Civil Integrated Management (CIM) for Advanced Level Applications to Transportation Infrastructure: A State-of-the-Art Review

Ali Taheri and John Sobanjo *

Department of Civil and Environmental Engineering, Florida State University, College of Engineering, 2525 Pottsdamer Street, Tallahassee, FL 32310, USA; ataheri@fsu.edu
* Correspondence: jsobanjo@fsu.edu

Abstract: The recent rise in the applications of advanced technologies in the sustainable design and construction of transportation infrastructure demands an appropriate medium for their integration and utilization. The relatively new concept of Civil Integrated Management (CIM) is such a medium; it enhances the development of digital twins for infrastructure and also embodies various practices and tools, including the collection, organization, and data-management techniques of digital data for transportation infrastructure projects. This paper presents a comprehensive analysis of advanced CIM tools and technologies and categorizes its findings into the following research topics: application of advanced surveying methods (Advanced Surveying); geospatial analysis tools for project planning (Geospatial Analysis); multidimensional virtual design models (nD Modeling); Integrated Geospatial and Building Information Modeling (GeoBIM); and transportation infrastructure maintenance and rehabilitation planning (Asset Management). Despite challenges such as modeling complexity, technology investment, and data security, the integration of GIS, BIM, and artificial intelligence within asset-management systems hold the potential to improve infrastructure’s structural integrity and long-term performance through automated monitoring, analysis, and predictive maintenance during its lifetime.

Keywords: Civil Integrated Management; asset management; GeoBIM; digital twin; artificial intelligence; BIM for infrastructure

1. Introduction

Civil Integrated Management (CIM) can be generally described as a centralized repository of digital information related to the transportation infrastructure network, having at its core, the idea of a “digital twin” [1,2]. The digital twin is a 3D electronic model such as the Building Information Model (BIM), created to represent a real-world object, and the model can be interrogated by users to acquire detailed information or simulate various scenarios [3]. The CIM is also defined as the process of collecting, organizing, managing, and sharing digital information between all the involved stakeholders throughout the entire lifecycle of a project, from early planning to construction and operation and maintenance (O&M) phases [4,5]. Implementing CIM in a transportation project will affect the entire course of the project, from the critical initial decision-making process to project delivery among the various stakeholders involved, including agencies, contractors, suppliers, and legal authorities [6,7]. While construction contractors have implemented BIM practices such as 3D modeling, cost estimation, clash detection, etc., for building projects, other CIM practices have not been frequently implemented on transportation projects [8,9].

Transportation agencies often collect and store a vast amount of data from the surveying, design, construction, and O&M phases [10]. It is necessary to integrate and correlate all the existing data through a workflow model and provide access to all the involved parties to increase the use of digital project-delivery practices [11,12]. The digital information of...
an asset increases throughout its lifecycle, stage by stage, but the data become lost when migrating between different stages of a project using traditional workflows [13]. Pertinent information identified during the design stages of an asset can be confirmed and corrected during construction, as well as linked to the asset-management systems (AMSs) after the project completion and utilized for maintenance and operation [14].

The National Cooperative Highway Research Program (NCHRP) defines three levels of CIM maturity (initial, intermediate, and advanced) depending on the capacities of divisions responsible for project phases, extending from the planning phase through the operation and maintenance stages [15,16]. It was discovered that implementing the intermediate levels of CIM practices could be challenging for some companies [17]. This review article identified the necessity of expanding the research scope to the advanced level of CIM implementation. The concept of each trend and its relative usage in various phases of a project are presented, as well as their related challenges. The objective of this review is to investigate the most recent findings and practices that facilitate the advanced level of CIM implementation in which model-based project execution throughout the asset lifecycle becomes the standard practice.

The objective of this review study was related to topics that align with the advanced maturity level of CIM implementation, characterized by lifecycle adoption of CIM including scoping and surveying, construction planning, information management, and operation and maintenance phases. Considering the extensive range of available CIM tools and practices, the scope of this study was strategically narrowed down to encompass a lifecycle approach to integrated digital project management, focusing on innovative practices and transformative technologies that facilitate data-driven and model-centric advancements in transportation infrastructure. Consequently, detailed explorations of contract and material-management systems, comparative assessments of design platforms, and traffic-modeling systems were excluded from this review. The mentioned areas, although critical to the operational execution of CIM, are beyond the intended macro-level synthesis of this review.

This paper provides a comprehensive summary of the findings from the literature review, highlighting the key insights and identified research gaps at the end of each topic. In addition to presenting these results, the authors delve into discussions on potential opportunities for future research, emphasizing areas with high potential. In the following sections of the paper, the methodology of this review paper is first presented, describing the approach utilized in conducting the literature review, as well as analyzing and categorizing the findings in terms of research topics. Then, a detailed discussion is presented on each of the identified research topics, including a thorough comparison of tools and applications, with recommendations and suggestions for future research.

2. Methodology

The present review study explored several databases of publications, including different search engines and sources, such as Scopus, ProQuest, and Google Scholar. The study first identified a wide range of academic articles, graduate theses, conference papers, and technical reports from state departments and government agencies, focusing on construction automation and innovation, engineering informatics, and transportation infrastructure management. To create an effective keyword search query for a broad topic such as CIM implementation in transportation infrastructure, it is essential to identify pertinent studies across various research domains in the field. Therefore, constructing a comprehensive search query that accurately captures various CIM tools and practices throughout the different stages of an infrastructure’s lifecycle is crucial. Therefore, an iterative process using Python script was implemented to analyze the collected publications through keyword identification. Figure 1 depicts the process of creating search queries for identifying relevant CIM capabilities. The search query is mainly constructed from three clusters encompassing the lifecycle of the infrastructure including scoping and surveying, planning and design, and operation and maintenance. The term “infrastructure” in this query context refers to “Highway” and “Bridge”, which are linked together using the OR
command. Initially, key terms are extracted from the collected papers. Each cluster is further refined by reviewing the frequency and context in which related terms appear in the title. Utilizing different libraries for data processing and keyword exploration, the classification algorithm processed each collected publication’s abstract to count the occurrence of combined keywords within a corresponding cluster. Each paper was required to contain at least one keyword from each identified cluster, rather than all keywords within. Following the clustering process, the findings were filtered by most keyword appearances to identify the most relevant publications. In cases where multiple topics achieved the maximum keyword count for a single publication, it was assigned to all such topics, capturing the multidisciplinary nature of some studies. Lastly, the classification for each publication was manually checked and confirmed to ensure methodical relevancy to the present study.

<table>
<thead>
<tr>
<th>Scoping and Surveying</th>
<th>Survey</th>
<th>GPS</th>
<th>3D Scanning</th>
<th>Point Cloud</th>
<th>LiDAR</th>
<th>UAV/UAS</th>
<th>MMS</th>
<th>Laser Scanning</th>
<th>GIS</th>
<th>Clash detection</th>
<th>Geospatial modeling</th>
<th>Route analysis</th>
<th>Roadway Planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning and Design</td>
<td>nD Model</td>
<td>Virtual Design</td>
<td>3D Visualization</td>
<td>BrIM</td>
<td>Information Modeling</td>
<td>BIM</td>
<td>As-built BIM</td>
<td>Constructability</td>
<td>BIM/GIS</td>
<td>GeoBIM</td>
<td>Integrated Modeling</td>
<td>Digital Twin</td>
<td></td>
</tr>
<tr>
<td>Operation and Maintenance</td>
<td>Data Integration</td>
<td>CityGML</td>
<td>IFC</td>
<td>BMS</td>
<td>Asset Management</td>
<td>Infrastructure Management</td>
<td>Smart Infrastructure</td>
<td>M&amp;R Planning</td>
<td>IoT</td>
<td>AMS</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

This framework served as a foundation for a coherent and organized analysis, enabling a detailed assessment of the current state of the field and identification of emerging trends, gaps, and challenges. The conducted query analysis facilitates the identification of relevant studies while eliminating subjectivity from the process, contributing to a comprehensive understanding of CIM in infrastructure projects.

