological improvements. This paper presents a structured literature review based on a comprehensive keyword-driven search strategy, which initially identified 2,124 literature documents from the Scopus database. A top-down screening approach was applied, beginning with the evaluation of titles and keywords, followed by abstract screening and full-paper review where necessary, resulting in a refined sample of 509 documents. A keyword clustering strategy further narrowed the sample to 29 documents based on methodological rigor and the problem-solving focus of the studies. Through content analysis, the identified R&L were categorized into three key domains: (1) data-related, (2) technical, and (3) modeling and analysis challenges. Data-related R&L include issues with data integrity, volume, reliability, and standardization, with a focus on difficulties in integrating geospatial and historical data into 3D modeling workflows. Technical R&L reveal challenges related to tool availability, limitations in processing large geospatial datasets, visualization complexity, and topological inconsistencies in 3D models. The modeling and analysis R&L highlight computational inefficiencies, inaccuracies in 3D model extraction, challenges in workflow optimization, and semantic data integration. The findings emphasize the need for enhanced data standards, improved computational workflows, and open-source digital tools to support urban research and planning. This review provides a foundation for addressing methodological gaps and fostering innovations in the digital analysis of the built environment.

KEYWORDS _ *Digital tools, Built environment, Research gaps, Literature Review*

INTRODUCTION

Contextual Background: Digital Transformation in the Built Environment Disciplines

The increasing integration of digital technologies within built environment disciplines has been recognized as a critical area of strategic importance by numerous international policy and strategy documents. These frameworks emphasize that while digital tools offer significant potential to advance architectural, urban, and cultural heritage practices, understanding the associated risks and limitations is essential for ensuring sustainable and responsible innovation. The European Commission's Digital Agenda for the Built Environment highlights the urgent need for deeper integration of digital technologies such as Building Information Modeling (BIM), digital twins, and AI-powered design tools into traditional built environment practices (European Commission, 2024). Similarly, the Royal Institute of British Architects (RIBA) Digital Strategy 2020–2030 underlines the transformative impact of digital technologies on architectural practice, design methodologies, collaboration models, client engagement, and sustainability strategies. The strategy explicitly calls for the evolution of architectural education and practice to move beyond technical proficiency, encouraging critical reflection on how digital tools fundamentally reshape design thinking, professional relationships, and the built environment itself (RIBA, 2020). The Construction Industry Council's Digitalization and Innovation Policy (Construction Industry Council, 2023) further supports this perspective by (1) framing the study of digital and built environment interrelations as a strategic priority for overcoming major industry challenges, including productivity shortfalls and sustainability pressures, and (2) affirming collaborative, cross-sectoral research initiatives to foster integrated understanding and practical innovation. Finally, UNESCO's Guidelines on Digital Transformation in Cultural Heritage and Built Environment provide a critical cultural perspective, emphasizing that digital technologies not only offer tools for documentation and preservation but also act as transformative forces reshaping heritage management practices. The guidelines call for interdisciplinary research to ensure that digital innovation aligns with ethical standards, supports the safeguarding of cultural values, and fosters inclusive approaches to heritage interpretation and management (UNESCO, 2023). Against this policy backdrop, the paper addresses the pressing need to systematically analyze the risks and limitations associated with digital tools and methods in built environment disciplines. By doing so, it contributes to the broader strategic goal of developing ethically grounded, and methodologically robust frameworks for digital integration across architecture, urbanism, and cultural heritage sectors.

