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Review

Trends and Opportunities of BIM-GIS Integration in the Architecture, Engineering and Construction Industry: A Review from a Spatio-Temporal Statistical Perspective

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Abstract: The integration of building information modelling (BIM) and geographic information system (GIS) in construction management is a new and fast developing trend in recent years, from research to industrial practice. BIM has advantages on rich geometric and semantic information through the building life cycle, while GIS is a broad field covering geovisualization-based decision making and geospatial modelling. However, most current studies of BIM-GIS integration focus on the integration techniques but lack theories and methods for further data analysis and mathematic modelling. This paper reviews the applications and discusses future trends of BIM-GIS integration in the architecture, engineering and construction (AEC) industry based on the studies of 96 high-quality research articles from a spatio-temporal statistical perspective. The analysis of these applications helps reveal the evolution progress of BIM-GIS integration. Results show that the utilization of BIM-GIS integration in the AEC industry requires systematic theories beyond integration technologies and deep applications of mathematical modeling methods, including spatio-temporal statistical modeling in GIS and 4D/nD BIM simulation and management. Opportunities of BIM-GIS integration are outlined as three hypotheses in the AEC industry for future research on the in-depth integration of BIM and GIS. BIM-GIS integration hypotheses enable more comprehensive applications through the life cycle of AEC projects.

Keywords: BIM; GIS; BIM-GIS integration; AEC; spatio-temporal statistics; smart sustainable city

1. Introduction

Worldwide growth of cities with rapid urbanization and global climate change are the two most critical issues in current world [1–3]. Smart sustainable city is an innovative city that has widely spread since the mid-2010s and aims at improving quality of life of present and future generations under the conditions of urbanization and global climate change [4–6]. With the wide utilization of information and communication technologies (ICTs) and internet of things (IoT), urban services will be more efficient and cities will be more competitive for their socio-economic, environmental and cultural conditions [7]. Thus, smart sustainable city is characterized by widely used technology and comprehensive improvement of sustainability of urban life, which requires massive and multi-source data for the use of technologies and management.

The integration of building information modelling (BIM) and geographic information system/science (GIS) is a strong support for smart sustainable city due to its capabilities in data integration, quantitative analysis, application of technologies and urban management [8–10]. BIM-GIS integration on construction management is a new and fast developing trend in recent ten years, from research to industrial practice. BIM has advantages on rich geometric and semantic information through the building life cycle [11], while GIS is a broad field covering geovisualisation-based decision making and geospatial modelling [12]. Their respective advantages have been discussed in some of the previous review articles [8,13,14]. BIM-GIS integration is to integrate the strong parts of both BIM and GIS for building and city modelling. During the past ten years, BIM-GIS integration has been applied on multiple cases such as visualization of construction supply chain management [15], emergency response [16–18], urban energy assessment and management [19–21], heritage protection [22,23], climate adaption [24] and ecological assessment [25].

In previous BIM-GIS integration studies, researchers spent a lot of effort on the integration technologies. Various BIM-GIS integration methods are proposed to address different problems [13,14]. For the integration pattern, more than half of the researchers prefer to extract data from BIM to GIS, and others integrate GIS data to BIM systems or integrating both BIM and GIS data on a third-party platform [8]. For instance, Industrial Foundation Class (IFC) and City Geography Markup Language (CityGML) are two most popular and comprehensive standards for exchanging semantic 3D information and geographical for BIM and GIS, respectively, and they are the primary standards for BIM-GIS integration [26–28]. During the integration process, some significant details are lost due to the extraction and simplification of data from one system to another [29]. To avoid information losses, unified building model (UBM) is proposed to cover information of both IFC and CityGML models [30].

Even though many technical issues related to the integration of BIM and GIS have been or partially been addressed, few theoretical studies address how to fully integrate the respective strengths of BIM and GIS for further quantitative analysis. Spatial or spatio-temporal statistical modelling for the analysis of patterns and exploration of relationships is regarded as the central function of GIS [31–35], but it is scarcely mentioned in BIM-GIS integration studies. During the past thirty years, spatio-temporal statistical modelling is widely applied to geosciences including geology, geography, agriculture, ecology, atmospheric science, hydrology, etc. [36], and location-based studies in other fields such as urban planning [37–39], public health [40,41] and social science [42–45]. From the perspective of the architecture, engineering and construction (AEC) industry, with the widely application of BIM, especially the collection of massive data, accurate mathematical modelling is required for the analysis and assessment of each stage of AEC industry, quality, cost, progress, safety, contract and information management, and coordination of various sectors.

However, BIM-supported analysis and decision making cannot fully satisfy the user requirements of the AEC industry, including the improvement of quality and productivity, decrease of project cost, real-time tracking progress across construction space, ensuring safety, decreasing environmental risks, and effective information update, interaction and management. A primary gap between user requirements and current condition is that the requirements during construction process cannot be accurately and dynamically described, modeled and managed. The traditional construction methods are still main stream and comprehensive data-driven spatio-temporal modelling is rarely utilized, even though the data-driven analysis of real time and dynamic progress is increasingly critical in mega projects and the construction management of smart sustainable city, and the stages of AEC industry are typical spatial and temporal processes. In addition, the space surrounding and far away from construction sites is not fully involved in the construction management. For instance, supplying and delivery processes during feasibility study, design and demolition stages require spatial analysis from large spatial scales, but the quantitative analysis of spatial and temporal processes is seldom involved in the BIM-based decision making of AEC industry. Therefore, this paper aims to summarize applications of BIM-GIS integration and propose the potentials of its future development in AEC industry from a spatio-temporal statistical perspective.

In this paper, we review the applications of BIM-GIS integration to characterize its evolution progress from three aspects: (1) applications of BIM-GIS integration in the AEC industry during past ten years; (2) history of BIM-GIS integration from the perspective of surveying and mapping; and (3) comparative study of the evolution progresses of GIS, BIM and integrated BIM-GIS. The analysis of evolution progress of BIM-GIS integration enables further and deep understanding of the central functions and primary scopes of BIM, GIS and their integration. Based on the analysis, this review aims at summarizing the trends of applying BIM-GIS integration in the AEC industry and proposing potential opportunities of BIM-GIS integration from the perspective of spatio-temporal statistical modelling. As a result, we propose three hypotheses for future development of BIM-GIS integration.

This review is structured as follows. Section 2 summarizes the current applications of BIM-GIS integration to capture the status quo of BIM-GIS integration globally. Section 3 analyzes the evolution progress of BIM-GIS integration from the three aforementioned aspects. Section 4 discusses future trends and proposes potential opportunities of BIM-GIS integration in the AEC industry. Section 5 concludes this review.

2. Current Applications of BIM-GIS Integration

2.1. Methodology of Review

In this paper, the applications of BIM-GIS integration are reviewed to characterize the evolution progress of BIM-GIS integration, evaluate the academic and practical trends and gaps, and propose the future opportunities. To achieve this goal, literatures is analyzed from three aspects. First, it should be explored that the current application trends since the concept of BIM-GIS integration was proposed. To learn the trends, publications associated with the applications of BIM-GIS integration are collected and statistically analyzed. The literature is summarized according to multiple indicators including the annual number of publications, annual citation times, distributions of countries/regions and universities/institutes of the publications, research areas the publications belong to, and the primary journals and conferences for BIM-GIS integration studies. Then, the evolution progress of BIM-GIS integration needs to be described and the reasons why it was developed in this direction should be further discussed. Finally, the potential prospects, opportunities and drawbacks should be evaluated from the spatio-temporal statistical perspective so that the function of analysis could be fully utilized in the practice of AEC industry.

