Towards an Integrated Building Information Modeling (BIM) and Geographic Information System (GIS) Platform for Infrastructure

A. Ammar[a] and G.B. Dadi[a]

[a]Department of Civil Engineering, University of Kentucky, USA
E-mail: ashtarout.ammar@uky.edu, gabe.dadi@uky.edu

Abstract

Due to the increasing global population, the Architecture, Engineering, and Construction (AEC) industry is placed in front of a significant challenge to provide and maintain the necessary urban development and solid infrastructure systems to support this increase. Infrastructure systems must be resilient and sustainable, especially being critical to the nation's economy and progress. Creating such systems can be achieved by implementing emerging technologies and adopting efficient and cost-effective approaches to rehabilitate and expand the existing infrastructure systems and creating new ones. A major technology implemented in the horizontal construction sector is Building Information Modeling (BIM), which also has proven beneficial for the vertical construction sector. However, implementing BIM in horizontal construction is still emerging. To maximize its potential, BIM will require its integration with another technology pillar: Geographic Information System (GIS). Generally, BIM's central focus is to provide comprehensive semantic information of the construction projects, while GIS provides spatial data and details about the surrounding environment. Thus, their integration can leverage their adoption, and it becomes vital to study how BIM and GIS interact. This paper addresses the BIM-GIS integration by synthesizing the existing research corpus and provide insights into the current usage of an integrated BIM-GIS system for infrastructure. The paper's findings show that the applications mainly cover modeling and design of infrastructure assets, infrastructure construction and scheduling, monitoring and compliance check, and infrastructure facility and asset management. Furthermore, this paper investigates the requirements to optimize the adoption of integrated BIM-GIS for infrastructures.

Keywords –BIM; GIS; Infrastructure; Emerging Technologies

1 Introduction and Background

The integration of BIM and GIS in the Architecture, Engineering, and Construction (AEC) industry has been trending in recent years in both research and industry. The term integrated BIM-GIS system first appeared in literature in journals and conference publications in 2008 [1]. In 2012, the researcher's interest in the integrated BIM-GIS system increased sharply and peaked in 2016-2017, indicating an increased awareness of this integration's potentials [2]. The integration of BIM and GIS can provide a digital representation of architectural and environmental entities, manage spatial information, facilitate a transformative direction to integrate spatial data at different levels of detail, and permitting efficient, standardized, and coherent methods to plan construction development [2].

GIS technologies date back to the 1960s with the establishment of the Canada Geographic Information System (CGIS) as the first recognized GIS application [3]. Esri, an "Environmental System Research Institute" responsible for supplying GIS software and the web GIS geodatabase management applications, defines GIS as "a framework for gathering, managing, and analysing data. Rooted in the science of geography, GIS integrates many types of data. It analyses spatial location and organizes layers of information into visualizations using maps and 3D scenes. With this unique capability, GIS reveals deeper insights into data, such as patterns, relationships, and situations—helping users make smarter decisions".

BIM, on the other hand, has contradicting views about its date of origin; some researchers date BIM back to 1982 with the development of the ArchiCAD software, while others suggest that the real implementation of BIM started with the establishment of the Revit software program in 2000 [4]. Autodesk defines BIM as "a process that begins with the creation of an intelligent 3D model and enables document management, coordination and simulation during the entire lifecycle of a project (plan, design, build, operation and maintenance)".

Although BIM and GIS provide a digital representation of buildings or environmental surroundings, their approaches are different. BIM's central focus is directed towards construction projects with its massive ability to detail geometric and semantic construction information [5]. On the other hand, GIS is specialized in covering the geospatial data of the outdoor environment surrounding the construction project but provides limited comprehensive information about the building itself [6]. Thus, the strengths and weaknesses of both pillars make them extremely compatible. For instance, BIM can benefit from GIS's spatial information to optimize the tower cranes' location on a construction site [7]. Conversely, GIS applications can benefit from the detailed design of the pipe network provided by BIM for efficient management and analysis of the pipeline network [8]. Also, information from GIS such as site selection and on-site layout materials can facilitate BIM applications, while detailed BIM models can assist GIS with better utility management [2]. Therefore, the integration between these two systems will lead to the effective management of information in all stages of the project's life cycle, a better understanding of how the projects interact with its surrounding, and the availability of heterogeneous multi sourced-data will enhance decision making [9].

