Preprint Cambridge Centre for Computational Chemical Engineering ISSN 1473 – 4273

The slow engagement of planning scholars with BIM-GIS-Semantic integration: A literature review

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released: July 26, 2022

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Preprint No. 296

UNIVERSITY OF CAMBRIDGE

Keywords: BIM-GIS integration, Semantic Web, ontology, urban planning, smart city, City Information Modelling

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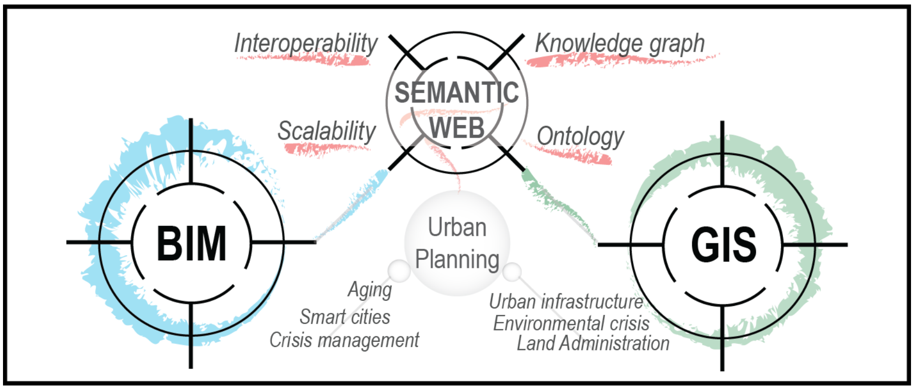
Abstract

The growing research interest in the integration of Building Information Modelling (BIM) and Geographic Information Systems (GIS) arise from their potential to overcome the growing urban complexities for a sustainable future. In understanding their capabilities, this paper attempts to shift the perspective from the prevailing Architecture, Engineering, and Construction (AEC) industries towards that of urban planning, which is at the intersection of all urban domains. However, are planners reluctant to fully adopt these technologies due to the rigid techno-centric mindset, the prevalence of weak interoperability and collaborative processes, or other reasons? We conducted a systematic literature review to understand the ongoing planning discourse for BIM-GIS integration, their integration opportunities with the semantic web, and identify future research needs. This review of 43 articles first reinforces the significance of BIM-GIS for planning more sustainable futures. Second, it highlights the limited research scopes and resources dedicated to this endeavour. Third, in advancing BIM-GIS-semantic web integration, proactive dialogue with planners is necessary. This would re-acknowledge the mediatory role of urban planning, to untangle and accommodate the complex network of actors and their conflicting interests involved in the city's development across disciplines and scales, for more sustainable cities.



Highlights

- Contrasting the active BIM-GIS integration discourse in AEC against the slower pace in planning discourses
- Semantic web integration with BIM-GIS could progress the bottleneck challenge of interoperability
- Rapid growth of BIM-GIS papers over time mostly in AEC and smart city journals
- Lagging behind commercial work, BIM-GIS planning scholars are still exploring theories with few applications
- As urban interdependencies grow, the mediator role of planners should be considered more in BIM-GIS discussions

Contents

1 Introduction

Rapid urbanisation and its ramifications on climate change have placed new and extra demands for urban sustainability solutions across all industries. With various city domains (like transport, healthcare, business, and climate change adaption) becoming more interdependent over the years, the mediation role of urban planning and the influence of urban planners becomes critical to ensuring a sustainable future. Planning practitioners are crucial to orchestrate and expedite the implementation process by suggesting solutions that could accommodate the conflicting interests of various stakeholders and experts of their individual domains across the economy, environment, and society [60].

Amidst greater urban complexities, it becomes critical to harness the growth in information communication technology, big data, and Artificial Intelligence for more credible, timely, and diversified evidence in the form of digital data to support planning [58, 64]. Digital planning technologies such as Geographic Information System (GIS) and City Information Modelling (CIM)[1] are anticipated to be capable of supporting planners in their mediatory role and enable a more consultative dialogue between stakeholders. Through this promise of sustainable and efficient urban planning processes in the pursuit of smarter cities, such technologies are developing at unprecedented rates [24].

However, planners remain reluctant to fully adopt digital technologies even if they are established in other industries. This reluctance towards digital tools occurs for many reasons such as the techno-centric mindset adopted by planning researchers, policymakers, and technologists, which often ignores the humanistic aspects of cities [59], the prevalence of data silos, which leads to weak interoperability and collaborative processes [52, 64], as well as planning itself being able to fulfil its core tasks with GIS systems and e-planning portals [55].

Given the dichotomy between urban planning research and practice, this paper aims to identify how planning research and practice engages with these digital planning technologies and builds on their opportunities and challenges. Specifically, we are interested in the integration of BIM and GIS, which are already integral to digital planning and CIM tools for their prowess in providing detailed building models and geospatial capabilities [36, 48]. Through a structured literature review of urban planning and smart city journals, we complement the existing literature on the integration of BIM and GIS with a new perspective from the urban planning domain as well as highlight further opportunities through the adoption of semantic web integration.

The organisation of the paper is as follows. Hereafter, section 2 introduces the research problem in more depth. Section 3 present the Systematic Literature Review (SLR) methodology. The findings are discussed in section 4 before concluding the paper in section 5.

[1]The practice of using interactive digital technologies including digital twins, urban informatics, and Building Information Modelling (BIM) in the process of urban planning, by all actors and stakeholders, to collaboratively deliver the vision of a Smart City. CIM is also synonymous with other terms found in the literature such as Urban Information Modelling [24].

2 Research Problem and Goals

Planning processes are inherently reliant on information flows from diverse stakeholders [64]. The accelerating advances in technologies such as the Internet of Things and online social networks and their ubiquitous presence in urban spaces have led to a proliferation of immense and sometimes uncontrolled data flows across domains [22]. When consolidated and interpreted by digital planning and CIM tools, these big data streams create new opportunities for planning processes to engage stakeholders in a more consultative capacity [51, 67]. Specifically, these tools have been proposed to visualise public policies, provide a more centralised service management across domains, evaluate a project proposal, reduce the lifecycle costs, and assess the performance of urban infrastructures [58].

In streamlining data for planning, these tools require both BIM and GIS inputs for their detailed building models and geospatial capabilities respectively to support the complex modelling processes involved. Today, GIS has already been acknowledged and adopted in planning practice while there is still much hesitancy in accepting BIM processes. Many planning authorities have yet to mandate BIM submissions as a legal requirement, despite it becoming commonplace in the Architecture, Engineering, and Construction (AEC) industry. GIS is recognised for its contribution to real-world modelling and analysis as a geographical information science that store, represent, describe, and calculate geospatial information in a digital format for spatio-temporal analysis, processing, or visualisation to support decisions [42, 57]. In contrast, there is still a notion that BIM is primarily a collaborative methodology for the design process while ignoring its ability to create, share, exchange, and manage building and urban information throughout the whole lifecycle for all stakeholders [42, 57].

Despite these perceptions, the integration of BIM and GIS technologies would unlock many opportunities as indicated by the growing interest within the AEC industry alongside rapid developments (See **Figure 1**). These have contributed at least 600 publications on BIM-GIS integration in the literature body inclusive of several literature reviews [6, 48, 57, 66].

In this paper, we draw on the literature review conducted by Karimi and Iordanova [36], which aims to understand the research scope of BIM-GIS integration in the construction automation field while including a broader perspective on the state-of-the-art. They observed that researchers have yet to fully explore the range of integrated BIM-GIS applications. Past studies are usually considered within the context of individual building projects, which overlook their opportunities for urban planning or the smart city despite the feasibility of scaling upwards. However, BIM-GIS integration is promising as a data and information source at multiple spatial scales, which provides comprehensive building geometry and material information, as well as a visualisation-based analysis to address complex city-scale problems while improving the efficiency and performance of infrastructure projects across scales [57]. From this perspective, their integration should be of great interest to planners to manage the growing complexities of cities while meeting sustainability goals. Thus, this paper aims to summarise and complement the existing academic discourse on BIM-GIS integration, which are usually discussed in the AEC industry, with an SLR focusing on BIM-GIS for urban planning.