Following the initial selection and examination, a detailed analytical framework was established to categorize the findings into five specific research topics representing different stages of a lifecycle. As fully illustrated in Figure 2, a systematic approach was employed for the selection and review of studies pertinent to CIM and its application in civil infrastructure. Initially, studies were assessed for relevance to civil infrastructure and CIM. The collected studies were initially assigned to three main stages during the infrastructure lifecycle (based on the predefined advanced level CIM maturity model provided by NCHRP), including scoping and surveying, planning and design, and operation and maintenance. From the scoping and surveying phase, the authors derived two thematic topics, namely Advanced Surveying and Geospatial Analysis. This delineation is intended to concentrate on the initial stages of project development, allowing for a focused examination of the technical challenges and advancements within these preliminary phases both in terms of availability of tools and framework. The nD Modeling research topic delves into advanced CIM practices for the construction planning and design phase. It begins with an analysis of various aspects of nD models, from creating structural components tailored to the project’s specific levels of detail (LOD) to enhancing both accuracy and visualization ca-
pabilities. Advanced visualization and constructability analyses are further explored using comparative analysis. Additionally, the operation and maintenance phase were divided into two separate research topics: GeoBIM and Asset Management. This division was strategically employed to enhance the granularity of the analysis, facilitating a more detailed exploration of the technical challenges and advancements in the later stages of the infrastructure lifecycle. The GeoBIM topic focuses on the advancement and challenges related to development of model-based workflow, while the Asset Management topic investigates the practical challenges associated with information-management systems, emphasizing the integration of data and preservation of collected information across infrastructure lifecycle. This approach ensures a comprehensive evaluation across all critical phases, promoting a thorough understanding of CIM’s application and its developmental trajectory in civil infrastructure. This thematic classification facilitated a detailed gap analysis and discussion, aiming to illuminate areas needing further investigation and to propose new directions for future research within the field. This structured approach ensures a comprehensive and organized review, promoting a clear understanding of the current landscape and research trajectories in CIM implementation. The five research topics with the abbreviations shown in parentheses are listed as follows:

(i) Application of advanced surveying methods to produce digital geospatial data (Advanced Surveying);
(ii) Geospatial analysis tools for project planning (Geospatial Analysis);
(iii) Multidimensional virtual design models (nD Modeling);
(iv) Integrated Geospatial and Building Information Modeling (GeoBIM);
(v) Transportation infrastructure maintenance and rehabilitation planning (Asset Management).

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**Figure 2.** A flowchart representation of the review methodology.

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**Figure 3.**
(a) Annual and (b) cumulative distribution of CIM publications by research topic.

The increasing trend in the occurrence of CIM-related keywords within publications of recent years reflects the significance of applying modern tools and technologies throughout the lifecycle of transportation infrastructures. Based on the findings of this review study, detailed discussions on each of the five research topics identified in the literature review are now provided in the following sections of the paper. Table 1 represents...
The proposed thematic research topics serve as the basis of this state-of-the-art review. The organization of this review paper is such that in the following sections of this paper, detailed discussions and research gap analyses is provided for each of these research topics with recommendations, as well as suggestions for future research.

The cumulative number of CIM publications, as shown in Figure 3a, from 2015 to 2023 show a significant increase. Figure 3b reveals that publications related to “Asset Management”, “GeoBIM”, and “nD Modeling” constitute a combined 74 percent of the total collected CIM publications, indicating a noticeable trend within the industry towards adopting geo-enabled, model-based asset-management systems. This paradigm shift could be interpreted as the industry’s willingness to move toward using a geo-enabled model-based asset-management system that facilitates the seamless integration of stored data across the complete lifecycle of transportation infrastructure.

The increasing trend in the occurrence of CIM-related keywords within publications of recent years reflects the significance of applying modern tools and technologies throughout the lifecycle of transportation infrastructures. Based on the findings of this review study, detailed discussions on each of the five research topics identified in the literature review are now provided in the following sections of the paper. Table 1 represents a summary of the classification approach in the literature review in reference to the defined research topics.

**Table 1.** Summary of the classification of reviewed articles based on the defined research topics.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Advanced Surveying</th>
<th>Geospatial Analysis</th>
<th>nD Modeling</th>
<th>GeoBIM</th>
<th>Asset Management</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>[18]</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>2023</td>
</tr>
<tr>
<td>[19]</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2023</td>
</tr>
<tr>
<td>[20]</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>2023</td>
</tr>
<tr>
<td>[21]</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td>2023</td>
</tr>
<tr>
<td>[22]</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td>2023</td>
</tr>
<tr>
<td>[23]</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>2023</td>
</tr>
<tr>
<td>[24]</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>2023</td>
</tr>
<tr>
<td>[25]</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>2023</td>
</tr>
<tr>
<td>[26]</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>2022</td>
</tr>
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</table>
3. Application of Advanced Surveying Methods (Advanced Surveying)

The introduction of modern surveying tools has significantly expanded the collection of precise and detailed digital geospatial data on infrastructure projects. For instance, surveying tools such as Light Detection and Ranging (LiDAR) and Unmanned Aerial Vehicles (UAVs) have enabled the whole construction workflow to proceed in a model-centric format, ranging from storing pavement structural condition data to improving inspection operation performance schedules [29,31,42,60–62]. Studies have discovered that most digitally archived asset information from both pre- and post-construction can be critical for surveying and future project developments [63–65].

Employing LiDAR for capturing faster and more accurate geospatial data from construction sites provides substantial advantages over the existing traditional methods [55,66,67]. LiDAR is proven to be very practical in situations such as bridge mapping, pavement-subsidence measurements, road detection, etc. [48,68,69]. Mounted-on-drones are remotely operated airborne vehicles that are equipped with high-resolution cameras to capture detailed visual data for scoping and surveying operations [54]. Several UAV utilizations in the construction industry include those for project assessments, aerial sur-
veys, site mapping, enhanced 3D modeling [70], and vehicle tracking [71]. In the field of transportation infrastructure management, UAVs can be useful for condition assessment to capture aerial pictures from pavement surfaces due to their high flexibility, portability, and cost-effectiveness [30,72–76]. Digital images concerning pavement distress such as cracks, rutting, or patching failure can be captured by mounting a high-resolution camera on a drone from a fixed height [77,78].