Moreover, the integrated BIM-GIS system is considered a pillar for developing sustainable smart cities for its ability of data interoperability, quantitative analysis, technology applications, and urban management [10]. Since GIS is limited in providing 3D models, the best practice to leverage its scope and implement detailed spatial analysis is by using 3D models offered by using BIM software such as Revit, CAD, and SketchUp [11].

The research done by [1], summarized the benefits of an integrated BIM-GIS system compared to using BIM on different aspects of AEC's user requirements including quality management, progress and time, cost, contract, health safety and environment (HSE), information, and the coordination of various sectors. It was found that the benefits of an integrated BIM-GIS system are way more efficient compared to using only BIM and can widely benefit the AEC's industry user requirements. Knowing that the integrated BIM-GIS system has shown successful implementation in the AEC industry and has been trending in recent years, the objective of this paper is to investigate the existing research corpus and identify the applications of the integrated BIM-GIS system in the AEC industry with a focus on infrastructure systems. Also, this paper highlights the gap in the existing literature and investigates the requirements to leverage the implementation of the integrated BIM-GIS system in the horizontal construction sector.

2 Applications of Integrated BIM-GIS System in the AEC Industry

Several researchers investigated the integration between BIM and GIS with a wide range of various applications. A comprehensive literature review of the published research on integrated BIM-GIS applications in the AEC industry was conducted. We used Google Scholar to search English language articles published since 2008 (the year when the term integrated BIM-GIS system first appeared in literature) by using "BIM/Building Information Modeling" and/or "GIS/Geographic Information System", and "AEC/ Architecture, Engineering, and Construction" as key terms for the literature's topic. Since the focus of this paper is to highlight the applications of the integrated BIM-GIS system, only publications with applications of the integrated system in the AEC industry were selected by reading the abstract or the full text sometimes. As a result, 100 literature items were obtained.

The obtained literature items were then analysed and classified into three categories based on the application object: 1) integrated applications on urban districts and cities; 2) integrated applications on buildings, and 3) integrated applications for infrastructures. The distribution of the publications based on the application object is represented in Figure 1. As expected, the major applications of integrated BIM-GIS covered buildings with 57 publications, then urban districts and cities with 28 publications, and the least are infrastructures with only 15 publications.

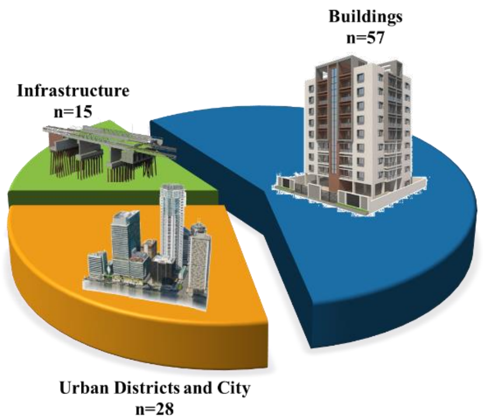

Figure 1. Integrated BIM-GIS Application Object Distribution in the AEC Industry

2.1 Integrated Applications on Urban Districts and City

It is common to use BIM to create, manage, and share lifecycle data of buildings, while GIS provides more holistic information on the urban environment. As such, the integrated BIM-GIS system is beneficial for Smart City applications and urban representation where data of the building facilities and urban environment is required [10] [12]. It was found that the integration of BIM and GIS on urban districts and cities has been applied mainly in activities including urban data management [13] [14]; urban representation, 3D city models and urban visualization [14], 3D cadaster [15] [16]; waste management [17]; energy efficiency and management [18] [19]; urban facility management [20] [21], traffic planning [22] [23]; safety and disaster management and prevention [24] [25].

2.2 Integrated Applications on Buildings

Conversely, the application of integrated BIM-GIS for buildings can be divided into four sections based on the construction phase, i.e., planning and design, construction, operation and maintenance, and demolition.