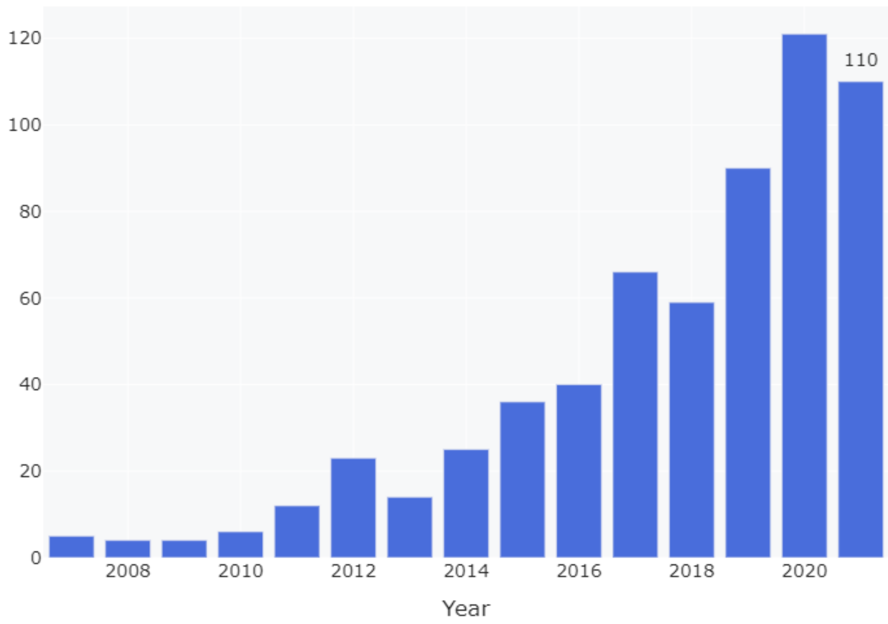


Figure 1: *Time series of published publications on Scopus related to BIM-GIS integration.*

Consistent with previous findings, a strong focus on the data level to minimise conversion errors, file sizes, and runtime between BIM and GIS systems [6, 48], Karimi and Iordanova [36] present the interoperability issues and their significance in BIM-GIS integration. Existing workflows and systems, even in BIM and GIS, remain reliant on largely manual human inputs rather than autonomous computation in performing these analytical tasks. However, in meeting the modern demands of urban planning, more intelligent systems are necessary for more robust urban management capabilities, capable of autonomously analysing information and generating insights to support decisions across domains and scales [22, 29].

In striving for smarter city planning, the semantic web is a potential opportunity to interpret, reuse, and integrate data structure and formats for greater interoperability between systems and produce higher-quality data insights and evidence across domains [16, 26, 29]. The semantic web achieves this through the provision of semantically rich data formats and ontologies that are explicit about their description, reference, and relationships between real-world objects, like people, buildings, and contracts, and are able to be extended to incorporate new data sources or relationships in the future [1, 15, 22]. Accordingly, unlike current technologies, the semantic web is expected to overcome the interoperability issues in the existing planning systems and enable a distinct and more efficient digital planning process compared to previous planning paradigms [36, 51]. Given this background, the second goal of the SLR further considers the interoperability of BIM and GIS systems with the semantic web.

3 Methodology

This paper applies the SLR methodology, supported by bibliometric analysis. SLR is defined as the identification, evaluation, and interpretation of all relevant research to a specific topic [37]. Building on the comprehensive BIM-GIS integration literature review by Karimi and Iordanova [36], this paper targets the overlooked smart city and urban planning domain by identifying publications in relevant planning journals. As a transdisciplinary field with no clear disciplinary boundaries [49], it is difficult to identify the relevant disciplines and their journals for the planning dialogue. Given the close links with urban phenomena in cities [49], we can consider urban planning in the economic, environmental, and social dimensions proposed for sustainable development in the 1987 Brundtland Commission Report [46], as well as the burgeoning role of digital technologies and CIM in smart cities [51, 58].

In searching for the relevant journals, we utilise the popular Scopus database which is known to host key planning journals and possess search and scoring functionalities. Our selection criteria consist of the subject area of "Urban Studies" and "Geography, Planning and Development" with a CiteScore measuring research impact of at least 5.0 in 2020. We also reviewed and selected journals only if the journal's scope encompassed the economic, environmental, social, and technological aspects of urban phenomena in cities. Amongst the 99 journals returned, 24 journals, listed in **Table 1**, fit our criteria. The selected journals can be broadly categorised based on their scope into two distinct categories of urban planning and smart cities.

Our first search included "BIM-AND-GIS" as keywords, which retrieved 89 publications. We conducted a second search with the keywords "BIM-AND-GIS-AND-Semantic-Web", "BIM-AND-GIS-AND-Ontology" and "BIM-AND-GIS-AND-Knowledge-Graph" but discarded the results as there were fewer than five relevant search results that overlap with the first search. Acknowledging that BIM and GIS are synonymous with CIM in some literature, a third search was conducted using the keywords "BIM-AND-GIS-AND-CIM-AND-City-Information-Model", as the short form of CIM may also refer to other irrelevant terms such as Common Information Model and Computer Integrated Manufacturing. This process retrieved four publications, which are duplicates of the previous search results. Only publications in the English language are included. There are no bounds for the publishing year as the earliest literature occurred in 2007, which is relevant to our research goals. In identifying the eligible publications, their titles, keywords, abstracts, introductions, and methodologies are carefully read to determine their relevance to the topic.

Given the scarce deliberation for BIM-GIS in urban planning, we introduce only one exclusion criteria. The selected papers must mention BIM and GIS or their related terms for planning applications. Based on this criteria, 46 publications were excluded (see **Figure 2**). The evaluation and interpretation of the eligible 43 publications are supported by four bibliometric analysis techniques: (i) temporal analysis; (ii) research site analysis; (iii) keyword co-occurrence analysis; and (iv) qualitative investigation. Temporal analysis identifies the evolution of the planning discourse over a period, while research site analysis identifies the key cities with BIM-GIS literature. The keyword co-occurrence analysis accentuates the key research topics and developments, while the qualitative investigation

Table 1: *List of selected journals fitting inclusion criteria.*

Urban Planning and Development	*Smart Cities*
1. Landscape and Urban Planning 2. Habitat International 3. Cities 4. Land Use Policy 5. Urban Climate 6. Journal of Planning Literature 7. Journal of the American Planning Association 8. Urban Studies 9. European Urban and Regional Studies 10. International Journal of Urban and Regional Research 11. City, Culture and Society 12. Progress in Planning 13. Urban Ecosystems 14. Global Environmental Change 15. Cambridge Journal of Regions, Economy and Society 16. World Development 17. Sustainable and Resilient Infrastructure 18. International Journal of Sustainable Development and World Ecology 19. Environment and Urbanization	1. Computers, Environment and Urban Systems 2. Sustainable Cities and Society 3. Building and Environment 4. Journal of Urban Technology 5. Environment and Planning B: Urban Analytics and City Science