Research Problem and Paper Outline

The integration of digital technologies into built environment disciplines has introduced new methods for design, construction, management, and analysis. However, alongside the adoption of tools such as BIM, digital twins, IoT systems, and AI-driven platforms, significant risks and methodological limitations have been identified. Existing literature predominantly focuses on the benefits of digitalization, while systematic evaluations of associated challenges remain fragmented, domain-specific, and lacking in structured analysis. Accordingly, clear research gap is recognized: despite the widespread adoption of digital tools in built environment related disciplines (architectural, urban, and cultural heritage practices), there is insufficient consolidated knowledge regarding their technical, organizational, and epistemological limitations. The absence of a structured assessment constrains the ability to address reliability, operational efficiency, and ethical concerns in the application of digital technologies within the built environment. This paper addresses the need for a systematic and domain-sensitive analysis of the risks and limitations (R&L) associated with the use of digital tools and methods. The objective is to identify, classify, and critically examine these challenges to support methodological refinement, inform policy development, and enhance practical implementation within built environment disciplines. The paper is structured to address this research problem through a systematic literature review (SLR). It first presents the methodological approach applied to identify and select relevant literature (Section 2), followed by the categorization and analysis of extracted

risks and limitations into three overarching domains—data-related, technical, and modeling and analysis-related challenges (Section 3). The concluding section (Section 4) discusses the broader implications of the findings for research and practice, identifies the contributions of the study, outlines its limitations, and proposes directions for future research.

METHODOLOGY

The research is structured as a systematic literature review (SLR) conducted through three synchronized cycles: (1) data search and initial selection — establishing the initial sample of literature documents followed by preliminary screening; (2) data verification — finalizing the selection of literature documents; and (3) data analysis — performing an in-depth content analysis of the finalized sample.

Data Search and Initial Selection

The data search was conducted in the Scopus database using a structured keyword string: ("built AND environment" OR "urban AND morphology" OR "urban AND typology" OR "urban AND form") AND ("digital AND tools" OR "digital AND methods" OR "data AND visualization"), targeting Article Titles, Abstracts, and Keywords (Author and Indexed). This search retrieved 5261 documents. The initial refinement applied three criteria: (1) selection of English-language publications, (2) restriction to subject areas corresponding to the thematic framework of the study, and (3) limitation to documents published from 2013 onward. After applying these filters, the dataset was narrowed to 2124 documents and exported in CSV format for further analysis. A preliminary screening was then performed using a top-down approach — starting from titles and keywords, through abstracts, and full-texts where needed. Selection was based on: (1) direct relevance — focus on digital tools and methods applied to the built environment; (2) disciplinary fit — research rooted in AEC, UPD, or CH sectors, including interdisciplinary studies; and (3) methodological transparency — clear articulation of research design, data collection, and analysis. This process narrowed the dataset to 507 documents, forming the basis for identifying risks and limitations of digital methods within architecture, urbanism, and cultural heritage domains.

Data Verification

The second cycle of the study focused on verifying 507 literature documents through a two-stage process. First, documents were screened by mapping relevant keywords derived from the SPATTERN Review of methodological approaches, which defines four clusters bridging urban morphology (UM) and information technology (IT) (Djokic et al., 2024). This step retained 372 documents containing at least one verified keyword, refining the sample toward research trends emphasizing digital methods, techniques, and tools. Second, a full-paper screening was conducted, with the primary criterion being the applicability of findings to practical contexts. As a result, the sample was narrowed to 29 literature documents.

Keyword Clustering and Sample Refinement

The final, third cycle of the study consisted of an in-depth content analysis of the final sample of 29 literature documents. Each document was systematically examined with a particular focus on research questions addressing the identification of potential risks and limitations related to the use of digital tools and methods in the context of built environment disciplines. Through close reading and detailed examination of each paper, specific risks and limitations were extracted and recorded from 23 documents. Subsequently, the identified risks and limitations were thematically organized based on their nature, resulting in the formation of overarching categories (umbrella groups) and

corresponding subgroups. The content analysis was guided by a dedicated challenges and limitations criterion, structured to capture methodological weaknesses, evidence gaps, and domains requiring further development. This criterion aimed not only to identify recurring obstacles but also to highlight areas where methodological refinement, empirical validation, or conceptual clarification is necessary to advance existing knowledge.