Applications of BIM in the buildings' planning stage include building modeling, site analysis, and architectural planning. Moreover, in the design stage, BIM applications consist of program demonstration, visualization design, collaborative design, quantity statistics, building data collection, energy analysis, safety design, and sustainable design [26]. However, the applications of the integrated BIM-GIS system in the planning and design phase of building projects extend to cover the energy and climate adaptation design of buildings and to facilitate energy simulations and buildings' energy management [27] [28]. Also, it was implemented for building design [29]; building site selection [30]; space conflicts [31]; preconstruction operations, structural and post-construction analysis, and construction safety planning [32] [33], which optimizes the entire design process and improves the building's performance.

BIM has also been applied during the construction of buildings to conduct construction progress and organization simulations, digital construction, material tracking, site coordination, construction visualization, construction safety, and green construction [26]. As such, BIM can be protracted and integrated with GIS to support visualization of construction time control, supply chain management, construction process, and construction activity tracking [34] [35]. This integration supported the visualization of the construction process and improved the coordination between different stakeholders. Besides, the integrated BIM-GIS was used for urban renewal projects by conducting building retrofit projects to support decision-making on building renovation from an economical and environmental perspective [36].

Traditionally BIM was used for designing buildings; however, the application phase of BIM is recently moving toward pulling its implementation throughout the whole building lifecycle. The application of BIM in the operation stage of buildings includes completing model delivery, develop a maintenance plan, assist in facility management, provide indoor space management, analyze building systems, and conduct disaster emergency simulations [26]. However, this implementation will face several problems such as insufficient levels of details, lack of information accuracy, and lack of information standardization. Thus, implementing BIM for the operation and maintenance phase should be pull-driven by asset owners and requires integration with other technologies [26]. As such, most of the applications of the integrated BIM-GIS system for buildings collected from literature reveal that more than half (35 out of 57) of these applications are in the operation and maintenance phase. These applications included indoor navigation and emergency response [37] [38]; heritage management and visualization [39] [40]; safety management [6] [41]; hazard identification and prevention [42]; energy consumption by buildings and transportation networks based on people's behavior [43] ; and building facility management [44] [45].

Furthermore, BIM-GIS integrated system was used in the demolition phase of buildings. Data from BIM and GIS was integrated to facilitate demolition waste management by calculating the number of trucks needed to load and haul the generated waste and estimating the required travel distance between sites, storages, and landfills [46].

2.3 Integrated Applications on Infrastructures

Since it was found that the applications of the integrated BIM-GIS system in the AEC industry for infrastructures are still limited, this paper aims to highlight and elaborate on the use of the integrated BIM-GIS for infrastructure. As such, the investigated applications were clustered based on the construction phase, i.e., planning and design, construction, operation and maintenance, and facility and asset management.

2.3.1 Applications in Planning & Design

The planning and design of extensive infrastructure facilities such as tunnels, bridges, subways, and utility networks require a massive amount of detailed data and the consideration of different scales; i.e., demanding a multi-scale representation of data [47]. As such, researchers of [47] utilized BIM and geometric semantic modeling to achieve multi-scale models to support shield tunnels' design. Also, they proposed the concept of explicit Level of Details (LOD) in tunnel design by extending and using concepts from GIS to help to detect clashes between the designed tunnel and the existing infrastructure facilities. This mapping supported the analysis and evaluation of the tunnel design based on geographical criteria. Similarly, [48] investigated BIM and GIS integration in China's tunnel engineering. They stated that this integration would simplify the modeling and analysis process of tunneling and optimize BIM technology implementation in China's tunnel engineering.

Also, researchers of [49] developed a system that integrates BIM and GIS to estimate the cost of building a national road to be applied in the feasibility stage. The cost estimation included construction costs, land acquisition costs, and operation and maintenance costs. The user-defined GIS information was imported to the CAD system, and the output data related to bridge and tunnel properties, earthwork quantities, lot numbers, and boundary lines and images were imported to a web system that was used to estimate the total project cost. In the proposed approach, the end-user can choose the best route because of the better 3D visualization, better understanding of the project, and the generated cost estimation. Also, [50] developed 3D Geotechnical Extension Model or 3D-GEM to integrate semantic information models to contain surface and subsurface objects such as subsurface geological and geotechnical objects to support the development of infrastructure projects.