Researchers and practitioners have used less expensive substitutes such as mounted cameras on vehicles and smartphones to capture pavement conditions [79,80]. Subsequently, image-processing techniques were adopted to detect potholes and pavement distresses on the surface of the pavements [81–86]. It is worth mentioning that innovative approaches such as video processing, laser scanners, and point cloud data were also utilized to detect, generate, and evaluate 3D information models of the terrain condition [53,87] and roadway elements [33,40,58,88,89]. A new method utilizing a mobile laser scanner (MLS) has been presented as providing more information including road segmentation, potential crack point detection based on point elevation, crack point clustering using a region-growing algorithm, and extraction of crack geometric attributes [34]. The vertical and horizontal clearances of highway viaducts and gantries can be automatically estimated using MLS point clouds for routing oversized transport items, infrastructure reconstruction, maintenance, and settling legal claims after incidents [90]. The point cloud data of road infrastructure was mapped via the built-in camera and LiDAR sensors integrated into the iPhone 14 Pro using real-time kinematic positioning systems, which consequently improved the geo-referencing accuracy [91]. For the maintenance of existing railway infrastructure, a platform that combines 2D panoramic virtual reality photos and a 3D model generated using a 3D scanner has also been demonstrated [18]. The possibility of settlement, which is a maintenance condition evaluation item for fill-dam bodies, was investigated using point clouds based on the Unmanned Aerial System (UAS) from motion and terrestrial laser scanner point clouds [19]. An automated technique employed 3D point cloud tiles with trajectory points to construct Industry Foundation Class (IFC) models of roadways and determine their alignment and width [92].

Table 2 presents a thorough comparison of various technological tools utilized for surveying purposes, based on documented literature. While LiDAR and 3D Scanning are particularly recognized for their high precision and extensive 3D data gathering, the Geographic Information System (GIS) stands out in terms of advantages in advanced surveying for its multisource data analysis and thorough data management. UAVs and the Mobile Mapping System (MMS) are both prized for their rapid large-area coverage, with UAVs also being cost-effective. Remote Sensing’s strength lies in its ability to capture vast areas swiftly, and the Ground Penetrating Radar (GPR) is unparalleled in its subsurface structure and utility data capture. However, a shared issue among LiDAR, 3D Scanning, and MMS is the time-consuming nature of their data processing.

Spatial resolution is a key parameter in surveying technologies, indicating the level of detail that can be captured from a particular distance. The precision of the sensor, determined by its resolution, is critical in defining the accuracy with which traffic infrastructure elements can be mapped and analyzed. Higher-resolution sensors provide finer details, essential for the accurate recognition of elements like road signs, signals, and markings, which are crucial for safety and efficient traffic management [93,94]. Three-dimensional scanning, which encompasses technologies such as LiDAR, allows for detailed measurements and high-fidelity models, particularly with terrestrial setups where the equipment is stationary. For instance, a higher-resolution sensor influences the detection capabilities, distinguishing between different types of surfaces markings, obstacles, and traffic [95–97]. Conversely, the spatial resolution in Remote Sensing, which involves a broader range of technologies including aerial imagery and satellite photos, can vary significantly. For example, the ground sample distance, which is crucial in determining the detail captured in imagery from UAVs, is dependent on both the camera’s resolution and the altitude of the flight [98]. The increased resolution in UAV imagery is crucial for accurately identifying
potholes on road surfaces, facilitating timely maintenance and management decisions [99]. It is these variations in resolution and ground sample distance which influence the choice of technology based on the required accuracy and the nature of the terrain or project at hand. In terms of data formats, point cloud is a common format shared by LiDAR, UAVs, MMS, and GPR. While 3D scanning can generate mesh, CAD, and BIM outputs, GIS primarily employs vector and raster formats.

Applications of these tools often overlap in infrastructure and environmental monitoring. GIS is widely used for traffic and road network management, offering essential tools for spatial analysis and data integration, which aid in effective civil infrastructure monitoring. Its versatility also benefits urban and environmental planning by handling and analyzing spatial data for sustainable outcomes. UAVs, while less common in traffic management, provide high-precision aerial imagery for monitoring road conditions, supporting emergency response, and environmental studies. The deployment of 3D scanning, UAVs, and MMS varies by industry and organization. Three-dimensional scanning is efficient for capturing complex geometries, UAVs are beneficial for rapid aerial data collection, and MMS excels in data collection for transportation infrastructure. Additionally, GPR is specialized for underground mapping, while Remote Sensing is used for land cover mapping and disaster response.

<table>
<thead>
<tr>
<th>Tools</th>
<th>Benefits</th>
<th>Limitation</th>
<th>Resolution</th>
<th>Data Format</th>
<th>Application</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic Information System (GIS)</td>
<td>Multisource data analysis, comprehensive data management, spatial analysis, and modeling capabilities</td>
<td>Requires specialized training, steep learning curve, limited 3D visualization</td>
<td>Dependent on the source</td>
<td>Vector, Raster</td>
<td>Traffic management, road network planning, public transport planning, urban planning, environmental planning</td>
<td>[100–103]</td>
</tr>
<tr>
<td>Light Detection and Ranging (LiDAR)</td>
<td>High accuracy, detailed 3D data, rapid large-area data capture, change detection, and monitoring capabilities</td>
<td>High costs, time-consuming data processing, data capture specific to a point in time</td>
<td>50–300 mm</td>
<td>Point Cloud, DEM, Raster</td>
<td>Transportation infrastructure design and inspection, flood risk assessment, topographic mapping, utility mapping</td>
<td>[19,68,104,105]</td>
</tr>
<tr>
<td>Unmanned Aerial Vehicle (UAV)</td>
<td>High-resolution data capture, rapid large-area coverage, cost-effective data collection</td>
<td>Weather-dependent, limited flight time, requires specialized training</td>
<td>Depends on the mounted sensor: 10–100 mm</td>
<td>Point Cloud, DEM, Raster</td>
<td>Bridge inspection, road condition assessment, pipeline monitoring, construction progress monitoring</td>
<td>[104,106–109]</td>
</tr>
<tr>
<td>3D Scanning</td>
<td>Highly accurate data capture, capable of capturing complex geometries, rapid data collection</td>
<td>Time-consuming data processing, data capture specific to a point in time</td>
<td>0.1–10 mm</td>
<td>Point Cloud, Mesh, CAD, BIM</td>
<td>Construction site monitoring, as-built modeling, asset management</td>
<td>[110–112]</td>
</tr>
<tr>
<td>Remote Sensing</td>
<td>Rapid large-area data capture, change detection and monitoring, high-resolution imagery</td>
<td>Data capture specific to a point in time, weather, and atmospheric conditions dependent</td>
<td>0.3–100 m</td>
<td>Raster</td>
<td>Land cover mapping, disaster response, flood modeling, environmental monitoring</td>
<td>[100,113,114]</td>
</tr>
<tr>
<td>Mobile Mapping System (MMS)</td>
<td>Rapid large-area data capture, high accuracy, and precision, change detection, and monitoring capabilities</td>
<td>High costs, time-consuming data processing, limited to road and highway data capture</td>
<td>50–300 mm</td>
<td>Point Cloud, DEM, Raster</td>
<td>Pavement assessment and management, mapping, and modeling for decision-making</td>
<td>[33,115–118]</td>
</tr>
</tbody>
</table>
As discussed above, many studies have focused on employing advanced surveying tools to generate topography maps, monitor construction progress, detect different construction elements, and generate alignment models. By employing a comprehensive database for the performance model, the prediction of the future condition of the assets will be more accurate, which will lead to a better maintenance execution plan. Considering the workforce and the amount of time required for state Departments of Transportation (DOTs) to collect information on smaller segments (e.g., 0.1 miles instead of 1-mile segments), using automated tools to collect road distress data on smaller segments seems inevitable in the near future. This paper suggests that agencies should improve their current standard of practices in crucial areas such as cloud data pool, data processing, and computing power to take full advantage of automated assessment technologies. Further research is required to address the application of these modern technologies to automate the performance-assessment process while evaluating their potential temporal and financial benefits.