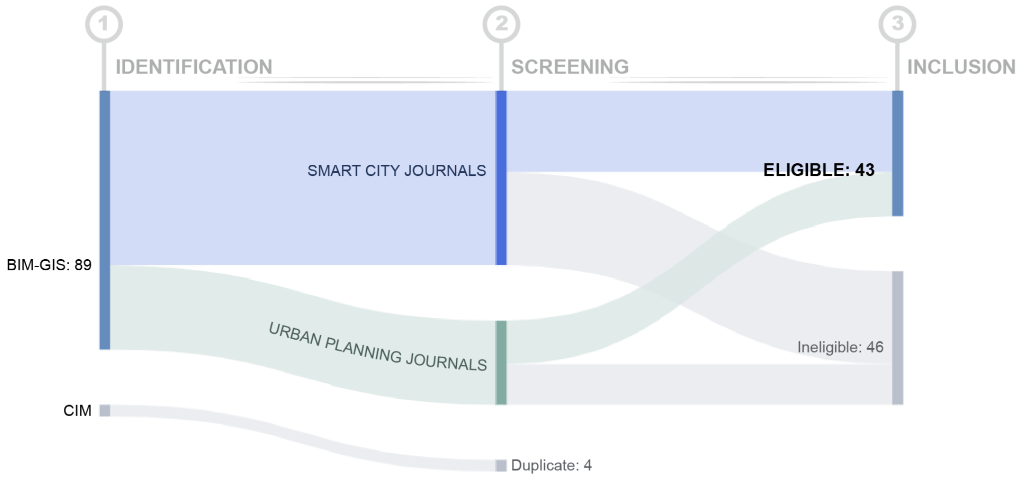


Figure 2: *Sankey diagram of the publication selection process.*

scrutinises the articles for commonality in approaches, applications, and challenges to guide future research. Additionally, as the planning community have largely ignored the technical components such as their methodologies and formats, we complemented the BIM-GIS planning discourse with relevant background knowledge from other domains to frame and understand the context of these technologies and their opportunities.

4 Findings

4.1 Overview of research trends

In recent years, there is a burgeoning body of BIM-GIS literature that occur predominantly in the AEC domain, as illustrated in **Figure** 3. This is a stark contrast to the disproportionately fewer planning-related publications in **Figure** 4. Even within the planning journals, most are published in the smart city journals, which suggest that the current BIM-GIS conversation are led by technologists and policymakers rather than planners. Accordingly, planners are often not involved in these conversations despite their potential opportunities for planning. Nevertheless, the situation has improved amidst the almost double growth of BIM-GIS publications in 2021 from 2020, and an equal number of publications for traditional planning and smart city planning journals at least in 2021.

4.1.1 Article types

The current academic discourse on BIM-GIS integration can be classified into four article types, namely, literature reviews, frameworks, applications, and future research. It should be noted that some articles could belong to multiple article types, resulting in a total of 13 Literature Review, 16 Framework, 5 Application and 11 Future Research articles as listed in **Annex** A.1 of the Supplementary Materials. The categorisation of these article types

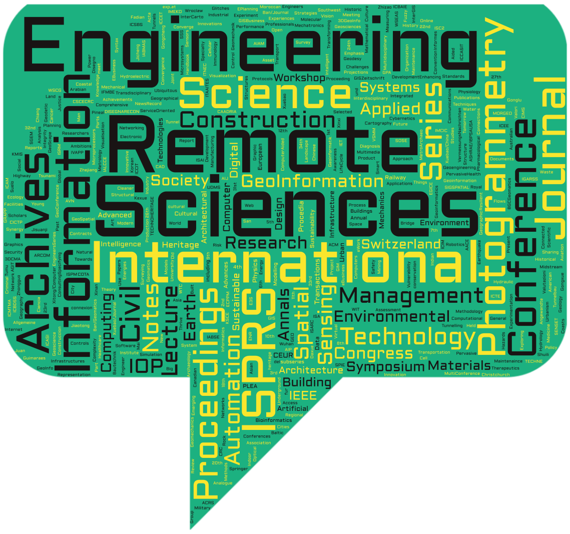


Figure 3: *Word cloud of journals with BIM-GIS integration publications.*

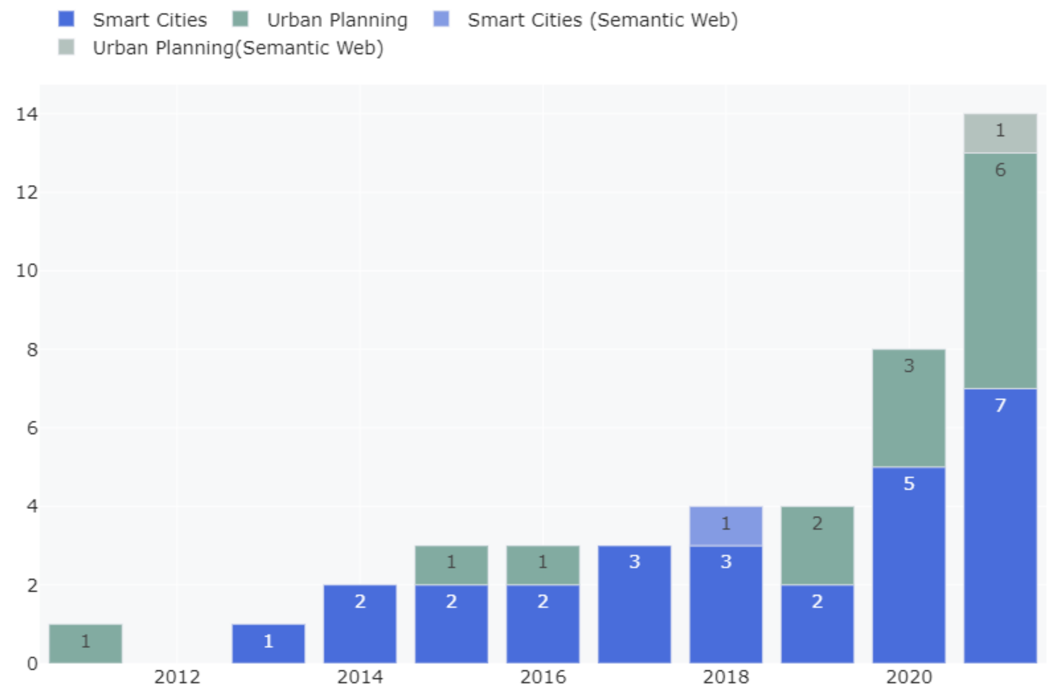


Figure 4: *Time series of publication published in planning journals related to BIM-GIS integration.*

indicates that the planning discourse is outcome-oriented with a specific application and domain in mind.

The application articles demonstrate a BIM-GIS methodology in a particular domain. The literature review articles are conducted for a specific domain or purpose unrelated to BIM-

GIS. For instance, Kylili and Fokaides [39] provide an overview of the relevant European policies and legislation for the built environment. Sola et al. [56] evaluate the existing urban energy modelling tools. These articles acknowledged the BIM-GIS opportunities for their domain in at least one of their reviewed publications.

The framework articles propose a new methodology or guidelines that set the foundation for future work in a specific domain. These theoretical articles often lack any real-world application. For example, Diakite and Zlatanova [18] develop an automated workflow to geo-reference BIM to GIS environments. Barzegar et al. [5] present a 3D urban land administration framework denoting their spatial analysis requirements.

The future research articles present their applications based on either GIS or BIM tools but acknowledge the potential of integrating BIM-GIS to resolve some of their current challenges and expand their scope. For example, Saretta et al. [54] develop a GIS-based methodology to assess the retrofit and building-integrated photovoltaics potential of buildings at the district scale. They suggest that the less precise current estimations can be improved through integrating with BIM's detailed building data.

When segregated by their journals, and unsurprisingly, it is noticeable that smart city journals have significantly more publications than their traditional planning counterparts (**Figure 5**). Given that the former's readership slant towards technologists and policymakers while the latter's readership involves planning practitioners, the planning discourse onBIM-GIS is predominantly driven by external stakeholders rather than planning practitioners.