Recently, [51] proposed a framework to integrate BIM and GIS for an innovative design approach for transport infrastructure. This framework aims to eliminate any possible conflict that could be faced between the infrastructure design and environmental limitations and provide an integrated technical and ecological indicator of the proposed design. The researchers tested the proposed approach on an airport infrastructure, where the information model was developed using Revit and Civil3D while the environmental model was produced using GIS. Also, [52] proposed a framework based on BIM-GIS integration to plan and design utility infrastructures to meet the needs of expanding cities in the future. The infrastructure utilities include freshwater networks, sewer networks, and electrical networks. The proposed framework emphasizes smart and sustainable cities' concept and supports decision-making for better planning and management.

2.3.2 Applications in Construction

For the construction of infrastructure projects, BIM and GIS were also integrated. [53] integrated BIM highway models with Digital Elevation Model (DEM) of the surrounding topography, and they utilized real-time on-site photos to generate highway construction schedules for further schedule management and analysis, to monitor construction delays.

[54] utilized BIM to save data about road components in highway construction and the GIS system to import data about land boundaries and topographic data. The integrated approach aims to provide spatial data analysis needed for earthwork calculation. Infrastructure geometric information such as road shape and different geometrical elements were exported from the corresponding BIM models. Conversely, geographical reference, soil type, infrastructure data, etc., were collected from GIS, then semantic web integration between the associated BIM files and GIS files was conducted. This approach permits end-users to perform several cut and fill simulations and facilitates the generation of an optimized construction plan. Moreover, [55] utilized BIM to manage all the information and data related to subway stations' construction. Also, they installed Global Positioning System (GPS) receivers on large, heavy, and high-risk pieces of equipment used in the construction process and linked the data with GIS to establish the 3D geographic spatial location of machines to eliminate high-risk accidents. The integrated GIS-GPS-BIM system was developed to assist in risk management associated with cranes, drilling machines, excavators, loaders, and dumpers used to construct subway stations. The risks include collisions between equipment or neighboring buildings, resulting in the deformation of foundation systems and retaining walls. This approach will be able to provide early warning signals, which will support its development and implementation.

2.3.3 Applications in Operation and Maintenance

Monitoring and compliance check for roads is essential to provide a certain level of serviceability; however, roads' maintenance and rehabilitation are complicated because of the widespread road systems. [56] developed a Road Monitoring and Reporting System (RMRS), which includes a mobile app and a web-based RMRS based on the integration of location-based services (LBS) and Augmented reality technologies (AR). The developed RMRS can be used by the public or engineers to monitor defects and report their spatial coordinates to the web-based RMRS using a downloaded app on their smartphones. The defect location will be determined based on the location of the person who reported the defect. The reported information will be shown on the field road engineers' phones, and they will be able to extract the relevant data from the web-based RMRS. The AR technology in the mobile RMRS was also programmed and used by field engineers to obtain real-time reports and support in visualization and planning the maintenance and rehabilitation operations.

Moreover, [57] developed an automated utility compliance check by integrating natural language processing (NLP) -which is an “algorithm that translates the description of spatial configuration into a computer processable spatial rules”- and spatial reasoning which logically extracts the spatial rules to a GIS system to identify its compliance. The researchers suggested that the developed method can be extended to various computing applications if implemented in the BIM platform with interoperable mapping and ontologies and integrating sensing technologies to obtain spatial data from construction sites.

2.3.4 Applications in Facility and Asset Management

Facility and asset management of buildings with the surrounding infrastructure can only be conducted using BIM and GIS integration. The building’s internal system information is extracted from BIM, and the external input of utility infrastructure can be extracted from GIS. In this context, [58] connected BIM models of the building's mechanical electrical and plumbing (MEP) systems with the surrounding subsurface pipeline network. Revit files and GIS data were imported and integrated to support the network visualization outside the building.

Moreover, [59] investigated the potential of improving asset management by integrating BIM and GIS systems. However, the researchers faced challenges in exporting the BIM geometry of an underground railway into 3D GIS. Also, [60] proposed integrating BIM with GIS, and they developed a web-based GIS management system to assist in the management of a bridge model. The developed system contributes an advanced 2D and 3D visualization, in addition to a real-time sensor data reception to permit real-time visualization and monitoring.