RESULTS AND DISCUSSION: CATEGORIZATION OF RISKS AND LIMITATIONS

This section of the paper addresses the overarching aim of identifying domains where methodological improvements or additional evidence are needed to advance existing knowledge, by analyzing the risks and limitations (R&L) associated with the application of digital tools and methods in built environment-related disciplines. Through the content analysis of the final sample of literature documents, individual R&L were systematically extracted from each study. These identified risks and limitations were subsequently organized into three overarching categories according to their characteristics and thematic focus: (1) Data-related R&L, (2) Technical R&L, and (3) Modeling and Analysis R&L.

Data-related Risks and Limitations

The sub-groups of data-related R&L in the effective application of digital methods and tools in built environment disciplines are categorized into four thematic groups: (1) data integrity and consistent data sources, (2) data volume and complexity, (3) data reliability and historical coverage, and (4) data standardization and interoperability. Although this group includes a wide range of R&L, the focus is recognized in the sub-group related to data standardization and interoperability with special reference to standards associated with 3D modeling procedures. The issue of data integrity and consistent data sources is primary recognized in line with the challenge that variations in data formats and data collection methods could lead to certain mismatches. Lao & Harder (2019) observe the context of private sector which does not have access to central databases having data naming conventions complicated as consequence. Furthermore, Bitelli, Girelli & Lambertinithe (2018) spotlight the limitation of using non-specialized LiDAR data to generate 3D city models, with reference to data quality, bearing in mind that low point cloud density can significantly affect the consistency of the produced models. In terms of data volume and complexity R&L, two sub-challenges are identified: (1) the issue of large data sizes from dynamic flow data related to human movement and public transportation in a city (Seto et al, 2020) which is not necessarily standardized and tend to be considerably large, placing a higher load on memory than background data, and (2) the issue of accessing and comparing large volumes of heterogeneous geospatial data affiliated with the extensive datasets, which often comes from various sources, including city, state, and national repositories, often in different formats (Boeing, 2017), or with the big data in urban informatics (Thakuriah, Sila-Nowicka & Paule, 2016) highlighting the need for extensive data processing and filtering to prepare the heterogeneous datasets for analysis. Regarding data reliability and historical coverage R&L three sub-challenges are derived from content analysis: (1) the availability of reliable spatial-temporal data (Yin and Shiode, 2014) encompassing missing information on the year of construction and demolition for buildings and challenges in accurately representing building heights and stories for historical buildings, (2) the limited availability of high-resolution images and maps from older periods, indicating the risk of loss of valuable historical interpretations when converting historical sources into vector format such as CAD plans, 3D models, and GIS maps (Salas, 2023), and (3) the need for more relevant and enriched data to improve analyses correlating with the need to explore and integrate more diverse data sources, such as point cloud data, as well as to enhance the comprehensiveness and accuracy of the 3D models (Wang, Wang & Zhang, 2023). The last group of identified data-related R&L concern data standardization and interoperability within four different domains. The first

domain addresses the immaturity of 3D geospatial data standards in terms of manipulating 3D geo-information and managing 3D models with two-fold challenge (Tsiliakou, Labropoulos & Dimopoulou, 2013): (1) challenge in building complete 3D virtual environments, although it is recognized that GIS-based software can handle spatial information and connect with databases, and (2) 2D surface representation remains the most frequent approach although it is recognized CityGML provides a standard for 3D object description through five levels of detail. Complementary, the second domain frames the lack of standardized 3D geographic data models in relation to interoperability and data sharing across various systems and organizations, including the technical difficulties when trying to combine 2D maps and 3D models into unified research systems (Salas, 2023). Additionally, Usta, Cömert & Akın (2023) address notable drawbacks in terms of 3D Tiles standard, including the absence of explicitly defined data structures and lack of guidelines for tile sizing, while Abburu (2019) identifies limitations in the CSSWC (CityGML-based Spatial Web Services and Clients), emphasizing the necessity for 3D city models to adhere to the CityGML standard and be stored in a 3DCityDB relational schema, while also noting constraints in executing queries based on Application Domain Extensions (ADEs). The third domain is associated with data synchronization formats and detail representation levels in geospatial data in multifaceted manner. To address this challenge, Carrasco, Lombillo, & Sánchez-Espeso (2022) highlight specific R&L in integrating GIS and HBIM models, such as interoperability, semantic definition of formats, and geometry of the models. Additionally, Becker, Nagel, & Kolbe (2013) underscore the lack of different levels-of-detail (LOD) in modeling procedure and the limitation of the 3D geometry to the usage of MultiSurfaces, Solids, and graph structures with a 3D embedding requiring further development for more fine-grained and semantically enriched representations. Finally, the need for exporting data to standard data transfer formats is recognized as critical for facilitating interoperability, as highlighted by Seto et al. (2020), who emphasize the importance of unifying data formats and reducing file sizes for efficient web rendering.