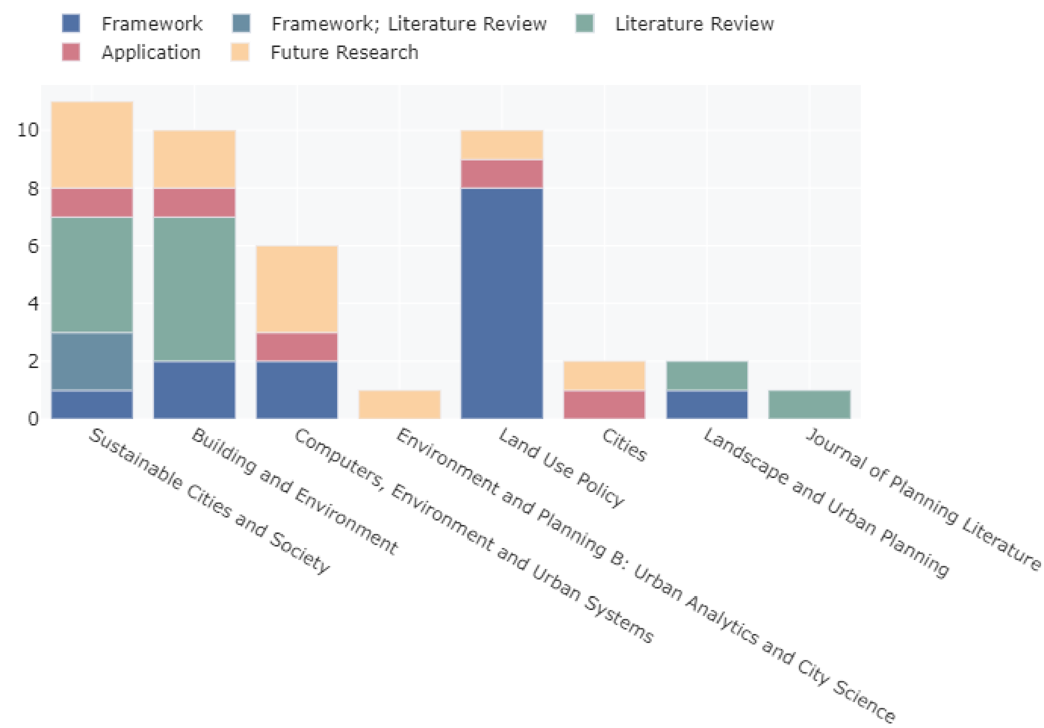


Figure 5: *Publications by article type and journal.*

4.1.2 Research site

Examining the research sites globally, much of the BIM-GIS research is concentrated within Europe. In other developed countries like the USA and Australia, the work is usually more theoretical as a literature review or a framework. In the East, there is a dearth of planning literature for BIM-GIS in most Asian countries. The limited BIM-GIS work is conducted in only five areas – China, India, Taiwan, Hong Kong, and Singapore. There is generally scarce research in the less developed countries in part due to limited resources and the lack of BIM or GIS use.

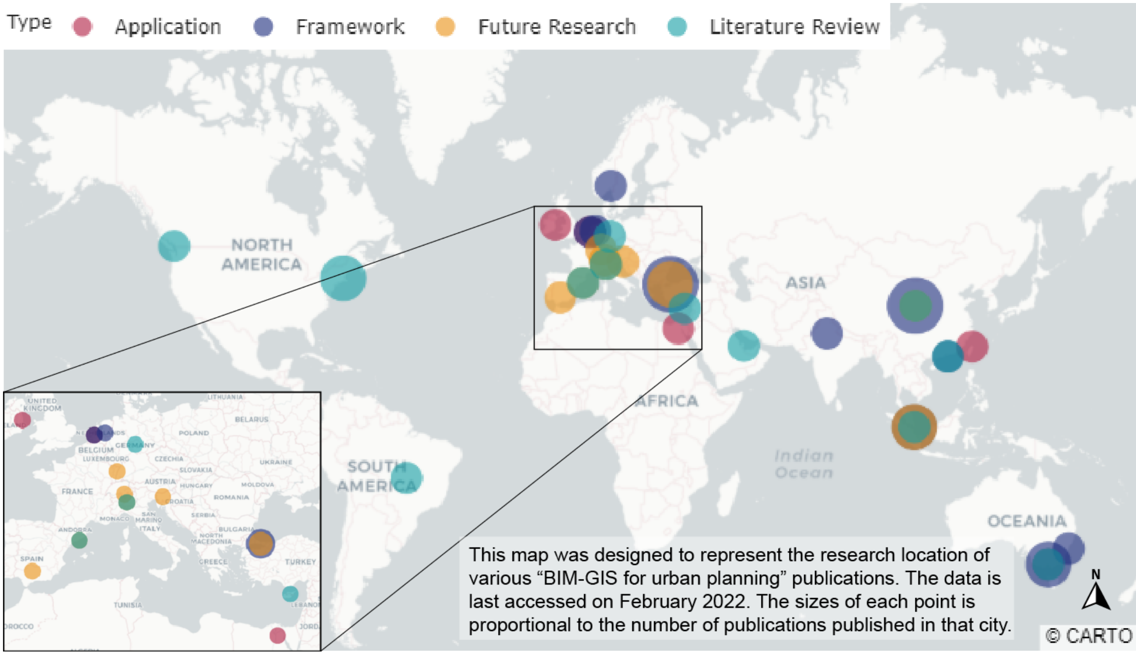


Figure 6: *Point map of selected publications by country and article type.*

4.1.3 Keywords co-occurrence analysis

The keyword network in **Figure 7** (constructed with Gephi) highlights the prominent keywords in the reviewed literature by their node sizes, having excluded keywords with zero links to other publications. Urban planning is the most popular keyword, followed by BIM and Land administration. At present, BIM-GIS integration for urban planning is associated with urban development, urban policy, urban design, land administration, smart cities, and their technologies for participatory planning, optimisation, and spatial analysis. Coupled with the weak association between each keyword represented by the edge’s width, these broad domains suggest a diversity of planning research and applications for BIM-GIS integration. Thus, the network highlights that the ongoing research efforts are in the exploratory phase, identifying the potential BIM-GIS applications for planning such as age-friendly housing and crowdsourcing.