2.4 BIM-GIS Platform for Infrastructures

Recently, there has been a considerable amount of studies and national efforts to encourage the use of BIM for horizontal projects on the one hand and extending the implementation of BIM to cover the operation and maintenance phases of construction projects on the other hand. Additionally, the increase in the construction projects’ complexity is associated with large amounts of challenging data that requires better approaches to store, share, and manage [61].

Moreover, researchers of [61] suggested five trends that will remodel how construction projects are conducted. The first trend that will shape the future of construction is a higher definition of surveying and geolocation, associated with the second trend of 5 dimensions of BIM, in addition to the digitization of processes and data sharing (third trend). This will be accomplished with the aid of the internet of things (IoT) (fourth trend), with intelligent asset management and smarter decision-making and designing with materials and methods of the future (fifth trend). As emphasized by [61], better geolocation and data mapping integrated with BIM, IoT, and digitized collaboration are the pillars for an inevitable and crucial transformation in the construction industry.

Also, [62] defined BIM for infrastructures as “a system of processes for collecting, storing, and exchanging data used to plan, design, construct, operate, and maintain highway infrastructure through the entire life cycle.” The researchers considered data as a keyword that pertains to anything that could be accessed in a seamless digital environment. Data extend beyond physical transportation assets and attributes to include functional values such as financial, design, and specification information. BIM allows the extraction and data sharing among different business units and segmented stakeholders to support the department’s infrastructure’s decision-making. Conversely GIS has proven to be beneficial in providing better visualization, simplified data sharing and data accessibility, proactive asset management, and informed decision making [63].

Therefore, to leverage the implementation of BIM for infrastructures, and as emphasized by [61] and [62], BIM should integrate with GIS to ensure a geolocation mapping that will support the allocation of infrastructure assets. This integration will provide information about the asset’s condition throughout its lifecycle within the surrounding environment. To optimize this integration, sensor technology should be used to facilitate real-time mapping, data sharing, and data collection, besides IoT that will facilitate storing, sharing, and integrating data. Integrating BIM, GIS, IoT, and Sensor technology will constitute a robust framework toward leveraging the implementation of BIM for infrastructures and throughout the project life-cycle. This will create one source of data instead of data silos, facilitate seamless integration, and allow for better decision-making. The BIM-GIS platform for infrastructures is presented in Figure 2.

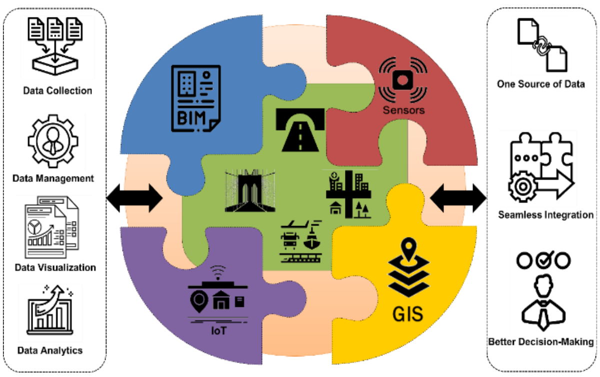

Figure 2. BIM-GIS Platform for Infrastructures
(Icons are downloaded from https://thenounproject.com/search/?)

2.5 Conclusion and Future Recommendations

This paper conducted a comprehensive review of the applications of integrated BIM-GIS systems in the architecture engineering and construction industry. This review showed that a total of 15 publications out of 100 discussed the application of the integrated BIM-GIS system for infrastructures. Also, it was found that these applications were mainly implemented for modeling and designing infrastructure elements, construction, monitoring, and compliance checks, and facility and asset management. Therefore, there is a noticeable gap in adopting BIM and GIS integrated applications in the horizontal construction sector compared to the vertical construction sector. As such, optimizing the implementation of BIM-GIS for infrastructure and leveraging their adoption requires its integration with other technologies including the Internet of Things (IoT) and sensor technology.

Data is a contributing element throughout the project lifecycle and is a critical asset for better resource allocation and decision-making. Thus, detailed models with comprehensive information from BIM with the advanced GIS capabilities of data integration and data analytics will enhance data interoperability and will ensure the existence of reliable and high-quality data. Therefore, future research is required to investigate the potential of this integration to optimize the implementation of BIM and GIS for infrastructure and identify the requirements and standards necessary for leveraging their adoption.

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