4. Geospatial Analysis Tools for Project Planning (Geospatial Analysis)

In the realm of transportation engineering, GIS has been widely adopted for a variety of purposes, showcasing its versatility and critical importance in modern infrastructure planning and management. GIS can be a powerful tool to organize spatial and attribute data and perform powerful geographical analyses. GIS has been effectively utilized across diverse studies to optimize road network sustainability and emergency routing, enhance safety and cost-efficiency in transportation, conduct roadway closure analyses, and perform seismic risk assessments on civil infrastructure, demonstrating its pivotal role in improving public safety and infrastructure resilience [122–125]. GIS visualization capabilities enable the identification of complications and design conflicts early, reducing the planning time and preventing unnecessary expenses [126–128]. To further utilize the visualization capability, spatial data can be collected and imported into GIS platforms, helping the project team better identify critical locations [129,130]. Project planning and scoping phases can also benefit from GIS-based decision-making tools for different purposes, such as construction site evaluation, alternative work schedule analyses, and simulating transportation network flow for disaster response [39,56,131–133].

Studies in the field of transportation infrastructure have shown that implementing GIS in a project could reduce project costs while increasing workflow accuracy and efficiency [37,134,135]. GIS capabilities were employed to find highway sections that received multiple reconstructions over their planning prospect [136], apply geotechnical considerations in a highway layout [102], detect utility conflicts in railway projects prior to construction [38], prioritize maintenance plans [137], create a geo-enabled geometric design for highways, conduct environmental assessment of concrete mixes [138], and optimize construction site material distribution layout [139]. Studies also employed GIS for pavement performance analysis to investigate the impact of different factors such as precipitation, [140–142], mass movement susceptibility prediction [143], sustainability-based management [144], construction quality evaluation [27], functional road classification [145], and climate change risk assessment of critical infrastructure [146]. More innovative approaches engineered an integrated system of Augmented Reality (AR) and GIS to map subterranean utilities using mobile devices [147].
Table 3 presents an organized analysis of key geospatial analysis tasks in the context of transportation engineering and planning. For instance, in pavement engineering, the focus is on monitoring pavement conditions and identifying deterioration patterns. While modern tools such as LiDAR and image processing significantly improve the efficiency of road maintenance, and potentially extend the road service life, the high costs and expertise required associated with them pose challenges. Similarly, infrastructure planning leverages GIS, CAD, and 3D modeling for tasks such as site selection and route alignment. However, the intricacies of 3D modeling necessitate specialized software and skills, making time consumption a noticeable factor when dealing with complex models. Road safety analysis employs GIS statistical analysis to enhance road safety by pinpointing the location of accident-prone areas.

Table 3. A comparison of geospatial analysis applications in transportation engineering.

<table>
<thead>
<tr>
<th>Task</th>
<th>Geospatial Analysis</th>
<th>Techniques</th>
<th>Benefits</th>
<th>Limitation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement Engineering</td>
<td>Pavement condition monitoring, identifying pavement deterioration patterns</td>
<td>LiDAR, Image Processing, CAD</td>
<td>Improves the efficiency and effectiveness of road maintenance</td>
<td>High cost and technical expertise required for LiDAR data collection</td>
<td>[27,148,149]</td>
</tr>
<tr>
<td>Infrastructure Planning</td>
<td>Site selection, route alignment, visualizing proposed changes</td>
<td>GIS, CAD, 3D Modeling</td>
<td>Improves the efficiency and accuracy of infrastructure planning</td>
<td>Complex 3D modeling may require specialized software and skills</td>
<td>[46,146,150,151]</td>
</tr>
<tr>
<td>Road Safety Analysis</td>
<td>Identifying accident hotspots, safety audits, visualizing accident data</td>
<td>GIS, Statistical Analysis</td>
<td>Enhances road safety by identifying and addressing accident-prone areas</td>
<td>It requires robust and accurate incident reporting systems</td>
<td>[152–154]</td>
</tr>
<tr>
<td>Traffic Engineering</td>
<td>Analysis of traffic flow patterns and congestion points, route optimization, incident management</td>
<td>GPS, GIS, Traffic Simulation</td>
<td>Improves traffic flow and reduces congestion through detailed traffic pattern analysis</td>
<td>It may require substantial data collection and processing</td>
<td>[154–156]</td>
</tr>
<tr>
<td>Public Transport Planning</td>
<td>Route planning and optimization, accessibility analysis, demand estimation</td>
<td>GIS, Network Analysis</td>
<td>Enhances public transport service and increases ridership through optimized route planning</td>
<td>Dependent on accurate and current demographic data</td>
<td>[157–159]</td>
</tr>
<tr>
<td>Environmental Impact Analysis</td>
<td>Analyzing potential environmental impacts of transport projects, noise pollution mapping</td>
<td>GIS, Noise Modeling</td>
<td>Helps protect the environment and comply with regulations through detailed environmental impact analysis</td>
<td>Limited by the availability and quality of environmental data</td>
<td>[102,160–162]</td>
</tr>
</tbody>
</table>

Most of the reviewed papers showed that GIS analysis could be a beneficial tool for the planning phase and for detecting design conflicts. However, fewer efforts have been conducted toward employing GIS techniques during the maintenance phase of transportation infrastructure. Using geo-referencing tools, the pavement distress data can be linearly referenced and correlated with the construction quality attributes. As recommended by the Federal Highway Administration [166], most DOTs collect and report distress data as a percentage of the surface in a milepost system. However, collected distress data can be geo-referenced and embedded within GIS models, including design and material attributes. The proposed integrated O&M database forms a geo-enabled performance model for a given roadway, where various types of distress data such as rutting, cracking, and faulting are presented and associated with their location on different lanes, as well as correlated with other construction quality-related attributes such as asphalt layer density, material type, air voids, etc. Future research studies can focus on developing a geo-enabled multi-layer...
distress model of a roadway pavement based on historical data that were collected with computer vision assessment technologies.

5. Multidimensional Virtual Design Models (nD Modeling)

In the context of nD modeling, the term ‘n’ transcends the three-dimensional space by incorporating multiple layers of data. A BIM model that operates with localized spatial attributes typically represents a three-dimensional (3D) engineered model embedding structural and architectural elements of a building or infrastructure in different layers. BIM models contain geometrical, aesthetic, and valuable semantic data, which provides a detailed understanding of the built environment, from structural composition to functional properties. While recent studies highlight a shift towards BIM as a complement to traditional Computer-Aided Design (CAD) formats [167–170], the transition towards fully integrated intelligent BIM models is not immediate but is seen as an evolutionary process where digitally captured 3D data are enhancing traditional conceptual design [171–175]. While 2D and 3D aspects are easy to implement in the traditional CAD designs, nD modeling simply extends the dimension of the BIM by incorporating more aspects of the design considerations and relating to all phases of the infrastructure lifecycle such as scheduling (4D), cost analysis (5D), environmental sustainability (6D), and maintenance operations (7D).