Literature about BIM-GIS integration are retrieved and collected from the major online database Web of Science ™ Core Collection. Both journal articles and conference articles are retrieved. Journals are limited to the Science Citation Indexed (SCI) or Social Sciences Citation Indexed (SSCI) journals, and conferences should be indexed by the Conference Proceedings Citation Index-Science (CPCI-S) or Conference Proceedings Citation Index-Social Science and Humanities (CPCI-SSH). "BIM" and "GIS" are keywords with the operator of "AND" for searching the topic of literature, which includes title, abstract, author keywords and keywords plus®, and the publication language is limited to English. As a result, 99 research articles are retrieved (before September 2017). Three articles among them are not related with BIM-GIS integration and they are removed. In addition, there is no need for additional collection of papers for this review. Thus, 96 articles of BIM-GIS integration are collected, where there are 36 SCI/SSCI indexed articles.

2.2. Literature Analysis

Figure 1 shows the trends and worldwide distributions of BIM-GIS integration studies during past ten years. The earliest studies appear in the early 21st century, where the earliest journal and conference articles appear in 2008 and some book chapters are published earlier (e.g., [46]). Progress of BIM-GIS integration studies is slow during the seven years of 2008–2014 with an average of six publications annually. Since 2015, the number of publications has significantly increased with 19, 27 and 8 articles published in 2015, 2016 and the first three quarters of 2017, respectively. The respective number of SCI/SSCI indexed publications are 7, 14 and 5. Meanwhile, the citation times of BIM-GIS integration studies especially the SCI/SSCI indexed publications have been continuously increasing.

Even though the studies of BIM-GIS integration are rapidly increasing during the last two years, the academic publications are widely distributed globally. Figure 1B also shows that authors of publications are from 99 universities/institutes in 30 countries/states. The universities/institutes with the number of publications larger than one are dotted in the map. There are ten countries where the numbers of publications are larger than five, as labeled on the map, and six universities whose numbers of publications are greater than or equal to four: Georgia Institute of Technology in USA, Curtin University and Melbourne University in Australia, The Hong Kong University of Science and Technology (HKUST) in China, Delft University of Technology in Netherlands and Politecnico di Torino in Italy. Figure 1C shows the distributions of SCI/SSCI indexed journal articles, where universities/institutes with more than one SCI/SSCI indexed articles are dotted in the map. Six countries have more than two SCI/SSCI indexed articles about BIM-GIS integration as labeled on the map, and four universities have more than or equal to three SCI/SSCI indexed articles including HKUST, University of Melbourne, Curtin University and Georgia Institute of Technology.

Tables 1 and 2 list the summary of the research areas (larger than two publications) and publication sources (greater than or equal to two publications) of the BIM-GIS integration studies. The top three areas of all papers are engineering, computer science and remote sensing, and the top three areas of SCI/SSCI indexed journal articles are engineering, construction building technology and computer science. The summary of these research areas indicates that the AEC industry has more studies on BIM-GIS integration than geosciences, and the computer science supported technology integration is a mainstream of current studies. Table 2 shows that for BIM-GIS integration studies, *Automation in Construction* is a primary SCI/SSCI indexed journal in the AEC industry, and *ISPRS International Journal of Geo-Information* and *Computers Environment and Urban Systems* are the primary SCI/SSCI indexed journals in geosciences. The CPCI-S/CPCI-SSH indexed conferences that have the largest number of publications are *eWork and eBusiness in Architecture Engineering and Construction* and *ISPRS Archives* in the AEC industry and geosciences respectively.

Table 1. Summary of research areas for the publications of building information modelling and geographical information system (BIM-GIS) integration.

Research Areas [1]	Number of All Papers	Number of Journal Papers
Engineering	41	23
Computer Science	30	13
Remote Sensing	24	5
Construction Building Technology	23	14
Physical Geography	19	5
Imaging Science Photographic Technology	13	
Architecture	9	
Environmental Sciences Ecology	8	4
Geography	5	3
Business Economics	5	
Urban Studies	4	
Geology	4	
Science Technology Other Topics	3	
Operations Research Management Science	3	3

[1] Research areas with more than three publications of BIM-GIS integration are listed.

Table 2. Summary of journals and conferences for the publications of BIM-GIS integration.

	AEC Industry		Geosciences	
	Source Title	**#**	**Source Title**	**#**
Journal [1]	Automation in Construction	8	ISPRS International Journal of Geo-Information	3
	Journal of Computing in Civil Engineering	2	Computers Environment and Urban Systems	3
	Computers in Industry	2		
	Building and Environment	2		
	Advanced Engineering Informatics	2		
Conference [1]	eWork and eBusiness in Architecture Engineering and Construction	7	ISPRS Archives	13
	Proceedings of The First International Conference on Sustainable Urbanization ICSU 2010	2	International Conference on 3D Geoinformation	5
	Proceedings and Monographs in Engineering Water and Earth Sciences	2	XXIII ISPRS Congress Commission	3
	Procedia Engineering	2	Urban and Regional Data Management	3
	Fabbrica Della Conoscenza	2	International Conference on Cartography and GIS	3
	Energy Procedia	2	International CIPA Symposium	3
	eCAADe	2		
	Applied Mechanics and Materials	2		

[1] Journals and conferences with more than two publications of BIM-GIS integration are listed.