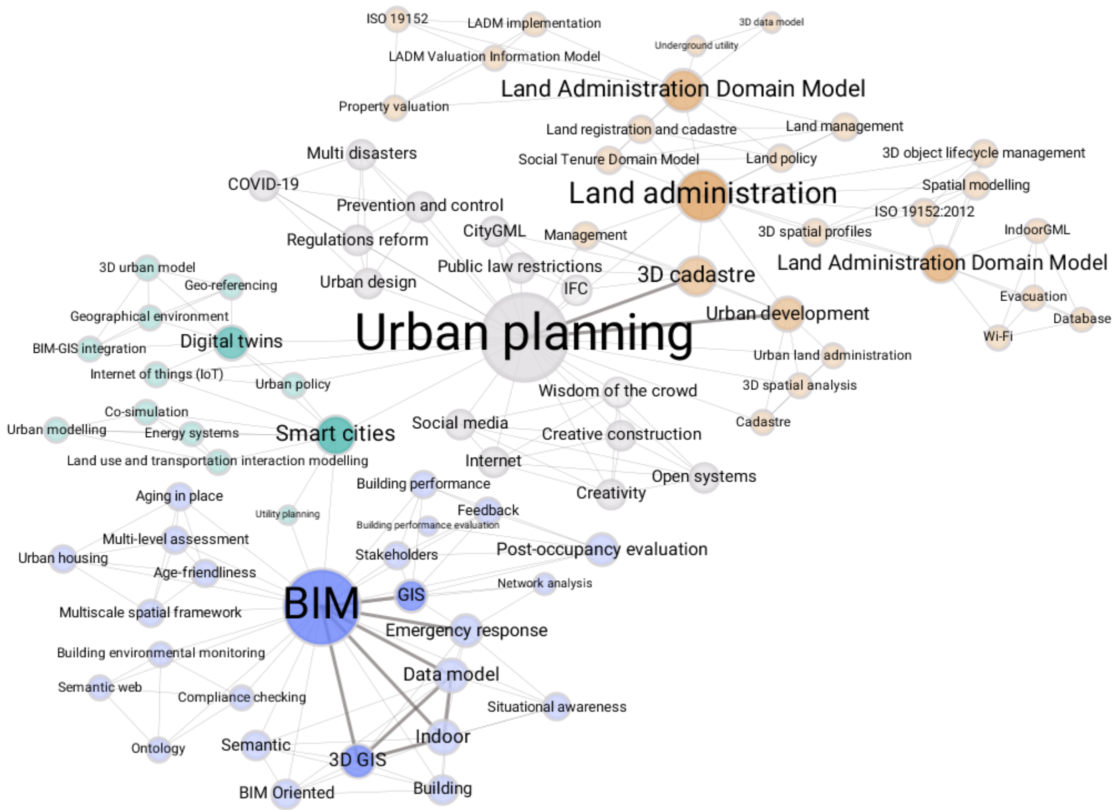


Figure 7: *The keyword network of selected publications.*

4.2 Research domains for BIM-GIS integration

The relevant domains for BIM-GIS integration can be classified into six key domains, namely, Urban Environmental Simulation, Urban Energy Modelling, Land Administration, Crisis Management, Urban Infrastructure Management, and Urban Social Sustainability. Three general-purpose publications could not be classified appropriately and were instead, incorporated into the overall discussion in section 4.3.

4.2.1 Urban Environmental Simulation

In light of the burgeoning evidence connecting urban developments and their immense energy, materials, and water consumption to unsustainable environmental consequences, researchers have developed various urban modelling techniques to simulate vertical urban growth [14], assess food-water-energy potential in buildings [54, 74] and the building environmental performance [10, 70, 76] in their attempts to alleviate the impending environmental disaster.

Kylili and Fokaides [39] conducted a literature review to assess and enact improvements to the existing European policies and legislation relevant to the environmental sustainability of the built environment and the construction materials. Given the current holistic lifecycle considerations, there is a growing interest in the integration of lifecycle assessment with BIM and GIS separately, with no consideration for BIM-GIS integration currently [39]. Despite their capacity to gauge environment performance, existing research focused on the separate capabilities of BIM or GIS, especially for the latter. Chen [14] devises a cellular automata model that simulates continuous horizontal and vertical urban growth, through GIS and other elements, to support the mitigation of climate change's impacts on human settlements. Through remote sensing and GIS technologies, Zambrano-Prado et al. [74] formulated a self-sufficiency framework to identify and integrate feasible rooftops with food, water, and energy systems for more sustainable developments. Saretta et al. [54] constructed a GIS-based method to evaluate the retrofit potential of facades for building-integrated photovoltaics to support the energy transition of existing buildings. Blàzquez et al. [10] present a GIS protocol to assess the existing housing energy performance and enable passive upgrading strategies at the urban and district scale. These studies also briefly describe the potential of integrating GIS with BIM for more detailed building models, realistic simulations, and precise assessments at finer scales.

A more formal discussion of BIM-GIS integration occurs in the geodesign domain, involving environmental planning and design at larger complex scales that capitalise on various digital technologies and modelling techniques [20]. A geodesign toolbox is proposed with 15 essential components, in which GIS contributes to the base maps and the visual and semantic representation of objects such as trees, highways, apartments, ecosystems, policies, laws, and more, whereas BIM contributes to the visual and semantic object representation, configurations, and their constraints on quantities and attributes [20]. Considering the reluctance of urban planners and designers to adopt these tools, Wong et al. [70] conceive a plan to develop a user-friendly urban design GIS platform for integrated urban microclimate assessment. The platform will overcome the challenges of interoperability and information workflows through integration with BIM capabilities on a web server in future [70]. In addition, another method of overcoming these interoperability issues is through semantic web technology. Zhong et al. [76] developed an ontological BIM-GIS integrated framework for automated building environmental monitoring and compliance checking to ensure sustainable environmental performance.

4.2.2 Urban Energy Modelling

As a subset of urban environmental simulation, the tremendous attention on energy sustainability warrants its own discussion. Attributed to their massive carbon emission contributions, it becomes imperative to develop an integrated urban energy system that generates and analyse building-level energy data across scales for a cleaner and affordable energy supply [12, 56, 69].

One common approach is the adoption of Urban Building Energy Modelling (UBEM) tools in this endeavour, which integrate multi-stakeholder perspectives and analyse the impacts of urban energy demand [44]. Malhotra et al. [44] highlight the distinction between top-down and bottom-up UBEM methodologies, in which the former utilises aggregated data at a broader scale i.e. historical national energy consumption to understand the relationship between energy and economics, but fails to measure the current and future building technologies' impact on energy demand. Instead, the bottom-up methodologies extrapolate detailed individual building energy consumption data to represent regional or national energy demands and are more popular in the literature for their capacity to evaluate the performance of different energy efficient measures and technologies [12, 44, 53]. Most of the UBEM tools are directly integrated with GIS and specifically, City Geographic Markup Language (CityGML) formats to generate less detailed semantic city models for different applications and stakeholders at a larger scale [21, 44, 53, 56]. In contrast, integrating these tools with BIM and Industry Foundation Classes (IFC) formats is expected to overcome the lack of detailed building models in GIS databases, and facilitate a more precise and detailed energy simulation and optimisation at district and smaller scales, through identifying and generating building archetypes [21, 53]. Carnieletto et al. [12] have demonstrated the development of these prototype building archetypes with GIS data but highlight the need to integrate with BIM to attain detailed and accurate building archetypes and enable interoperability and collaborative workflows in future.

In the renewable energy domain, Wijeratne et al. [69] conducted a literature review to examine the features, functions, and limitations of existing solar photovoltaic design and management tools based on the requirements of diverse users. As solar photovoltaic technologies are mounted on buildings, the tools are mostly integrated with BIM systems. However, GIS and its capabilities are not discussed in the review, even though some of the tools do adopt some GIS functionalities.

4.2.3 Land Administration

The land administration system encompasses various processes involving the registration, dissemination, and demarcation of rights, restrictions, and responsibilities related to land value, ownership, usage, tenure, and development [5, 27]. When these proprietary rights are secured through clear registration and demarcation, they can alleviate social conflict arising from land disputes, augment economic developments through transparent land dealings, and achieve sustainable development at a global scale [23, 27].

However, current practices rely on 2D digital or analogue survey plans, which are insufficient to manage the growing complexity of infrastructural projects with mixed-use functionalities and vertical growth [5, 23, 38]. Given the significance of the land administration domain, city administrations must consider the adoption of digital technologies and techniques to enable smart and effective land management and e-government services that will raise productivity, harness big data streams, and increase the ease and access to public services [27].

The current work is in the midst of investigating the requirements and capabilities of 3D urban data [23, 38, 40] and establishing a standardised global land administration vocabulary to facilitate cadastral data exchange, support application software development, and ensure data quality [40]. There is also research on conceptualising suitable frameworks to incorporate these 3D data for their respective land administration processes ranging from the approval of building permits [27], spatial analysis [5], the management of property valuation information [34] to the assessment of local urban planning regulations [11]. Much of the work is theoretical in nature and slanted towards GIS methodologies. Regardless, they do acknowledge the need to integrate and convert to other data standards such as BIM and IFC, albeit briefly for future research [11, 27, 34, 40]. BIM-GIS integration is expected to address the need to represent and conduct spatial analysis on cadastres, buildings, property rights, and restrictions in 3D urban data formats [5, 23, 38]. Furthermore, these interoperable data formats will facilitate collaborative workflows at a wider scale across agencies [23].