Technical Risks and Limitations

This section identifies and discusses four primary groups of technical R&L: (1) tools availability and access, (2) technical shortcomings in data processing, (3) visualization complexity, and (4) topology challenges. The grouping of R&L and their analysis indicated that the mentioned technical challenges mostly relate to the context of the modeling procedure and the representation of the built environment, including the time dimension of space and the relationship between 2D and 3D representation. The first identified technical R&L group is related to tools availability and access with two-fold challenge: (1) limited availability of open-source tools both in terms of availability of databases and processing or integrative tools, and corresponding (2) economic constraints for accessing commercial desktop mapping software. Pepe et al. (2021) indicate that conversion process from GIS to CAD require intermediate processing tools, while Chundeli (2017) emphasizes the critical need for creating easy-to-use and freely available 3D tools that can effectively integrate spatial and non-spatial data. Additionally, Lao & Harder (2019) point out the sectoral-rooted challenge regarding tools availability denoting that most private companies, especially small and medium enterprises (SMEs), lack the substantial financial support needed to access advanced geospatial tools and technologies. Furthermore, this advancement becomes demanding when dealing with large volumes of geospatial data (Tsai and van Gasselt, 2022). The second recognized group of technical R&L is related to the issue of technical shortcomings in data processing associated with: (1) the challenge of datasets resolution (Tsai & van Gasselt, 2022) especially regarding traditional mapping methods which undergo limited reproducibility, distribution and data reuse capabilities and (2) operability of traditional GIS environments (Jamonnak et al, 2020) when dealing with complex spatially linked media. The limited pixel resolution of the datasets is recognized within the context of public internet resources (Tsai & van Gasselt, 2022), where technical shortcomings of pixel resolution create challenges in observing and analysis the data effectively, particularly when dealing with static maps and special file formats. On the other hand, GIS environments face limitations when handling complex spatially linked media,

where Jamonnak et al, (2020) recognize that recent GIS improvements only allow for basic video viewing functionality with limited capability beyond using it as a simple digitizing source. The third sub-group tackle the issue of visualization complexity both regarding spatial and temporal features (Dalmau et al, 2014) with special focus on 3D modeling procedures: (1) lack of data indexing and hierarchical organization methods for large-scale visualization in 3D models (Wang, Wang & Zhang, 2023), (2) challenge of communicating multiple variations and uncertainty in one model (Judge & Harrie, 2020), (3) traditional 2D maps are limited in conveying complex volumetric information, as the third dimension of space must be abstracted using color or hatch indexes (Dalmau et al, 2014), while (4) 3D city model applications are very often restricted to just visualizing built forms rather than enabling comprehensive analysis (Ahmed and Sekar, 2013). Finally, topology challenges are identified concerning relationships for 3D GIS applications (Becker, Nagel & Kolbe, 2013) including methods for saving 3D information in geospatial databases, defining topology relationships for 3D GIS applications, and establishing 3D geospatial web services. Content analysis also reveals that the current 3D intersection implementation struggles with non-manifold 3D shapes due to limitations in the half-edge data structure (Usta, Cömert & Akın, 2023).