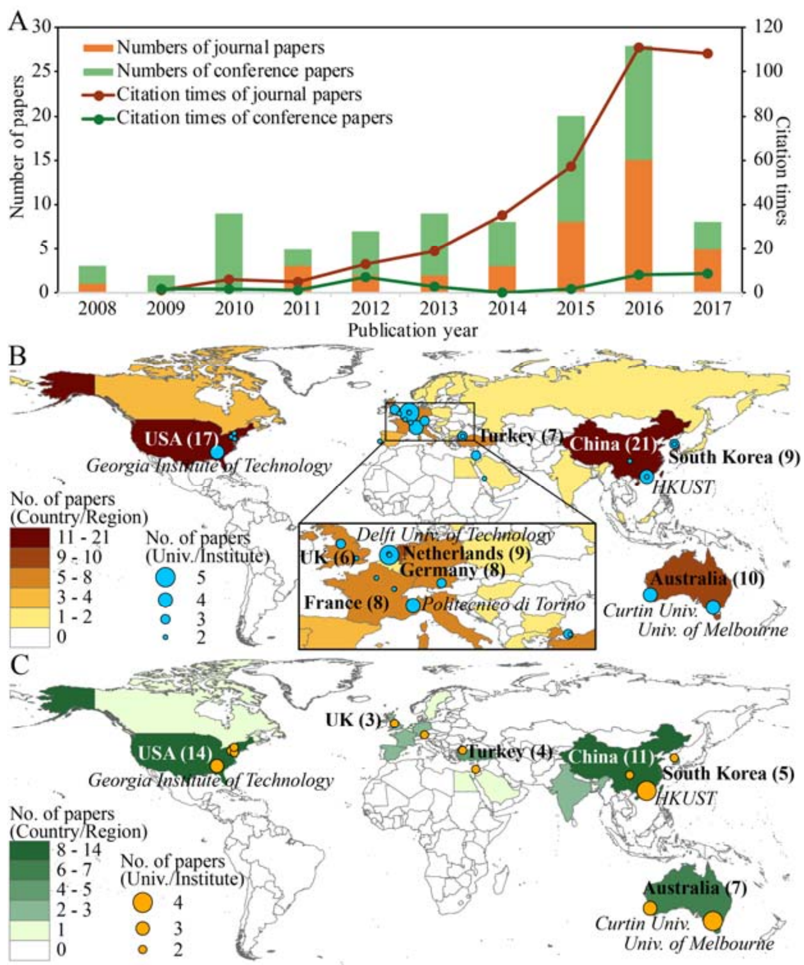

Figure 1. Trends and worldwide distributions of BIM-GIS integration during the past ten years: (**A**) trends of publications; (**B**) map of publications; and (**C**) map of the Science Citation Indexed (SCI) or Social Sciences Citation Indexed (SSCI) indexed journal papers.

3. Evolution Progress of BIM-GIS Integration

Evolution progress of BIM-GIS integration is characterized by three aspects: application evolution in AEC industry, history from the perspective of surveying and mapping, and comparison study of the evolution progresses of GIS, BIM and integrated BIM-GIS. The three aspects of BIM-GIS integration evolution are discussed in the following subsections.

3.1. Application Evolution in AEC Industry

The evolution process of BIM-GIS integration in the AEC industry reveals that BIM-GIS integration has moved from simple cases to deep considerations and complex applications.

Most of the early studies try to address technological problems of the integrations. In general, multiple integration methods are proposed to address various problems [13,14]. A mainstream of integration methods is extracting BIM data to the GIS context [47,48]. However, during this process, some significant details are lost [29]. To address this problem, a unified building model (UBM) covering both IFC and CityGML models is utilized to avoid details losses [30]. In addition, to ensure the construction details, geometric topological and semantic topological modelling are applied on capturing 3D features [49], such as the application of floor topology detection [50]. A series of methods are also proposed to ensure the interoperability of BIM and GIS, such as semantic web technology [51,52], semantic-based multi-representation approach [53], implementation of prototype [54], and resources description framework (RDF) [55].

After the initial development, researchers start to propose new standards and methods for the building and urban database management. Concept of level of details (LoD) in CityGML is applied on the representations and management of buildings and building elements during BIM-GIS integration [27,56,57]. Studies also explain the techniques for the storage, query, exchange and management of spatial information [58–63]. Web-based open source platform is considered as a well-behaved tool for the sharing and fusion of 3D information in digital buildings [52,64–67]. In addition to the building and urban database management, comparison studies and comprehensive applications are performed to explore the advantages and disadvantages of 3D display methods and software, including 3D GIS, BIM, CAD, CityEngine, 3D Studio Max and SketchUp [68–71].

More specifically, the publications are categorized based on their applications and publication years to reveal the application evolution of BIM-GIS integration in the AEC industry (Table 3). Applications are classified into two categories according to the application object, a building or a city, and the applications with the object of buildings are classified into four categories according to the construction phases, including planning and design, construction, operation and maintenance, and demolition. Results show that the application objects consist of both buildings and cities, which includes urban infrastructures. For the applications with objects of buildings, 61% of the studies focus on the operation and maintenance phase but only a few studies explore demolition phase.

As can be seen from the annual variations, applications tend to be diverse and complex from 2008 to 2017. Emergency and disaster simulation, response and management is a typical and hot topic [61,72–75]. It draws more attention recently as there are nine publications related to this topic in 2016 [16–18,76–81]. This topic is a typical BIM-GIS integration problem that should be addressed with both large spatial scale and detail considerations of construction components. Maintenance and renewal of existing buildings is studied since 2010 [82,83]. This topic has great potential in future studies, since most buildings are old buildings instead of new ones in developed nations and urbanized regions in developing nations. Maintenance and renewal of existing building is a great challenge for BIM and has a lot of opportunities for BIM-GIS integration. Compared with the management of old buildings, construction planning and design is more about new buildings. Applications of BIM-GIS integration on planning and design include multiple aspects, such as site selection and space planning [72,84], climate adaptation [24], safety planning [85], building design and preconstruction operations [86–88], energy design [89,90] and planning of disassembling process [91]. The popular topics of applying BIM-GIS integration on buildings also include indoor navigation [92], heritage protection [22,23,93–96], construction supply chain management [15,97], mega projects management [98], ecological assessment [25], etc. For the applications of BIM-GIS integration on cities, 3D urban modeling and representations [99–101], urban facility management [28,102], and emergency response [103] are the primary aspects at the beginning of the integration attempt. In recent years, more studies utilize BIM-GIS integration to characterize human activities and their relationships with cities, such as traffic planning and analysis [104,105], walkability analysis [106], and energy assessment and management [10,19–21,107–109].

The applications of BIM-GIS integration cover all construction phases of buildings, and city and urban infrastructures. In the applications, the strong parts of BIM and GIS are generally integrated for building and city modelling, but the respective functions of BIM and GIS utilized in these applications tend to be similar. BIM presents the rich geometric and semantic information of buildings, cities and infrastructures through the life cycle [11]. Meanwhile, GIS is commonly regarded as a 3D visualization system of built environment and urban system in current applications of BIM-GIS integration. The above summary of applications BIM-GIS integration reveals that current applications have three primary advantages. First, data and information with multiple spatial scales are integrated to address the problems related to both construction components and built environment even urban environment. This is also a starting point of using BIM-GIS integration. Second, the primary function of BIM has been applied that provides complete and detailed geometry and material information of building components. Finally, visualization-based analysis improves the efficiency and performance of construction management in AEC projects.

However, the applications are still limited in the use of integrated BIM-GIS, and the strengths of both BIM and GIS have not been fully integrated and utilized. First, the utilization of primary functions of GIS is very limited, since GIS is a broad field covering geovisualisation-based decision making and geospatial modelling [12] instead of a system of 3D visualization of built environment and cities. Spatial and spatio-temporal statistical analysis are seldom considered and used in the current applications of BIM-GIS integration. Second, BIM provide geometry and semantic information of construction components, but the information of user requirements of AEC projects is rarely involved in BIM. In recent years, it is a necessary part of BIM applications to study and propose solutions of user requirements such as quality, time and cost management. Third, LoD is applied on the representations and management of buildings and building elements in IFC and CityGML models, but it has not been treated as the spatio-temporal attributes during the integration processes of analysis and decision making.

Table 3. Application evolution of BIM-GIS integration in the Architecture, Engineering and Construction (AEC) industry.