In the context of transportation infrastructure, BIM models can be powerful for storing and visualizing inspection data and conducting different analyses, such as estimating pavement-repair cost, clash detection with underground utilities, and material quantity takeoff [176–179]. The most critical impairment to BIM implementation in managing and maintaining transportation infrastructures is the lack of specialized software [180]. The most common application of 3D modeling is for visualization, as-built documentation, and quality control tasks [181–183]. Many research studies believe that the adoption of 3D-engineered models is an essential step for agencies employing CIM, leading to more reliable workflow interaction, higher transparency in design, and rework and cost reduction [184–187]. BIM allows linking a 3D model of a facility to the detailed information of construction activity, which enables a transfer to digital management for civil projects [188–194]. As part of this digital transformation, a 4D model (3D model + schedule) plays a significant part in the planning phase of a construction project [195]. For instance, a study integrated 3D road design and pavement structure analysis based on BIM tools [196]. This comprehensive utilization of BIM can heavily improve task workflow accuracy during the maintenance phase. A collaboration-based BIM model development management (CBMDM) system was proposed, in which developing, tracking, and communicating regarding BIM models are three key components of the system [197]. For example, in an intricate project such as tunnel construction, a comprehensive BIM documentation system was prepared that entails the shape, specifications, and parametric modeling for applied material quantity takeoffs [198]. Another study developed a preliminary conceptual integration model for the underground built-environment elements by adopting collaborative examination, benefit analysis, and design practices [44]. Moreover, to enable interoperability between the design and construction phases of a bridge project, bridge information models have been developed to facilitate data analysis, decision-making, and management throughout the project lifecycle [199–201]. These examples further emphasize the value of collaboration in managing complex infrastructure projects, especially between the operation, maintenance, and rehabilitation phases.

Addressing the specific model-oriented challenges is key for broadening the scope of BIM implementation in infrastructure projects. As BIM models were not originally designed for horizontal model elements, a study encountered various challenges trying to model elements such as guardrails and retaining walls [47]. To overcome this problem, one study proposes an approach for managing and visualizing structural and functional conditions of pavements using a 3D smart object model [28,202]. The assembly line of a batch of precast wall elements has also been optimized to generate a micro-schedule sequence plan.
for each individual wall element from a BIM 4D model \[32,203\]. It should be noted that generating such models for mass infrastructure projects could be very data-intensive and computationally demanding. These innovative studies demonstrate the true potential of BIM in vertical construction, which can be fully adopted for horizontal infrastructure projects where thousands of microelements are involved in either the construction or maintenance phases.

Table 4 shows a detailed comparative analysis, highlighting the capabilities of various digital design tools. Key capabilities such as accuracy and visualization are consistently important across technologies such as BIM, 3D scanners and point clouds, VR and AR, and GIS, setting them apart from more traditional methods. These tools play a crucial role in managing data, and when their functionalities are integrated, they significantly enhance efficiency, reducing both time and costs involved in construction projects. BIM stands out for its contributions towards sustainability and performance analysis, attributes that are augmented through integration with other technologies. The capacity for real-time assessment offered by 3D scanners and point clouds, alongside BIM’s clash-detection capabilities, becomes more powerful when applied alongside nD modeling techniques. Generative AI is emerging as an innovative force, enriching the construction and design toolkit by introducing sophisticated functions like adaptive optimization and predictive dynamic analysis. This positions generative AI as a cutting-edge complement to nD modeling, pushing the boundaries of what is possible in the construction industry’s future.

Table 4. A comparative analysis of advanced design tools and their features.

<table>
<thead>
<tr>
<th>Capability</th>
<th>CAD</th>
<th>GIS</th>
<th>BIM</th>
<th>3D Scanning and Point Clouds</th>
<th>VR and AR</th>
<th>Generative AI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collaboration</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Accuracy</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Visualization</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Data Management</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Time/Cost Efficiency</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>3D Modeling</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Clash Detection</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Quantification</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Sustainability Analysis</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Performance Analysis</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Automated Design</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Real-time Assessment</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Adaptive Optimization</td>
<td>N/A</td>
<td>N/A</td>
<td>Low</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Predictive Dynamic Analysis</td>
<td>N/A</td>
<td>Moderate</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

The authors believe that while the programming aspect of BIM (both visual and non-visual) is a novel and valuable approach to modeling transportation infrastructure, it might be less appealing and rather complex for DOTs to perform on their large-scale projects. The main adaptation of visualization models for agencies is for clash detection, presentation of the proposed design for different stakeholders, and project progress visualization using different schedules and color-coding. Further research is required for the implementation of BIM in the operation, maintenance, and rehabilitation phases of infrastructure projects to facilitate lifecycle-management practices.

6. Integrated Geospatial and Building Information Modeling (GeoBIM)

The contrast in the capabilities of BIM and GIS underscores the distinctive values each system contributes to the model development and representation of built environments. However, this distinction signifies potential areas for integration and improvement, whereby GIS systems could be enhanced with the introduction of physical semantic model elements and BIM models could be improved to include more extensive geospatial capabilities. The development of a spatial data infrastructure (SDI) model utilizing data from individual BIM and GIS is a promising path for the future of interconnected models \[204\]. According to research, information modeling leads to 5–9% cost savings during construction stages through reduced rework \[205\], project schedule tracking, and improved structural monitoring \[206,207\]. Regarding the operation and maintenance phases of infrastructure,
several studies have developed management systems based on BIM and GIS integration approaches \cite{154,208–210} to improve inspection \cite{211,212}, bridge evaluation, maintenance decision-making, and structural health recovery \cite{213–217}. One of the most significant challenges for integrated management with the GeoBIM approach is the data format compatibility when exchanging information back and forth in collaborative environments \cite{46}.

Table 5 provides a comparative overview of the features associated with BIM, GIS, and GeoBIM systems. BIM employs object-oriented parametric modeling, and GIS utilizes relational vector-based modeling, while GeoBIM merges these approaches into a hybrid model. BIM’s modeling capabilities are centered around clash detection, quantity takeoff, and 4D simulation, while GIS excels in spatial query and network analysis. GeoBIM, integrating the strengths of both, offers a comprehensive suite of tools from clash detection to geo-statistics. Time series analysis in BIM is limited to 4D simulations, but GIS excels in this domain, with GeoBIM also integrating real-time data. Three-dimensional models and renderings are what define visualization in BIM, while maps and graphs define it in GIS. Interoperability varies across the systems, with BIM’s compatibility often relying on IFC, GIS boasting high interoperability with shapefile (SHP) formats, and GeoBIM facing challenges due to its diverse data formats.

Table 5. A comparative analysis of BIM, GIS, and GeoBIM systems across various feature parameters.