4.2.4 Crisis Management

With urbanites spending most of their time in indoor environments such as offices, homes, shopping malls, and educational buildings, the modern cities of today are developed to improve their inhabitants' health and wellness [3, 61, 67]. However, their increasingly complex high rise and underground structures are ill-equipped and vulnerable to the volatile and abrupt disasters and epidemics of today [3, 61, 67]. Often, the first few hours after a disaster occurs are decisive in influencing the possibility of mitigating tragic consequences, especially on human lives, their assets, and the environment [13, 61]. In this regard, it is critical to provide situational awareness for immediate emergency response and evacuation [3, 32, 67]. Wang [67] highlights the capabilities of emerging digital technologies such as big data and CIM to construct a complex 'digital cloud' capable of cross-validating information from diverse systems and generating prevention and control modes for integrated urban disaster strategies and management. For this purpose, GIS has been integrated with big data, dynamic virtual simulation methods, and efficient prediction models to build a quantitative group tool for urban design under the normalisation phase of epidemics, whereas BIM was integrated with a complex network of professional building systems for real-time optimisation [67].

At a smaller scale, BIM-GIS integration is important for the development of 3D models for indoor navigation to provide situational awareness in emergencies. Isikdag et al. [32] present a conceptual BIM-oriented indoor data model that is populated with data from IFC formats and is convertible into a GIS model through a test emergency response scenario for the Greater Municipality of Istanbul. The remaining literature presents different applications involving an integrated BIM-GIS system for fire-fighting simulations through a 3D geometric network model [13], simulating user movements in evacuation through the LADM-IndoorGML model [3], and integrated and seamless indoor/outdoor navigation through the 3D Indoor Emergency Spatial Model [61]. Although the existing work is at a smaller scale, there is some acknowledgement to the extension of these methodologies up to the city level which is only feasible in future when there are sufficient processing capacities [13].

4.2.5 Urban Infrastructure Management

As planners turn towards vertical and underground spaces to accommodate urban needs, the subsequently spatially complex built environment requires careful and deliberate consideration, even in the design and construction phase, for safety and sustainability [25, 33, 63]. In this context, urban infrastructure management plays an important role to anticipate and address their citizens' utility needs for a better quality of life while mitigating the environmental consequences, especially with the long lifecycle of cities [45, 63]. However, such management approaches are reliant on information flows that are currently unavailable [72] or difficult to access in fragmented systems [30, 33, 73].

The infrastructure domain is currently plagued by dynamic interdependencies, a fragmented data regime, and ineffective communication across organisations, that is incapable of processing and analysing the large volume of static and dynamic infrastructure data [73]. BIM-GIS integration is proposed as a viable solution to facilitating these information flows, streamlining the decision-making process, and improving their accuracy, timeliness, effectiveness, and efficiency throughout the entire lifecycle. Yang et al. [73] propose an integrated infrastructure asset management framework, RSM-IIAM, that integrates related processes and interdependencies with sustainability and resilience throughout the lifecycle for decision-making. In the framework, a BIM module serves as a lifecycle semantic editor, which is integrated with GIS capabilities for visualisation, information query, and analysis [73]. Marzouk and Othman [45] develop a BIM-GIS framework to forecast, analyse and visualise land use information and their respective consumption patterns for sewage, water, and electricity according to different development schemes. Anticipating the residents' infrastructure needs during the city planning and development stage, they highlight the significance of early planning in ensuring a thriving urban community and economy that delivers the promise of smart sustainable cities [45]. Kalogianni et al. [33] introduce the concept of 3D spatial profiles to support a holistic interoperable lifecycle development across phases and disciplines, especially in land administration. Collected during the design and construction phase, BIM is acknowledged as a valuable spatial and non-spatial data source for the operational phase in uses like cadastral data [33]. Although they acknowledge the synergy with GIS for spatial planning and land administration, more investigation should be conducted on the different encoding models such as IFC, GML, CityGML, LandXML and GeoJSON to support better implementation of BIM-GIS integration [33].

In the field of underground development, von der Tann et al. [63] advocate for a sustainable multi-disciplinary underground urbanism to regulate and reconcile the different agendas of various stakeholders. They mention that future work should critically assess BIM-GIS integration as a potential communication tool across diverse stakeholders and disciplines [63]. In addressing the urgent need for reliable underground utility information, Yan et al. [72] extended the underground utility data model to provide 3D geometric and functional information on utilities and land surveys through BIM and GIS that facilitates the upfront planning of underground spaces. Thus, the underground data provided by BIM-GIS integration are important to safeguard these underground spaces for future uses, eliminate the various uncertainty and risk during the planning process, and mitigate ground-related threats to human safety and health [63, 72].

Another plausible application is Post-Occupancy Evaluation (POE), which is necessary to provide feedback to discern expected and actual environmental performance and optimise resource usage during the building's lifecycle [25, 41]. Li et al. [41] conducted a literature review to introduce the POE field and its current trends, gaps, and future research directions to beginners. They briefly mention that BIM-GIS integration could improve the analysis, presentation, and interpretation of results, which enables more effective POE investigations [41]. Hua et al. [30] develop a GIS-based spatial mapping method to analyse and visualise POE results on occupant satisfaction and indoor environment quality for the identification of building performance issues and evaluation of green design strategies. [25] integrated this spatial mapping method into BIM, to demonstrate the capacity to link performance outcomes with spatial information while enhancing the visualisations of results in POE data management. However, their research study is confined to a campus experiment and has yet to explore a real-world application.

4.2.6 Urban Social Sustainability

Urban social sustainability involves building an equitable society with communities that enjoy continued viability, health, and quality of life [17]. Digital technologies such as BIM-GIS integration are anticipated to support these goals in diverse areas such as occupant comfort [2], age-friendly housing [75], places and their relation to human activities [50], and public participation [9, 68].

As buildings become more intelligent and cater to the occupants' comfort and performance, Al Horr et al. [2] conducted a literature review to understand the relationship between the indoor environmental quality of offices and their occupants' productivity. Remote sensing devices and their data are already linked with BIM and GIS to collect and analyse quantitative and qualitative data, such as physical building attributes and interview results, for visual and spatial representations on occupant comfort and satisfaction. This is expected to generate design layouts that cater to the occupants' comfort and quality of life.

In the residential domain, Zhang et al. [75] propose a multiscale spatial framework that is centred on evaluating age-friendly housing performance. BIM, geographical, and external data sources are utilised to compute housing age-friendliness index values. This is expected to aid individuals and local governments in selecting suitable housing and guide designers, planners, and property developers to develop age-friendly housing with a higher quality of life for aged residents.

Acknowledging that human activities have shaped the character of urban spaces, Lopez and Ferreira [43] develop a data-driven methodology, using points of interest from GIS databases, to explore the relationship between human choices and activities, and their influence on urban spaces at the neighbourhood level. Applying the methodology to more recent data, Ponce-Lopez and Ferreira Jr [50] construct a typology of commercial patches with specific activities or services, as a derived unit of analysis. In their papers, a place comprises of several patches, and the more diverse and denser patches are associated with more complex and attractive places. BIM-GIS integration is briefly suggested for future research to contribute data through standardisation of regulatory requirements, which is expected to facilitate detailed building-level analysis and replicate their analysis on other cities [50].