Application Object		Building				City
Construction Phase		Planning and Design	Construction	Operation and Maintenance	Demolition	
Year	2008	Site selection [72].		Fire response [72]; Web service [73]; Disaster scenarios [73].		3D city [99].
	2009	Climate adaptation [24].				Urban renewal projects [110].
	2010		Urban renewal projects [82].			Urban facility management [28,102] (e.g., road maintenance [111]); urban design [112].
	2011	Construction safety planning [85]; construction space planning [113].	Visualization of construction time control [114].	Existing buildings maintenance [83].		
	2012		Highway construction management [115].	Emergency response [61].		Urban crisis response [103]; human activity and land use [116].
	2013	Site selection of solar panels [84].	Visualization of construction supply chain management (CSCM) [15].	Indoor navigation [92]; heritage protection [93].		Urban representation [100,101].
	2014			Fire simulation and response [74]; heritage protection [94]; large building operation [98].		Urban facility management [117] (e.g., traffic planning [104]).
	2015	Building design and preconstruction operations [86,87]; building energy design [89,90].		Facility management [118]; indoor emergency response [75]; heritage protection [95,96].	Construction waste processing [119].	Tunnel modelling [120]; energy assessment and management [107–109]; district modelling [121].
	2016	Building design [88].	Urban renewal projects [122].	Flood damage assessment and visualization [76–78]; indoor emergency response and route planning [16–18]; hazard identification and prevention [79–81]; heritage protection [22,23]; ecological assessment [25].		Traffic noise analysis [105]; walkability evaluation of urban routes [106]; energy assessment and management [19–21]; utility compliance checking [123].
	2017	Lift planning of disassembling offshore oil and gas platform [91].	Resilient construction supply chain management (CSCM) [97].	Management of property interests [124].		Energy assessment and management [10].

3.2. History from the Perspective of Surveying and Mapping

Analysis of the application evolution of BIM-GIS integration indicates that it is a trend to use integrated BIM-GIS to address diverse and complex problems in the AEC industry. Seen from the perspective of surveying and mapping histories, integrated BIM-GIS would have broader and deeper theories and methods for applications. Figure 2 shows the history of BIM-GIS integration from the perspective of surveying and mapping. GIS and BIM are the products of digitization of two subdisciplines of surveying and mapping, geodesy and engineering survey. On one hand, a central function of GIS is to analyze patterns and explore relationships of spatial data, which are primarily collected by geodesy methods [31–35]. One of the primary products of field geodesy work is topographic maps with large spatial scales indicating terrain characteristics, infrastructure, buildings and land cover. After digitization of topographic maps, spatial data depicting natural attributes become data layers of GIS [125]. Further, due to the capability of spatial analysis, GIS becomes a science and system to analysis the spatial data and have deep and comprehensive understanding of natural process [36]. On the other hand, BIM is originally used as a platform for model visualization, data exchange and analysis of digitized engineering drawings of buildings or infrastructures [126]. With the wide applications from design to maintenance stages of construction management, BIM is changing the AEC industry [127]. BIM emerges as a system of creating, sharing, exchanging and managing building and urban information throughout the whole lifecycle among all stakeholders [128]. Thus, in theory, beyond the technology integration, i.e. platform or system integrations, BIM and GIS have great potential to be integrated from multiple aspects including integrations of database management, theories and methods, analysis and products, etc. For addressing urban problems, both BIM and GIS emphasize the utilization of ICTs and new technologies, and broadly cover the environmental problems. In addition to the ecological, energy and environmental issues solved by integrated BIM-GIS, BIM is also associated with the sustainability of buildings and urban infrastructures through a series of new methods such as lean production [129–132], carbon emission assessment [133–137] and green buildings design [138]. Therefore, BIM and GIS can be integrated at various stages for the analysis in AEC industry and these integrations together can contribute to the theory and practice of smart sustainable city.

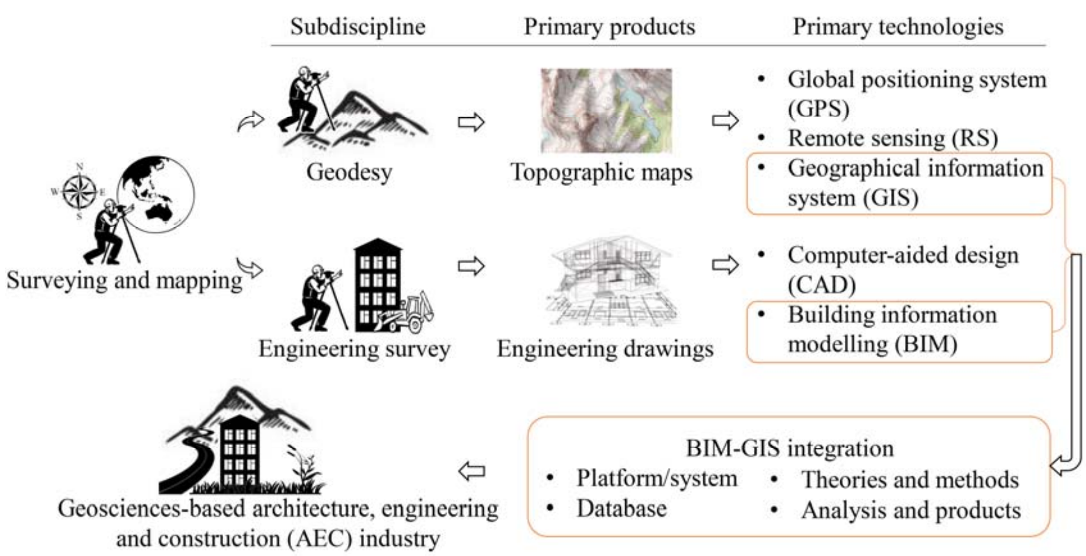

Figure 2. History of BIM-GIS integration from the perspective of surveying and mapping.

3.3. Comparison of Evolution Processes of GIS, BIM and Integrated BIM-GIS

Compared with GIS, BIM is still relatively young and primarily serves as a collaborative platform, and more efforts are required to deeply understand and apply BIM in the AEC industry

[139]. Integrated BIM-GIS is in the initial stage and it is rapidly developing in the last three years. In general, both GIS and BIM have experienced six primary evolution stages: origins, system development, digitalization and visualization, database management, visualization-based analysis and mathematical modelling (Figure 3).

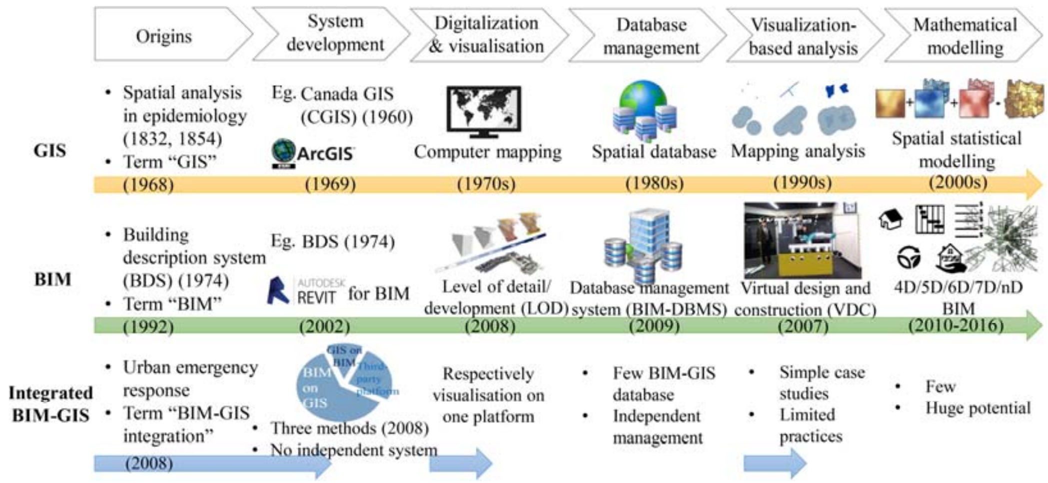

Figure 3. Comparison of evolution progresses of GIS, BIM and integrated BIM-GIS.