<table>
<thead>
<tr>
<th>Features</th>
<th>BIM System</th>
<th>GIS System</th>
<th>GeoBIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Type</td>
<td>Object-oriented parametric modeling</td>
<td>Relational vector-based modeling</td>
<td>Hybrid (Combination of object-oriented and vector-based modeling)</td>
</tr>
<tr>
<td>Data Format Support</td>
<td>IFC, RVT, DGN, CAD, SKP</td>
<td>SHP, GDB, KML, GML</td>
<td>IFC, CityGML, GML, GeoJSON</td>
</tr>
<tr>
<td>Modeling Capabilities</td>
<td>Clash Detection, Quantity Takeoff, Cost Estimation, 4D Simulation</td>
<td>Spatial Query, Geo-statistics, Network Analysis, Geocoding</td>
<td>Integrated Geospatial Analysis with BIM Tools (Clash Detection, Quantity Takeoff, Cost Estimation, 4D Simulation, Spatial Query, Geo-statistics, Network Analysis)</td>
</tr>
<tr>
<td>Time Series Analysis</td>
<td>Limited (primarily 4D simulations)</td>
<td>Time Series Analysis, Real-time Data Integration</td>
<td>Time Series Analysis, Real-time Data Integration</td>
</tr>
<tr>
<td>Visualization</td>
<td>3D Models, Renderings</td>
<td>Maps, Charts, Graphs</td>
<td>3D Models integrated with geospatial components (Maps, Charts, Graphs)</td>
</tr>
<tr>
<td>Interoperability</td>
<td>Depending on the software, IFC offers broad compatibility</td>
<td>Generally high with standard formats such as SHP, KML</td>
<td>Can be challenging due to the integration of diverse data formats, but improving with standards such as CityGML</td>
</tr>
<tr>
<td>Scalability</td>
<td>Highly scalable but can be resource-intensive</td>
<td>Highly scalable, can handle large datasets</td>
<td>Depending on the model types and data formats being integrated, can be resource-intensive</td>
</tr>
<tr>
<td>Software Vendor</td>
<td>Autodesk, Graphisoft, Bentley Systems</td>
<td>Esri, QGIS, Google</td>
<td>ESRI, Autodesk, Bentley, Leica</td>
</tr>
</tbody>
</table>

Integrated BIM-GIS applications have been developed and evaluated in several studies for inspection management systems \cite{112,218}, 3D to nD modeling \cite{41,219}, inventory tracking \cite{220,221}, conflict detection \cite{222,223}, procurement \cite{224}, decision-making analysis \cite{225–227}, and maintenance management \cite{150,228,229}. An underground utility management system based on integrated BIM-GIS was developed to facilitate stakeholders through the entire lifecycle of projects \cite{36}. Both BIM and GIS models need to sync their semantics in terms of element classification and data administration to maximize compatibility across GIS and BIM data formats \cite{51}. Studies have compared the difference in file formatting extensions of BIM and GIS models (RVT, IFC, SHP, GDB, KML) and identified
the challenges of the integration process. Generally, the IFC format [230] was used to exchange data in between the two environments considering that the information stored in BIM models are more detailed and element-based, whereas GIS models are more focused on spatial relationships and geographic data [49,231]. It was observed that interconnecting BIM and GIS models through the IFC standard after the construction stage would facilitate an appropriate information interchange between different entities in a project [45,50]. A study suggested that IFC can be transformed into shapefile models with the cost of losing the geometry of some elements of the model [35]. Findings showed that interoperability issues that are common in integrated environments are increasing file sizes, inconsistent object types, geometric misrepresentation, loss of volumetric relations between objects, and physical properties, with the latter being the most problematic [232].

Table 6 compares the applications of BIM, GIS, and GeoBIM systems throughout a project’s lifecycle, highlighting their implementation advantages and disadvantages. BIM excels in the design stage with detailed parametric 3D modeling and structural and energy analysis. In contrast, GIS is tailored for spatial and cartographic representation, excelling in spatial, network, and terrain analyses. BIM’s coordination capabilities include clash detection and 4D scheduling, whereas GIS focuses on global spatial analysis through buffer and overlay techniques. In asset management, BIM is strong in 4D modeling and condition assessment, while GIS emphasizes site and spatial asset analysis. GeoBIM integrates BIM and GIS strengths, offering comprehensive spatial and 3D design, along with combined site and 4D analysis. However, merging BIM and GIS elements in GeoBIM is complex and requires careful data interoperability management.

**Table 6.** A Comparative analysis of the capabilities, advantages, and disadvantages of BIM, GIS, and GeoBIM implementation in various tasks.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>BIM Systems</th>
<th>GIS Systems</th>
<th>GeoBIM Systems</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis</td>
<td>Structural Analysis, Energy Analysis, Quantity Take Off</td>
<td>Spatial Analysis, Network Analysis, Terrain Analysis, Hot Spot Analysis, Temporal Analysis</td>
<td>Integrated Structural and Spatial Analysis</td>
<td>[196,236]</td>
</tr>
<tr>
<td>Coordination</td>
<td>Clash Detection, 4D Scheduling</td>
<td>Spatial Coordination, Network Coordination</td>
<td>Integrated Clash Detection and Spatial Coordination</td>
<td>[32,179,224,237]</td>
</tr>
<tr>
<td>Planning and Decision Making</td>
<td>4D and 5D BIM (Time and Cost), Scenario Analysis</td>
<td>Spatial Planning, Network Planning</td>
<td>Integrated Spatial and Scenario Planning</td>
<td>[56,127,131,132]</td>
</tr>
<tr>
<td>Data Management</td>
<td>Data Layering, Parametric Data Management</td>
<td>Spatial Database Management, Metadata Management</td>
<td>Integrated Spatial and Parametric Data Management</td>
<td>[201,243,244]</td>
</tr>
<tr>
<td>Spatial Analysis</td>
<td>Local Space Planning, Site Analysis</td>
<td>Buffer Analysis, Overlay Analysis, Network Analysis</td>
<td>Integrated Space Planning and Spatial Analysis</td>
<td>[46,245]</td>
</tr>
<tr>
<td>Construction</td>
<td>4D BIM (Time), Quantity Take Off, Digital Twin</td>
<td>Site Analysis, Network Analysis</td>
<td>Integrated Site and 4D Analysis</td>
<td>[27,55,87,184,186,248]</td>
</tr>
</tbody>
</table>
### Table 6. Cont.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>BIM Systems</th>
<th>GIS Systems</th>
<th>GeoBIM Systems</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance</td>
<td>Condition Assessment,</td>
<td>Spatial Asset Management, Network Analysis</td>
<td>Integrated Condition Assessment and Spatial Asset Management</td>
<td>[189,190,249–251]</td>
</tr>
<tr>
<td></td>
<td>Maintenance Scheduling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benefits</td>
<td>Detailed design, 3D</td>
<td>Powerful spatial analysis, handling large datasets, integration with other</td>
<td>Combines the advantages of both BIM and GIS, powerful in both design and spatial</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>visualization, and</td>
<td>systems</td>
<td>analysis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>integration with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>construction processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limitation</td>
<td>Handling of large spatial</td>
<td>Detailed design, 3D visualization, and integration with construction</td>
<td>Requires integration of BIM and GIS, which can be complex and challenging</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>datasets, integration with</td>
<td>processes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>other systems</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Recent studies have focused on the technical aspects of transferring data from BIM platforms to GIS platforms, which requires a modified IFC shared model. Although novel algorithms, scripts, and many other methods have been developed, most efforts have resulted in losing at least a portion of the data when exchanging models back and forth between the two platforms. Thus, future research studies could focus on the possibility of developing an integrated model for roadway infrastructure for the entire lifecycle of the asset, while maintaining an equal level of control for both models.