Some digital technologies have already been demonstrated to support public participation in the planning process effectively [9, 68]. Bizjak et al. [9] introduce a conceptual public participation framework that leverages a flexible modular platform and the three-tier architecture of presentation, logic, and data. Users can include or exclude different social media and open Web-based GIS tools depending on the specific demands or level of participation required. Although their implementation only involves GIS tools, they briefly indicated one could easily replicate the framework for BIM tools. White et al. [68] demonstrate the digital twins' capacity for collecting citizen feedback in simulations of skylines, green spaces, user tagging, flooding, and crowds. Amongst their five-layer architecture, BIM was adopted for the detailed building models in the first layer whereas GIS contributed infrastructure data in the second layer. In this research, BIM-GIS data are necessary to support the platform's interface and provide more effective flexible interactions with their users to engage in more consultative planning processes.

4.3 Discussion

4.3.1 BIM-GIS for planning

BIM-GIS integration is an emerging topic in the planning domain, which has garnered significantly less attention compared to their individual BIM or GIS technologies. A rudimentary search on the Scopus database within the selected planning journals retrieved 206 BIM documents, including conference papers, books, book reviews, and articles, 2,318 GIS documents, and 14 BIM-GIS documents. These findings are unsurprising as the planning community is known to have willingly embraced GIS technologies for their unique and relevant geospatial capabilities while remaining ambivalent towards BIM processes. For instance, planners usually generate urban building models for their work through a GIS data schema, while overlooking the more suitable detailed BIM models as an alternate data source. Although BIM models may be omitted in planning submissions for many cities globally, it is bizarre that planners do not consider using the burgeoning and available repository of BIM models that are legally mandated in the AEC industry. This dichotomy in attitudes towards BIM and GIS individually have implications on BIM-GIS integration, which follows the adoption of BIM processes. Thus, the relatively lag in incorporating BIM into planning practice has slowed their interest in BIM-GIS integration.

As an emerging planning research field, BIM-GIS discussions are predominantly theory-based with only five application articles out of the 43 publications selected. Despite the lack of knowledge on the technical components, the current planning discourse recognised several benefits of BIM-GIS integration for planning. First, it would capitalise on existing BIM resources while preventing duplicate work to collect and process GIS data to generate building models. Second, BIM-GIS would enable more applications across scales when considering that BIM's relatively more detailed data inputs are more relevant for applications at a district or smaller scale, whereas GIS models are more relevant for applications on the city and larger scale due to the lower level of details and smaller computing capacity required for rendering [21, 44, 67]. Last, BIM-GIS integration is crucial for CIM technologies to establish a comprehensive, updated, and standardised urban database across domains that can inform and realise diverse applications through urban simulation, presentation, or analysis [58, 64]. CIM tools have demonstrated their revolutionary capacity to support the planning process by permitting greater public participation, reducing the fragmented data regimes, and reinforcing policies with data-driven evidence [58]. Given the opportunities presented, it is crucial to promote BIM-GIS discussion and guide future research to incorporate CIM tools into the planning process and enable seamless data sharing processes, which have yet to be accomplished in the ongoing research projects.

4.3.2 BIM-GIS Challenges

When the ongoing theoretical discussion is not informed by technical expertise, it fails to translate the expectations, requirements, and concerns of all users in the complex multidisciplinary urban planning field into concrete guidelines for implementing BIM-GIS applications. With the information overload and unfamiliarity of technological developments at a breakneck pace, planners may be overwhelmed and not grasp the underlying technical workings without compromising on their main responsibilities. As a result, planners are unable to engage with the current discussion for planning technologies and their implementation strategies. When the research findings are not translated into practice, the resultant dichotomy between planning research and practice leads to the impracticalities of these planning tools for the planning process.

In facilitating this dialogue, this paper introduces the two research phases of BIM-GIS integration. The initial phase explores several methodologies, based on three data exchange schemas, to primarily extract BIM data into the GIS context for their geospatial capabilities while there is less attention on the reverse [57, 66]. IFC is the open-format data schema adopted as the BIM standard. For the GIS standard, the geospatial industry commonly adopts the native community-supported Shapefile data schema of GIS tools like ArcGIS whereas the research community focuses on the XML-based CityGML data schema to represent the 3D models of cities and landscapes [36, 77]. A key distinction is that Shapefile is a data format in which any related data can be stored as attribute tables (so where any semantics remain implicit), whereas CityGML is a data model with defined classes for building components and their relationships [77]. Accordingly, the two interoperability paths are IFC-to-CityGML and IFC-to-Shapefile.

Moreover, integration approaches in the initial phase often encounter a significant loss of information and geometry invalidity when attempting to convert BIM to GIS standards or vice versa. Such challenges occur as BIM and GIS standards do not fully describe the same concepts. Although there are some partial overlaps between their concepts such as building, walls, and furniture, both standards include some mutually exclusive concepts. For example, IFC include concepts to represent building management information such as property sets, costs, maintenance schedules, whereas CityGML include concepts to represent larger scale elements such as water bodies, land use, and transportation. Given the asymmetry in their concepts, BIM and GIS standards are not interchangeable.

The significant loss of information and geometry invalidity encountered after the conversion process led to the next phase [36]. In circumventing this issue, the next phase developed the concept of CityGML Level of Detail and IFC Level of Development to categorise different building models based on the semantic and geometric information available [36]. With the new standards at different granularities and computing requirements, methods for building and urban database management could be modified to fit their applications and processing capacity accordingly [57]. Thus, these standards standardise the work processes, improve data quality, and minimise geometry errors [57].

Regardless, these distinct standardised formats and research directions have aggravated the challenges associated with data interoperability between the disparate native BIM and GIS environments. For instance, Diakite and Zlatanova [18] devised an automated workflow for the geo-referencing process of BIM models in GIS environments that addresses the visual aspects. Although the researchers acknowledge that their workflow is inadequate for more advanced analysis and information enrichment, they fail to benchmark their current integration approach against other approaches. Furthermore, the extensive variety of tools and approaches available in the literature body often possess many redundancies and overlapping procedures. Meanwhile, their knowledge and insights are shared in a limited capacity with other studies that compromise reproducibility. Thus, the existing integration approaches diverge into different isolated directions that may be partially duplicated, leading to a failure to benchmark their performances, engage extensively with broader trends, and facilitate discussion with non-technical experts to achieve seamless data sharing protocols.

4.3.3 The potential of the Semantic Web

With the growing complexities of urban needs, current approaches may be inadequate to tackle the disparate data requirements, implementation barriers, and policies on data privacy [58]. Partly due to the growing interdependencies of cities alongside their empirical traditions and growing interest in data-driven planning decisions, planning processes are arguably predisposed to adopt some form of the semantic technologies to enable interoperability across domains and scales [64].

In the AEC industry, the semantic web has demonstrated its potential to represent information while enabling interoperability, logical inference, and scalability across complex systems and domains [48, 64, 71]. By adopting a standardised Resource Description Framework (RDF) following the principles of Linked Data [7, 8], the semantic web semantically annotates data and their relationships through ontologies to provide context [28, 65]. By describing all information alongside their context in this machine-readable standardised format, it enables the discovery, integration, query, and transfer of information between different domains and systems via the World Wide Web [1, 26, 47]. Some applications extend these capabilities using knowledge graphs. Knowledge graphs represent a network of interlinked descriptions for real-world entities, data, and their relationships through ontologies, and can be subjected to a reasoning engine to derive new knowledge [19]. In other words, the semantic web technology provides the capability to represent all data from various domains and systems into a standardised data format through ontologies often in the form of knowledge graphs, providing a basis for interoperability between domains and systems in any workflow, facilitating greater data sharing and collaborative processes [35, 62].