Risks and Limitations related to Modeling and Analysis

This section provides review on primary groups of R&L related to Modeling and Analysis: (1) geometric simplification and computational efficiency, (2) model accuracy and extraction, (3) workflow optimization, and (4) semantic data enhancement. The first identified group revealed three aspects that are recognized as a need and possibility for achieving geometric simplification and computational efficiency: (1) the need for extensive geometric simplification to reduce computing time particularly as the number of layers and types of data displayed in digital bases increases (Seto et al, 2020), (2) the process of triangulating complex polygons recommending the use of convex polygons to simplify the process to overcome difficulties in the recognition of complex building shapes (Pepe et al, 2021), and (3) the need for more efficient computation of impact analyses, especially in real-time scenarios (Neuville et al, 2019). The second group is related to model accuracy and extraction and includes three sub-groups: (1) the accuracy of 3D models and the height extraction process within 3D intersection analysis (Usta, Cömert & Akın, 2023), geometric analyses of building volumes (Pepe et al, 2021) and the assessment of Digital Elevation Models (DEMs) (Bitelli, Girelli & Lambertini, 2018; Stal et al, 2013), (2) accuracy of representation of the heights and stories of historical buildings stemming from the scarcity of high-resolution images and temporal information, which hinder accurate estimation of construction features (Yin & Shiode, 2014), and (3) insufficient detail in input data which significantly impacts the accuracy and performance of change detection approaches including errors in DSMs, model noise, and low spatial resolution (Stal et al, 2013). Third group of modeling and analysis related R&L concern workflow optimization with two-fold perspective: (1) optimization of computational workflows and implementation of iterative modeling based on scenario performance (Wang, Wang & Zhang, 2023), and (2) accuracy of the estimation of transformations (such as such as scaling, rotation, and translation) during the iterative workflow (Urech et al, 2022) noting that the setup, data conversion, and simulation required for each design scenario could be time-consuming. Finally, content analysis indicates that challenges related to semantic data enhancement concern: (1) the need for enhanced semantics in input data (Lüscher & Weibel, 2013) to improve pattern recognition, and (2) the need for aligning cadastral databases with planning databases (Dalmau et al, 2014) stimulated by limitations in the utility of public data from the cadaster, attributing these challenges to non-standard storage formats.

CONCLUDING REMARKS: IMPLICATIONS FOR RESEARCH AND PRACTICE

This study provides a comprehensive and systematic analysis of the risks and limitations (R&L) associated with the application of digital tools within built environment disciplines, including architecture, urbanism, and cultural heritage. By categorizing R&L into data-related, technical, and modeling and analysis domains, the research addresses a critical gap in the literature, which has often focused on the benefits of digital transformation while neglecting its inherent challenges. The findings underscore the complexity of integrating digital technologies into traditional built environment practices, as highlighted by international policy frameworks. While current literature largely focuses on the benefits of digitalization—such as improved efficiency, precision, and predictive capabilities—it often overlooks the persistent technical, organizational, epistemological, and ethical challenges that compromise the reliability, usability, and societal relevance of digital tools. The primary contribution of this study lies in its structured literature review methodology, which not only consolidates fragmented knowledge but also provides a nuanced classification of R&L. This approach enables stakeholders to better understand methodological weaknesses, evidence gaps, and areas requiring further development. The study's insights are particularly valuable for informing policy, guiding methodological refinement, and supporting the responsible and sustainable integration of digital tools in the built environment. By systematically mapping the challenges related to data integrity, technical tool availability, and modeling accuracy, the research offers a foundation for future innovations and cross-disciplinary collaboration. Future research should expand the contextual background by exploring underrepresented regions and disciplines, and by empirically validating proposed solutions to identified R&L and by focusing on three areas: (1) longitudinal assessments of how technical and organizational risks evolve across different contexts, (2) deeper investigation into the epistemological boundaries of digital modeling and representation, and (3) empirical testing of strategies for mitigating ethical and data management risks. Advancing these research directions will require interdisciplinary collaboration to ensure that the future development of digital tools is not only technologically innovative but also methodologically robust and socially responsible.

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