Spatial analysis of patterns and relationships is the central function of GIS [31–35], which is first utilized in the analysis of epidemiology in France and London in the mid-nineteenth century [140–142]. The term GIS is first used for regional planning by Roger Tomlinson in 1968 [143–145]. The development of computer technology promotes the system development of GIS, such as Canada GIS (CGSI) for natural resources mapping [146,147] and ArcGIS for commercial applications [148]. GIS is gradually developing and goes through the computer mapping, spatial database management, visualization-based mapping analysis and spatial statistical modelling from the 1970s to the 2000s, and has been widely applied to natural resources, facility management, public health, business and agriculture fields [12]. In this paper, the theories and methods of spatio-temporal data analysis are summarized according to the research and application objectives, as listed in Table 4, including the description of spatio-temporal characteristics, exploration of potential factors and spatio-temporal prediction, modelling and simulation of spatio-temporal process, and spatio-temporal decision making. In this way, researchers and practitioners of AEC industry can easily access the methods and select proper methods in the AEC projects.

Table 4. Summary of theories and methods of spatio-temporal data analysis.

Research and Application Objectives	Theories and Methods of Spatio-Temporal Data Analysis [149]	Exemplar Models
Description of spatio-temporal characteristics.	- Spatio-temporal visualization [150]; - Time-series of spatial statistical indicators; - Spatio-temporal indicators that reveal the comprehensive statistics of spatial and temporal variations [149]; - Spatio-temporal clustering and hotspots exploration [149]; - Spatio-temporal interpolation.	- Spatio-temporal scan statistics [151]; - Self organization mapping [152]; - Spatio-temporal kriging [153]; - Bayesian maximum entropy (BME) model [154].
Exploration of potential factors and spatio-temporal prediction.	Spatio-temporal regression.	- Spatio-temporal multiple linear regression; - Spatio-temporal panel model; - Spatio-temporal Bayes hierarchical model (BHM) [155];

		- Geographically and temporally weighted regression (GTWR) [156]; - Spatio-temporal generalized additive model (GAM) [157].
Modelling and simulation of spatio-temporal process.	- Spatio-temporal process modelling; - Spatio-temporal evolution simulation.	- Cellular automation (CA) [158]; - Geographical agent-based model (ABM) [159]; - Computable general equilibrium model [160].
Spatio-temporal decision making.	Spatio-temporal decision-making model.	Spatio-temporal multi-criteria decision making (MCDM) [161,162].

BIM is first known as building description system for digitization and visualization of building components in 1974 [163]. BIM is first termed by Van Nederveen and Tolman in 1992 [164], but it becomes popular in the 2000s due to wide commercialization by Autodesk, Bently, Graphisoft, etc. [165,166]. BIM is fast growing in the past ten years. For digitization and visualization stage, level of details/development (LoD) is applied in BIM to reflect the progressions of the modelling geographic representation from the lowest LoD of general 2D to the highest LoD of BIM involving 3D models and corresponding detailed non-geometric information [167–169]. BIM database management system (BIM-DBMS) is used for AEC data organization and management, and requires BIM-specific data management practices to ensure efficient applications for teams and projects [170,171]. BIM-supported virtual design and construction (VDC) is a significant and fast expanding technology for visualization-based analysis and decision-making in the AEC industry [172,173]. Due to the requirement of applying BIM on mega projects, urban management and other complex situations, multiple dimensions such as time, cost and environmental impacts, are added to 3D BIM for mathematical modelling and analysis. For instance, 4D BIM enables project time allocation and construction sequence scheduling simulations. 5D BIM supports real time cost planning. 6D BIM is used for sustainable element tracking, and 7D BIM can help the life cycle of facility management [174,175]. The concept of nD BIM is also proposed to allow all stakeholders to work cohesively and efficiently during the whole project life-cycle, and retrieve and analyze information of scheduling, cost, sustainability, main tenability, stability and safety [176–179].

Analysis of application evolution of integrated BIM-GIS in the AEC industry in Section 3.1 reveals that BIM-GIS integration is primarily used for urban emergency simulation, response and management. There are primarily three types of integration methods, extracting BIM data on GIS platform, extracting GIS data on BIM platform and using the third-party platform, where more than half of the researches prefer the first methods [8]. Even most of the current studies focus on the integration technologies, few of them proposes an independent system to achieve integrated BIM-GIS. For the digitalization and visualization of integrated BIM-GIS, a mainstream approach is still to visualize elements on respective BIM or GIS systems. Meanwhile, few studies discuss the issues about BIM-GIS database management and the data sets of BIM and GIS tend to be managed independently. Discussion in Section 3.1 also reveals that studies about BIM-GIS integration have been rapidly increasing since 2015 and tend to be applied to more complex AEC cases and scenarios in the recent three years. However, there is still a limited number of practical case studies and the integration lacks well supported theories.

A key problem of current BIM-GIS integration is that the integrated BIM-GIS supported analysis and decision making is still in the initial stage. For the visualization-based analysis, the advantages of mapping analysis of GIS and VDC of BIM are combined and fully utilized (Figure 3), especially the mapping analysis such as spatial proximity analysis, overlay analysis and network analysis. For the mathematical modelling, few studies involve both spatial or spatio-temporal statistical modelling of GIS and 4D/nD BIM to address AEC issues. In previous BIM-GIS integration studies, very limited studies utilize spatio-temporal statistical modelling in the applications, even though it is the central function of GIS. Most studies treat GIS as a 3D display platform for the geovisualisation of large spatial scale data. However, it should be noted that in the recent twenty years, GIS is generally known as "geographical information science" that covers theories, concepts, methods, systems, database management, applications and decision making [180]. Spatio-temporal statistical modelling is used for accurate modelling of spatial and temporal patterns, explorations of relationships and potential statistical factors, prediction of future distribution scenarios and statistics-based decision making. Therefore, there are great potentials for more accurate, deep and flexible application of integrated BIM-GIS and development of its specific theories and methodologies.

In addition to the lack of deep analysis and mathematical modelling, there are still massive blanks to be filled for future BIM-GIS integration as shown in Figure 4. There are primarily seven stages of BIM-GIS integration, including technology, database, management, concept, analysis methods, theory and application integrations. Technology integration means how to integrate both systems from technological aspects, such as the utilization of IFC and CityGML models. Database integration is to link, interact and merge data from BIM and GIS. Management integration is the collaborative management of respective works, data and information, and systems. Concept integration is to link the terms, definitions, and professional ideas from both fields. Analysis methods integration allows the applications of mutual methods and new methods in the context of AEC industry. Theory integration is driven by scientific objectives covering technologies, data and information, concepts, methods and management. In the above six integration stages, technology integration of systems can promote the development of concept and database integrations. The development of database integration improves management integration. Meanwhile, concept integration promotes analysis methods integration. Both management and analysis methods integration can help the development of theory integration, which in turn can improve the technology integration of systems. In addition, application integration is to apply the above outcomes in the applications, including professional applications of experts, general applications of researchers and practitioners in AEC industry, and public applications of public participants. The accumulation of applications can also improve the above six integration stages.