It is arguably more crucial for BIM-GIS integration methodologies to incorporate the semantic integration in the transdisciplinary urban planning context over other individual domains that are of smaller scale and complexity. Zhong et al. [76] introduce an ontology-based framework comprising of four layers for the building environment management domain that integrates building information from BIM, environmental information generated by sensors, and regulatory information based on building regulations and design requirements. The first information acquisition layer collects and stores the heterogeneous information into several formats such as databases, text files, GIS, and BIM. The second ontology development layer develops specific ontologies to describe the knowledge and information of different domains. The third semantic processing layer builds a rule container and reasoning engine to support the management and application of information described in the ontologies. Through programmable user interfaces, the fourth application service layer provides multiple service applications, including environmental monitoring, compliance checking, information storage, and information sharing services. Given the immense demands and inputs involved in the urban planning domain, the automated semantic representation and logical inference of immense heterogeneous urban information via ontologies are critical to facilitate knowledge sharing across the larger, more complex urban scale comprising a dynamic ecosystem of applications, systems, and domains. Thus, compared to system integrated methodologies, semantic web technologies are more suitable to enable the seamless automated bilateral interoperation between BIM and GIS data that is scalable to different systems, domains, and complexity at relatively lower costs.

4.3.4 BIM-GIS for the future of cities?

In framing future research direction, we consider the data, process, and application levels introduced in other reviews. These levels emerged initially from Irizarry et al. [31]'s categorisation at two interrelated fundamental and application levels, which was further extended to the third process level by Amirebrahimi et al. [4]. Research at the application level seeks to reconfigure or rebuild an existing BIM or GIS tool to become integrated with each other's functions for seamless user interactions. At the process level, a certain system architecture is employed for the participation of BIM and GIS at the data level in a real-time workflow as distinct systems to incorporate into applications [4]. Research at the fundamental or data level investigates data interoperability and exchange standards through methods like linking, translation or conversion, extension, and metamodels. With an expanding literature body, Zhu et al. [78] extended the data level further into the geometry and semantic level. The geometry-level research explored the geometry transformation between BIM and GIS, whereas the semantic-level research discussed full attribute data translation from IFC to CityGML or Shapefile formats.

Today, the key bottleneck occurs at the data level in aligning and linking both technologies' heterogeneous schemas, which have yet to be resolved even with the semantic web's involvement [6]. Given the significant attention on this aspect, there is almost a lack of consideration for the process and application level, which is crucial for the practicality and feasibility of BIM-GIS applications. Existing solutions at the data level are usually developed for specific application scenarios that neglect other scenarios, in particular, the planning practices [6]. This becomes a misstep for developing an ideal, holistic BIM-GIS integration solution for planners. In guiding future work, we have identified several research gaps as follows:

- **Data level:** The data requirements of planners should be consulted while research on aligning their schemas progresses. One notable requirement is real-time integrated spatial and non-spatial data monitored for the long term for more meaningful interpretations and analysis of long-term planning strategies [64].
- **Process level:** More ontological frameworks and knowledge graphs are necessary to link the currently segmented data regime and semantic creation methods and

enable a more robust and generative design system across all scales that extends data access across administrative bodies [64].

- **Application level:** These tools must develop a smooth, intuitive, and flexible user interface experience that provides adequate access privileges to all stakeholders for their operational needs while quelling legal concerns on data privacy and ownership.

5 Conclusion

“Are planners late to the game?” is a misnomer of the present situation. Rather, BIM-GIS enthusiasts are more accurately considering “Are planners even necessary to the game?”, evident by their past exclusion of planning inputs. It becomes critical to re-acknowledge the mediatory role of urban planning to untangle and accommodate the complex network of actors and their conflicting interests involved in the city’s development across disciplines and scales for more sustainable cities [60]. Acknowledging the planners would mean explicitly incorporating their expectations, requirements, and concerns into the functionality of BIM-GIS for planning purposes.

In guiding the future research direction for urban planning, this paper complements the existing BIM-GIS discourse with a review of BIM-GIS planning applications, as well as progress their interoperability research through discussing the semantic web technology. Over the years, the growing interest in BIM-GIS for planning applications have spurred exploratory research into six domains – urban environmental simulation, urban energy modelling, land administration, crisis management, urban infrastructure management, and urban social sustainability. Reviewing these works further solidifies the importance of BIM-GIS for planning as an urban building and geospatial data source to simulate, represent, and analyse the volatile, complex urban dynamics across domains, scales, and borders.

However, the current research is limited in scope and location, with a predominantly theoretical discourse contained in developed cities. Often, the neglect of BIM in the planning field translates into a lack of inquiry for BIM-GIS integration, which is observable as more GIS-based planning literature discusses the potential for BIM-GIS than their BIM counterparts. Given the more active discussion in smart city journals, planning research also seems to be dominated by technologists and policymakers with few inputs from planning practitioners, and what seems to be a missing dialogue. Moreover, new developments such as the semantic web, inclusive of ontologies and knowledge graphs, which could provide a new form of inclusive urban management systems, are yet another example of digital developments that develop outside the planning sphere – but may take over the planning sphere. It becomes obvious that planners are not simply late to the game but fail to be considered at all. This comes with a risk of its own for city management. As the city’s domains become more interdependent, planners are critical to orchestrate the implementation of any urban projects to accommodate all perspectives for more sustainable outcomes. For example, adding a community garden without notice may drain water resources from the surrounding homes. When their requirements, expectations, and concerns are excluded, the lengthy development time and resources for planning tools could be wasted without any practicalities for planning work.

Conflicts of interest

The authors declare that no competing interests exist.

Acknowledgements

This research was supported by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme.

Thank you to Andrew Breeson for proofreading the article.

Nomenclature

AEC Architecture, Engineering, and Construction

BIM Building Information Modelling

CIM City Information Modelling

CityGML City Geographic Markup Language

GIS Geographic Information System

IFC Industry Foundation Classes

POE Post-Occupancy Evaluation

SLR Systematic Literature Review

UBEM Urban Building Energy Modelling

Appendix

Table A.1: *List of selected publications by article types.*

Index	Publication	Literature Review	Framework	Application	Future Research
1	Diakite and Zlatanova [18]		✓		
2	Souza and Bueno [58]	✓			
3	von Richthofen et al. [64]	✓			
Urban Environmental Simulation					
4	Blàzquez et al. [10]				✓
5	Chen [14]				✓
6	Ervin [20]	✓			
7	Kylili and Fokaides [39]	✓			
8	Saretta et al. [54]				✓
9	Wong et al. [70]		✓		
10	Zambrano-Prado et al. [74]				✓
11	Zhong et al. [76]		✓		
Urban Energy Modelling					
12	Carnieletto et al. [12]				✓
13	Ferrando et al. [21]	✓			
14	Malhotra et al. [44]	✓			
15	Reinhart and Davila [53]	✓			
16	Sola et al. [56]	✓			
17	Wijeratne et al. [69]	✓			
Land Administration					
18	Barzegar et al. [5]		✓		
19	Brasebin et al. [11]				✓
20	Ghawana et al. [23]		✓		
21	Guler and Yomralioglu [27]		✓		
22	Kitsakis et al. [38]		✓		
23	Kara et al. [34]				✓
24	Lemmen et al. [40]		✓		
Crisis Management					

Index	Publication	Literature Review	Framework	Application	Future Research
25	Alattas et al. [3]			✓	
26	Chen et al. [13]			✓	
27	Isikdag et al. [32]		✓		
28	Tashakkori et al. [61]			✓	
29	Wang [67]	✓	✓		
Urban Infrastructure Management					
30	Hua et al. [30]				✓
31	Göçer et al. [25]		✓		
32	Kalogianni et al. [33]		✓		
33	Li et al. [41]	✓			
34	Marzouk and Othman [45]			✓	
35	von der Tann et al. [63]		✓		
36	Yan et al. [72]		✓		
37	Yang et al. [73]		✓		
Urban Social Sustainability					
38	Al Horr et al. [2]	✓			
39	Bizjak et al. [9]		✓		
40	Ponce-Lopez and Ferreira Jr [50]				✓
41	Lopez and Ferreira [43]				✓
42	White et al. [68]			✓	
43	Zhang et al. [75]		✓		

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