### 7. Transportation Infrastructure Maintenance and Rehabilitation Planning (Asset Management)

An improved and effective AMS with an innovative framework could help agencies reduce the cost of their projects [43,252,253]. One of the main challenges of transportation infrastructure asset management is to monitor the condition and performance of assets in a timely and accurate manner [254]. Traditional methods of data collection and analysis are often labor-intensive, costly, prone to errors, and do not provide real-time feedback or predictive capabilities for optimal decision-making [255]. For instance, a free, open-source system for infrastructure asset management was proposed to mainly address the prior AMS issues of inextensibility and high implementation expenses [241]. On the other hand, the current maintenance and rehabilitation (M&R) procedures on roadway infrastructure involve complicated tasks such as overlapping planning periods, financial resource management, discrete datasets, outdated models, and collaboration challenges among various contractors [238,239,256–259]. Due to the extreme complexity level of transportation infrastructure projects, it is necessary to highlight the need for an intelligent model-based AMS. The advent of advanced technologies for data collection, utilization, and preservation has paved the way for the development of sophisticated infrastructure-management systems. Maintenance and the serviceability of an asset could be significantly improved with the application of these modern technologies [260]. Several studies believe that GIS services can integrate the digital data collected from the early phases of a project and combine them with O&M data in an AMS [26,52,234,261]. By effectively utilizing comprehensive geospatial analysis, organizations can evaluate pavement conditions and deterioration patterns with more precision, which in turn improves the planning of necessary maintenance and rehabilitation tasks [262,263]. To address these limitations, the concept of applying AI and IoT technologies envisions building an AMS that can collect, process, analyze, and report data from various sources, such as sensors, drones, cameras, and satellites, to create a digital twin model of the infrastructure asset.

The Internet of Things (IoT) is the interconnection of shared entities with embedded sensors, allowing them to exchange data and provide remote access over the Internet [59,264]. The combination of BIM and IoT technologies has been the subject of intensive research in recent years. For instance, studies have investigated the existing interoperability issues between these systems [265–268], enabling real-time big data analytics for
problem identification [251,269], and assisting construction operations [270,271]. Other studies examined the application of the integrated BIM and IoT system for various purposes, including securely storing and accessing digital information related to building operations [272], monitoring road pavement maintenance and rehabilitation processes at airports [273], reducing significant greenhouse gas emissions when focusing on pavement M&R [21], and implementing predictive maintenance by incorporating machine learning (ML) for condition assessment and planning of Mechanical, Electrical, and Plumbing (MEP) components [274].

Artificial Intelligence (AI) is gradually making its impact on asset management practices. For instance, by integrating two essential AI modeling techniques, Case-Based Reasoning (CBR) and Rule-Based Reasoning (RBR), the rapid parametric construction of bridge BIM models was achieved [275]. AI models can be beneficial tools for digital twin models to simulate and recognize their future conditions in various scenarios more accurately. The authors believe that an AI-driven AMS could prioritize maintenance and rehabilitation operations based on condition and risk assessments by utilizing predictive ML analytics. Applying AI and IoT technology to transportation infrastructure AMS holds great potential for enhancing efficiency, safety, and predictive maintenance [276]. This integration process involves deploying IoT sensors and devices across critical infrastructure elements such as roads and bridges to collect diverse real-time data on traffic flow, structural health, and environmental impacts [277,278]. The present study believes that a valuable application of an AI-based transportation AMS is to track a given defect or distress on a pavement segment or bridge location back to its construction quality and initial design flaws to identify the cause and present preventive solutions. The AI-driven analysis system helps in predicting maintenance needs and potential failures, thereby enabling proactive maintenance strategies, and enhancing the overall life span of transportation systems [274,279]. Studies highlight the adoption of IoT for data-driven decision-making within asset management, emphasizing the importance of integrating these technologies with existing systems for seamless functionality [244,273].

The digital twin of transportation infrastructure is a dynamic, virtual representation of a physical infrastructure asset that allows for comprehensive analysis, predictive modeling, traffic controlling, and optimized decision-making for the asset’s lifecycle management [280]. A digital twin model can also be coupled with virtual-reality or augmented-reality technologies to provide a real-time state of the system [281,282]. Studies have shown the use of integrated BIM and digital twin models for several purposes, including digital lifecycle bridge engineering [23,283], improving roadway safety [22,284], structural health monitoring by combining real-scene 3D models [285], operation and maintenance [286], and city information modeling based on the combined use of BIM, GIS, and IoT tools [20,43,228].

While numerous studies have leveraged Machine Learning and simulations to enhance BIM outcomes in vertical constructions, such as safety, optimization, conflict management, demolition, and scheduling [235,287–290], the application to horizontal infrastructure projects, particularly within operation and maintenance (O&M) phases, remains under-explored. For example, a study identified the potential of CIM-related technologies in improving transportation project outcomes but pointed out the scarcity of research focusing on the integration of AI and ML technologies for maintenance and rehabilitation forecasting in such settings [291,292]. This gap indicates a significant opportunity for the transportation industry, suggesting that DOTs could significantly benefit from predictive analytics empowered by AI and ML to forecast and effectively manage future performance, maintenance, and rehabilitation needs [293,294]. Thus, despite the demonstrated benefits of ML in vertical BIM applications, the horizontal integration across transportation infrastructure’s lifecycle phases, particularly in O&M, demands further scholarly attention to unlock similar efficiencies and advancements.

The authors believe that a visionary framework for an intelligent GeoBIM asset-management system should demonstrate a seamless digital information flow from initial design and specification to inspection and performance data for asset management. To
maximize the potential peak performance of civil infrastructure, a geo-enabled model-based asset-management system that could incorporate digital information from early design, in-service conditions, O&M, environmental conditions, and traffic is required. Despite the complexity of infrastructure projects, another constraining factor for wide CIM adoption is the technology itself. The technology exists in fragmented forms and does not work properly as a functional shared data resource across different platforms, in between organizations, or in working teams.

8. Further Discussion

The CIM approach has been demonstrated as an excellent medium for integrating the technologies available for the sustainable management of various phases of transportation infrastructure planning, design, construction, and O&M. Over the last two decades, infrastructure management has undergone substantial technological and methodological advancements, transitioning from primarily human-driven manual processes to digital and semi-automated operations. Modern technological breakthroughs brought forth tools such as CAD, GIS, and BIM, which were empowered by drones, 3D scanners, and LiDAR for data collection and surveys. Implementing these tools for infrastructure project planning involves significant technical challenges. One of the main issues is data-formating mismatch and integration processes from various sources into a cohesive platform for comprehensive analysis. Ensuring compatibility between different data types and formats often requires extensive preprocessing power and standardization algorithms. Additionally, maintaining the accuracy and timeliness of data, especially when derived from dynamic sources such as real-time inspection systems and traffic monitoring, is rather complex.