Current stage of BIM-GIS integration is at the technology integration and professional application stages. Technology integration is discussed in Section 3.1, and professional application means that most of the researchers and practitioners of integrated BIM-GIS are experts in the fields of either the AEC industry or geosciences. Few of them are general and public users. The stages of general application and public application is critical for the applications of technologies. GIS is utilized by experts, general users in institutes, companies and governments, and public users who can use simple codes even no code to develop their own tools and address their own problems [12]. For instance, Google Maps (https://www.google.com.au/maps) and OpenStreetMap (http://www.openstreetmap.org) enable public users to upload and download their own data and perform simple analysis such as distance measurement; and commercial companies such as Carto (https://carto.com/) and Mapbox (https://www.mapbox.com/) allow public users generate their own online interactive maps and perform spatial analysis use their own data and GIS methods. With the widespread mobile applications, millions of mobile applications are developed based on Google Maps (https://www.google.com.au/maps) [181], Gaode Map (http://ditu.amap.com/), Baidu Map (http://map.baidu.com/), etc., for general and public users. Even though BIM is not fully used by public users, a great number of general users such as workers have applied BIM on their practical works in industries [127,128,182]. Thus, research and practice of GIS and BIM indicate that integrated BIM-GIS can have wide and deep general and public applications in the future. Similar to the application integration, their respective concepts need to be integrated based on the combination of expert knowledge, innovatively integrated database tools and methods, and analysis methods and theories to address BIM-GIS specific smart sustainable city problems.

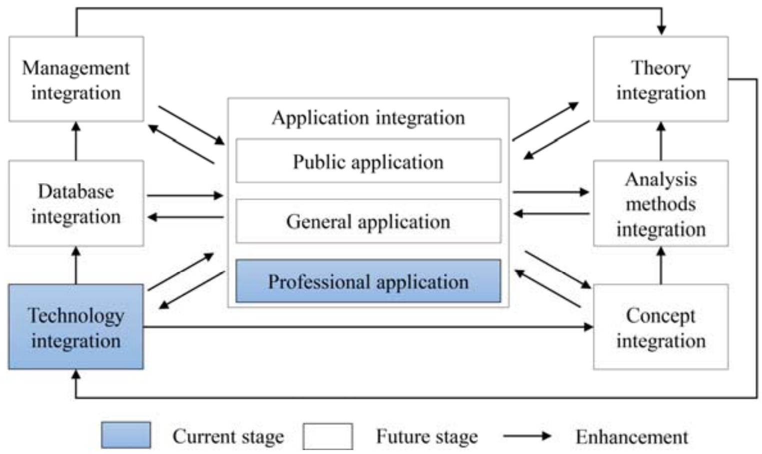

Figure 4. Relations among current and future evolution stages of BIM-GIS integration.

4. Future Trends of BIM-GIS Integration in AEC Industry

Based on the analysis of literature and explanations of BIM-GIS integration evolution progress, this paper summarizes the future trends of applying BIM-GIS integration in the AEC industry and proposes potential opportunities of BIM-GIS integration from the perspective of spatio-temporal statistical modelling. We propose three hypotheses for future trends and opportunities of BIM-GIS integration in the AEC industry, including the technology (loose integration) hypothesis, the science (tight integration) hypothesis and the data source hypothesis as shown in Figure 5. The explanations of the hypotheses are presented in Table 5 and discussed in the following subsections.

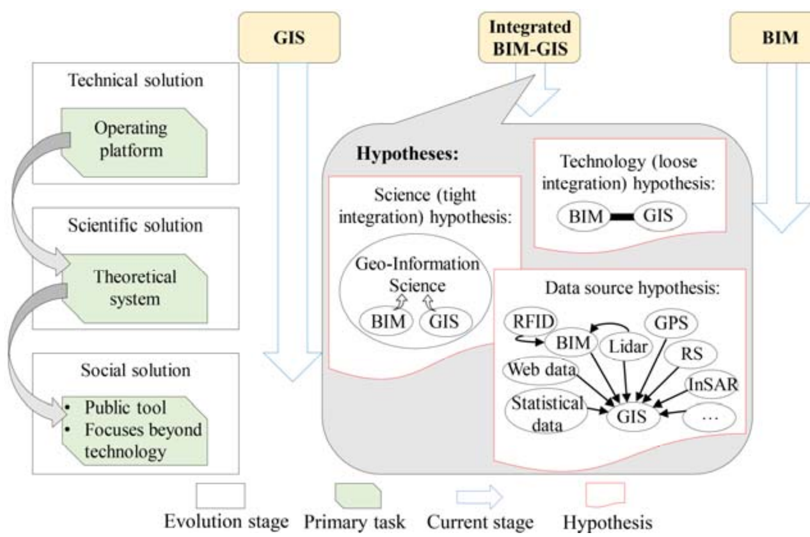

Figure 5. Hypotheses of future development of BIM-GIS integration.

Table 5. Contents of three hypotheses of future trends of BIM-GIS integration.

Hypothesis	Content
The technology (loose integration) hypothesis	BIM and GIS are independent systems and areas, and they are partially utilized together to address specific problems.
The science (tight integration) hypothesis	BIM will be developed as building information science for the AEC industry, and then a broader field of geo-information science will cover BIM, GIS and other location-based technologies, services and sciences.
The data source hypothesis	BIM is considered as a data source in the AEC industry for GIS and spatio-temporal statistical analysis.

4.1. The Technology (Loose Integration) Hypothesis

The technology hypothesis is also named as the loose integration hypothesis, which means BIM and GIS are independent systems and areas, and they are partially utilized together to address specific problems. Most of the current studies on BIM-GIS integration follow this integration model. The origin of BIM-GIS integration is that to address the AEC issues involving both building and its surrounding space, researchers try to combine the respective strong parts of BIM and GIS, especially the detailed representations of physical and functional components of facilities of BIM and spatial 3D models depicting building and urban environment of GIS. The integration means extracting data from one system to another or extracting both data on a third-party platform for analysis. The difference between future and current integration is that the more strengths of BIM and GIS will be explored and used, and spatio-temporal statistics and 4D/nD BIM are used for accurate mathematical modelling and analysis. The technology hypothesis has the following advantages:

- This is an easy integration model. There will not be too many changes of future integration methods compared with current ones.
- Concepts, methods, systems, and theories of BIM and GIS will not be changed.
- It is flexible for users. They can choose the integration methods, extracting data from one system to another or using a third-party platform, based on their specific problems to address.

The further development of the deeper integration of spatio-temporal statistics and 4D/nD BIM can provide more accurate analysis results, and new sense and knowledge for decision making to satisfy the user requirements of AEC industry in every stage. The benefits of applying the technology hypothesis of BIM-GIS integration on AEC industry can be explained by the comparison of using BIM in Table 6. Theoretical studies and industrial practices have proved that BIM can significantly improve the performance of both geometric modeling of buildings, infrastructures and cities, and the management of AEC projects [183]. For instance, most of the construction projects with the utilization of BIM report the cost reduction and effective control.

However, there are still challenges of using BIM and some cases show negative benefits during the application, especially the utilization of BIM software and coordination phase [183]. Software issues is relatively common in practice since multiple software have to be applied in a project, but they cannot be seamlessly combined due to the difference of software. Therefore, it is a trend to utilize IFC and CityGML models to integrate various functions and avoid details losses [30]. This solution also addresses the technical problems of integrating systems of BIM and GIS. In addition, the life cycles of AEC projects are typical spatial and temporal processes, but user requirements during construction process cannot be accurately and dynamically described, modeled and managed, due to the lack of comprehensive data-driven spatio-temporal modelling of AEC projects. By involving spatio-temporal statistical analysis, integrated BIM-GIS can more accurately quantify and address these issues.

Compared with BIM, BIM-GIS integration enhanced by spatio-temporal statistics and 4D/nD BIM provides spatial and temporal dynamic and predictive solutions for the user requirements in AEC projects. These solutions are significantly benefit for satisfying user requirements in quality, progress and time, cost, contract, health, safety and environment (HSE), and information management, and the coordination of various sectors. The spatio-temporal analyzed results and predicted scenarios become one of the primary evidence included in the database for decision making, in addition to the collected and monitored raw data that is commonly used in current BIM-based solutions. For BIM-GIS integration based solutions, management methods and coordination mechanisms are driven by the sense and knowledge sourced from data, information, and their analysis products, which are characterized as spatial and temporal varied, real-time, dynamic, interactive, accurate and practical.

Table 6. Comparison of benefits of BIM and BIM-GIS integration in satisfying the user requirements of AEC industry.

User Requirements of AEC Industry	Benefits of BIM	Benefits of BIM-GIS Integration (the Technology Hypothesis)
Quality management	- Improving design quality by defects detection, eliminating conflicts and decreasing rework; - Ensuring information consistency from design to construction [184].	- Exploring potential factors associated with defects dynamically across whole space during whole construction life-cycle; - Predicting potential spatio-temporal distributions of risks for predictive decision making.
Progress and time management	- BIM-based simulation of construction works enables significant time savings throughout construction period [183]; - Effective information management and enhanced communication reduces time consumption during information exchange.	Construction works could be simulated spatially and temporally for more accurate progress management and time reduction.
Cost management	Cost reduction and control are the most common benefit from BIM in construction projects [183].	Cost is controlled not only seen from the result of construction projects during each stage, but also by the dynamically monitored and analyzed spatio-temporal results.
Contract management	BIM enhances contract relationships, and optimizes construction procurement and contract management due to the improvement of execution efficiency of contracts [185,186].	Execution and management of contracts are based on the dynamic and predictive decision making.
Health, safety and environment (HSE) management	- Classifying, organizing and integrating fragmented HSE information; - Supporting maintenance by identification, data processing, rule-based decision making, and user interaction [187–190].	- Spatio-temporal statistical analysis plays more roles in the clustering analysis, correlation analysis, exploration of impacts of potential factors and prediction in HSE management; - A series of new methods can be proposed for the HSE management in AEC industry from the perspective of spatio-temporal statistical analysis by involving the characteristics of AEC projects.
Information management	Effective generation, collection, distribution, storage, retrieval, and disposition of component and project information [183].	- More information with large spatial scales is included in the AEC projects, such as the surrounding environment, suppliers far beyond the projects, road network and its geographical and socio-economic factors, and the participants of freight transportation, etc. - Spatio-temporal analyzed results and predicted scenarios become one of the primary evidence included in the database for decision making, in addition to the collected and monitored raw data.
Coordination of various sectors	BIM affects project coordination mechanisms in its specific ways and depending on the served purposes, such as a centralized-decentralized structure and a hierarchical-participative decision-making process [191,192].	Coordination mechanisms are driven by the sense and knowledge sourced from data, information, and their analysis products, which are characterized as spatial and temporal varied, real-time, dynamic, interactive, accurate and practical.

4.2. The Science (Tight Integration) Hypothesis

The science hypothesis, also named the tight integration hypothesis, is a relatively long-term hypothesis. This hypothesis assumes that BIM will be developed as building information science for the AEC industry, and then a broader field of geo-information science will cover BIM, GIS and other location-based technologies, services and sciences. Under this hypothesis, location-based theories and technologies can be tightly integrated by combining their similarities and highlighting strengths. Thus, this hypothesis of BIM-GIS integration primarily relies on the development of BIM. At present, only a few studies consider BIM as building information science for digitization, visualization and analysis of whole project life cycles [193], but it is a trend of BIM development due to the theoretical needs to manage sophisticated and mega projects in recent years. Correspondingly, new theories and methods will be proposed for the scientific studies of analyzing user requirements and solutions of AEC industry by involving the inherent spatio-temporal characteristics of AEC projects. The science hypothesis of BIM-GIS integration provides an opportunity for broadening the scope and comprehensive understanding of the AEC industry and smart sustainable city.

4.3. The Data Source Hypothesis

The data source hypothesis considers BIM as a data source in the AEC industry for GIS analysis. Under the data source hypothesis, the role of BIM in the AEC industry is similar with remote sensing (RS) in monitoring natural resources and light detection and ranging (LiDAR) in photogrammetry. Remote sensing is characterized as rapid acquisition, large spatial coverage, and accessing to land, sea and atmospheric data with diverse spatial and temporal resolutions in natural resources monitoring and management [194]. LiDAR including ground, vehicle, satellite-based and airborne LiDAR can rapidly and accurately measure and analyze dense point clouds without contact with danger and contaminants. Both remote sensing and LiDAR are primarily used as data collection tools, and they can also manage and analyze data, but they are generally combined with GIS to perform complex and comprehensive spatial and temporal analysis to deeply understand the attributes and phenomenon. In addition to remote sensing and LiDAR, there are a series of technologies that have similar roles of data source, such as traditional statistical data, surveying data, web-based data, global positioning system (GPS), and interferometric synthetic aperture radar (InSAR).

Table 7 lists the GIS data sources including potential data sources of BIM, and the comparisons of their data examples, general formats, characteristics and application examples. The comparison shows that BIM is a proper data source of buildings and urban infrastructures due to its rich geometric and semantic information, multi-level of details for various applications and building-level digital representation. In addition, geospatial analysis has been widely employed in the AEC industry including civil engineering and petroleum engineering [195]. Meanwhile, BIM can provide diverse data due to different user requirements of AEC projects, quality data, progress and time data, cost data, contract data, and HSE data, etc. For these studies, GIS provides spatial statistical methods for modelling AEC data and problems. Some of the spatio-temporal statistical analysis results can also be regarded as data source in the form of data and information products. Therefore, the data source hypothesis can enhance GIS applications and promote the strength of BIM for its role in the AEC industry.

Table 7. Comparison of GIS data sources.

Data Source		Data Examples	General Formats	Characteristics	Application Examples
Vector products		- Administrative boundary [196]; - Spatial data of infrastructure [197,198].	.shp	- Relatively low data volume; - Fast display; - Containing attributes information.	- Disease mapping [199]; - Road and traffic analysis [200,201].
Raster products		- Digital elevation model (DEM) [202]; - IPCC future climate change scenarios [203–205].	.tif/.img/Various formats	- Full coverage and spatially continuous; - Good visual effect.	- Gravity modelling [206]; - Future scenarios prediction [207,208].
Surveying data		- Wireless sensor network data [209–212]; - Air quality ground monitoring data [213,214].	Table/Various formats	- Including professional attributes; - Used for specific issues.	- Ecohydrological analysis [210]; - Air quality analysis [215,216];
Statistical data		- Population census data [217]; - Economic statistical data [218].	Table	- Including professional attributes; - Full coverage of a region.	- Urban development [219]; - Tracking migration [220].
Web data		Location-based social media data	Text/Various formats	- Current, fine-scaled and rich individual information [221,222].	- Urban and human mobility studies [223].
Global positioning system (GPS) data		- Location data - Ionosphere and troposphere data	ASCII/Binary/Text	- Accurate positioning and tracking.	- Trajectory analysis of human and vehicles mobility [224,225]; - Spatial uncertainty analysis [226,227].
Active remote sensing (RS) data	Radar	Meteorological radar	Various formats	- Regardless of weather conditions; - Capable in extracting water regions.	- Flood analysis [228].
	Light detection and ranging (LiDAR)	Point cloud (ground, vehicle, satellite-based, or airborne)	ASCII/LAS/Various formats	- Fast measuring and analysis; - Avoiding contacts with dangers and contaminants; - Accurate distance measurement and dense points.	- Generating accurate 3D models (e.g., DEM and BIM). - Landslide risk assessment [229–231].
	Interferometric synthetic aperture radar (InSAR)	- Topography data and ground deformation data	Various formats	- Slight deformation detection; - Large spatial coverage; - Regardless of weather conditions;	- Ecological analysis [232]; - Ground deformation analysis [233–236].

				- Obtaining underground information.	
Passive remote sensing (RS) data	Satellite RS images	- Land surface temperature [237]; - Vegetation data [237]; - Land cover data [237]; - Nighttime lights [238].	.tif/.hdf/ASCII /Various formats	- rapid acquisition; - Large spatial coverage; - Accessing to land, sea and atmospheric data with diverse spatial and temporal resolutions [194].	Vast applications. - Urban studies; - Roads and infrastructures; - Environment.
	Aerial photogrammetry data	- Land cover data; - Topography data.	.tif/Various formats	- Large spatial coverage; - Massive geometric and physical information of features; - Fast mapping.	- 3D analysis [239]; - Land use analysis [240].
	Unmanned Aerial Vehicle (UAV) measurements	- Land cover data; - Topography data; - Building data.	.jpg/Various formats	- Current and fine-scaled information; - High spatial resolution.	- 3D city modelling [241]; - Land use analysis [242].
Building information modelling (BIM) data		- Building projects [11,243]; - Civil infrastructure projects [244].	.ifc/Various formats	- Rich geometric and semantic information; - Multi-level of details for various applications; - Limited to building-level digital representation.	- Building indoor analysis [245]; - Mega project application [91,246].

4.4. BIM-GIS Integration for Project Life Cycles

From a spatio-temporal statistical perspective, the three hypotheses of BIM-GIS integration enable more comprehensive applications through the life cycle of AEC projects. Planning and design stages are highly influential in setting the directions for the whole business and project, where BIM-GIS integration not only provides multi-scale and rich geometric and semantic information for the decision makers [247], but also evaluates scheduling, cost and sustainability at early stage in 3D virtual environment [248]. Besides, BIM-GIS integration can also be used to perform complex building performance analysis to ensure an optimized building design of both building and its surrounding space.

During the construction stage, BIM-GIS integration is applied in different aspects that can impact the construction progress. For example, construction site is the main area that construction activities are conducted. BIM can provide building information to generate dynamic site layout models [249] and GIS can help optimize element distributions [250]. Safety is another important factor during the construction stage, since accidents during construction cause huge losses of human lives and project cost. An approach for safety management to use 4D/nD BIM visualization of construction components [251,252], and spatio-temporal analysis for risk distributions prediction and exploration of contributors. BIM-GIS integration can also be used for project cost control. BIM is used for cash flow and project financing recording during construction [243] and GIS can be applied to spatial and temporal analysis of cost clusters and prediction of cost scenarios.

Operation and maintenance stage is the longest stage of a project life cycle. Section 3.1 reveals that more than half of BIM-GIS integration applications for buildings are in this stage. Under the three hypotheses, the enhanced BIM-GIS integration can address sophisticated problems and provide comprehensive strategies for emergency and disaster simulation, prevention, response and management, heritage protection, mega projects operation, indoor navigation and ecological assessment. Deep application of spatio-temporal statistical modeling and 4D/nD BIM can inspire researchers and practitioners to utilize integrated BIM-GIS to deal with more general AEC issues such as sustainability assessment and asset management. The application objects can be buildings, infrastructures, cities and other larger spatial scale objects.

Demolition is the last stage of a construction project. In this stage, a building or structure is usually deconstructed which generates large amounts of waste materials. BIM is the digital representation of the existing buildings, so it is used for reliable and accurate waste estimation and efficient planning [253,254]. GIS can help analyze and optimize waste distribution processes, such as optimization of delivery network, transport services, and environmental assessment. Enhanced BIM-GIS integration can optimize the waste reuse and recycling to minimize waste materials, overall energy cost, demolition time and impacts on the surrounding environment.

5. Conclusions

With the explosive increase of studies and applications of BIM in the recent ten years and BIM-GIS integration in the recent three years, utilization of BIM-GIS integration in the AEC industry requires systematic theories beyond integration technologies, and deep applications of mathematical modeling methods, including spatio-temporal statistical modeling in GIS and 4D/nD BIM simulation and management. This paper reviews previous BIM-GIS integration studies from a spatio-temporal statistical perspective to reveal its evolution progress and recommend future development trends. Evolution progress of BIM-GIS integration is characterized by three aspects: application evolution in the AEC industry, history from the perspective of surveying and mapping, and comparison study of evolution progresses of GIS, BIM, and integrated BIM-GIS. Based on the analysis of literature and explanations of evolution progress, this paper summarizes the future trends of BIM-GIS integration in the AEC industry and proposes potential opportunities of BIM-GIS integration from the perspective of spatio-temporal statistical modelling.

We propose three hypotheses, including the technology hypothesis, the science hypothesis and the data source hypothesis of BIM-GIS integration in the AEC industry for future studies. From the spatio-temporal statistical perspective, the three hypotheses of BIM-GIS integration enable more comprehensive applications through the life cycle of AEC projects. The BIM-GIS integration based solutions are significantly benefit for the management methods and coordination mechanisms, including quality management, progress management and time reduction, cost reduction and control, improvement of health, safety and environment (HSE) performance, information management and the coordination of various sectors. These management methods and coordination mechanisms are driven by the sense and knowledge sourced from data, information, and their analysis products, which are characterized as spatial and temporal varied, real-time, dynamic, interactive, accurate and practical. Therefore, under the proposed hypotheses of BIM-GIS integration, comprehensive data-driven spatio-temporal modelling of AEC projects can provide more accurate and dynamic solutions for quantitative analysis, management and decision making in the future applications to satisfy user requirements of AEC industry.

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