Moreover, the literature revealed that current practices mainly focused on BIM's application in the design and construction stages of vertical construction, with specific emphasis on clash detection and visualization rather than maintenance and rehabilitation workflows. For DOT's large-scale projects, there is a need for further exploration into the programming aspects of BIM to automate certain repetitive tasks, particularly for improving performance-management practices during the operation phase. Recent studies have focused on the integration of BIM and GIS in an effort to provide a shared model that can exploit the advantages of both systems despite challenges in data translation between the two platforms. Challenges include data scale discrepancies, where geospatial data might embrace broader scales than BIM's detailed model-centric perspective.

In the realm of infrastructure management, there is a paradigm shift towards a proactive approach, where predictive analytics and real-time assessments drive the decision-making process. Technical challenges in this area include the aggregation and analysis of historical data alongside real-time data to forecast maintenance needs and performance accurately. This process involves sophisticated predictive analytics capabilities and the integration of various data sources, such as sensor data, maintenance records, and traffic, environmental, and operational data. The complexity increases with the need to handle geospatial variability and the temporal dynamics of infrastructure distress data, requiring machine learning analytics frameworks and considerable computational resources. Moreover, the review highlights a critical gap in data privacy and security. As CIM involves extensive data collection and sharing among various stakeholders, ensuring the confidentiality and integrity of this data is paramount. The transition to a fully digital workflow introduces vulnerabilities that must be addressed in advance to protect sensitive information.

Further study is also required to assess whether employing these digital techniques can effectively reduce potential conflicts, reconstruction time, and maintenance costs throughout a roadway's lifecycle. Current approaches to CIM implementation in transportation infrastructure entail the collection of pavement distress data using a linear referencing system based on predefined uneven mile points. Future research should aim to create an all-encompassing model for highway pavement distress, which includes geolocating the gathered data on cracking and rutting across various lanes, distinguishing between
wheel path and non-wheel path areas using an evenly segmented approach. Furthermore, a geo-enabled model-based framework was proposed that could relate collected distress data with real-time location and diverse material attributes and environmental factors, substantially improving the accuracy and effectiveness of maintenance plans, which would ultimately result in a more sustainable transportation infrastructure system.

From the authors’ point of view, a futuristic groundbreaking infrastructure-management system is expected to leverage AI capabilities, IoT sensors, blockchain technology for data security, and automated inspection tools to generate predictive and preventive maintenance models. By training the AI models using historical data including several design, construction, and environmental components, the lifecycle performance model of a constructed transportation system can be projected. This predictive maintenance model allows agencies to use both real-time and projected data to enhance their forecasting accuracy. The AI-based asset-management system should provide precise recognition of initial pavement cracking locations before their occurrence as well as critical insights into the primary factors contributing to their initiation, aiding in timely preventive maintenance interventions. Additionally, an advanced AI-based AMS should have the capabilities to interact with various stakeholders, such as engineers, managers, operators, contractors, and official agencies, through multiple mediums, such as dashboards, reports, alerts, and online portals, to provide them with relevant and crucial real-time insights. However, the true potential of AI-based approaches is yet to be fully realized as performing these tasks even on a small scale is still either exceptionally resourceful or time-consuming.

9. Conclusions

This review study has presented an extensive examination of the CIM concept and its implementation. Drawing insights from an exhaustive review of 280 publications from 2000 to 2023, this article not only provides a comprehensive assessment but also highlights prospective opportunities for further development. The central objective of this review was to assess the adaptation of the CIM concept within the domain of transportation infrastructure in recent years. The authors first identified five main research topics, namely: (i) application of advanced surveying methods, (ii) geospatial analysis tools for project planning, (iii) multidimensional virtual design models, (iv) integrated geospatial and building information modeling, and (v) transportation infrastructure maintenance and rehabilitation planning. Furthermore, the authors highlighted research gaps regarding the real-world implementation of CIM across the entire lifespan of transportation structures, while emphasizing the need for the necessary future steps.

Many state DOTs and agencies have pre-planned condition targets (e.g., percentage of total lane miles below a threshold surface crack or rut rating) for their pavement segments to perform. These mentioned rating systems validate that inadequately performing sections of the roads do not fall below pre-determined satisfactory standards, leading to expensive reconstruction projects. Additionally, transportation infrastructure projects usually experience many alterations in response to influences such as financial needs, environmental factors, maintenance, and construction conflicts. CIM incorporates a variety of methods and tools, including gathering, organizing, and managing digital information on transportation assets. From the early stages of surveying, through design and construction, to the very final stages in its lifecycle, e.g., maintenance and rehabilitation, CIM practices can enhance transportation asset performance and predictability. The authors propose a more detailed approach to collecting asset distress data using automated tools for smaller segments, e.g., 0.1-mile intervals, to replace the traditional milepost approach. The ultimate vision for the proposed AI-based AMS framework is to forecast asset lifecycles (performance, maintenance, rehabilitation cost, etc.) based on the design, material properties, and existing deterioration and traffic datasets prior to the construction phase.

While 3D-nD virtual conceptual models have been applied to the design stages, their benefits also can be identified for the operation and maintenance phases. Furthermore, AMS with AI capabilities could benefit from automated data gathering and processing,
greatly decreasing personnel and the possibility for human errors, which enables proactive rather than reactive maintenance and rehabilitation plans and therefore longer serviceability for civil infrastructure. Additionally, these AI-driven systems could support dynamic data-driven decision-making by utilizing historical and real-time data to optimize the performance, longevity, and sustainability of infrastructure. The review study illuminates a promising direction for leveraging GeoBIM with generative AI capabilities to enable comprehensive, real-time, predictive lifecycle management of civil infrastructure assets. By integrating geospatial intelligence and BIM with AI techniques, the vision of a digital twin for infrastructure systems that dynamically self-monitor, analyze, and optimize themselves is attainable. Transportation infrastructure systems can evolve from static as-built models to adaptive, responsive environments enriched with physics-based performance simulations, predictive maintenance, and automated decision-making algorithms for maximizing structural integrity and operational efficiency, which leads to increasing its effective service life. The authors recommend that additional analytical efforts be directed towards the integration of capturing real-time data from assets, automated condition assessment, GeoBIM AMS challenges, applications of the Internet of Things (IoT) tools and sensors, and generative AI nD modeling for infrastructures, thus constructing the core foundations for realizing the full vision of a digital twin model. However, the authors would like to point out that while the potential of AI-driven AMS is significant, the implementation of such tasks in civil infrastructure also comes with numerous challenges, including high technology investments, implementation complexity, data privacy concerns, extensive training sessions, etc.

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**References**


21. de Bortoli, A.; Baouch, Y.; Masdan, M. BIM can help decarbonize the construction sector: Primary life cycle evidence from pavement management systems. J. Clean. Prod. 2023, 391, 136056. [CrossRef]


23. Mohammadi, M.; Rashidi, M.; Yu, Y.; Samali, B. Integration of TLS-derived Bridge Information Modeling (BrIM) with a Decision Support System (DSS) for digital twinning and asset management of bridge infrastructures. Comput. Ind. 2023, 147, 103881. [CrossRef]

24. Tache, A.-V.; Popescu, O.-C.; Petrisor, A.-I. Conceptual Model for Integrating the Green-Blue Infrastructure in Planning Using Geospatial Tools: Case Study of Bucharest, Romania Metropolitan Area. Land 2023, 12, 1432. [CrossRef]

25. Zhang, F.; Chan, A.P.; Darko, A.; Chen, Z.; Li, D. Integrated applications of building information modeling and artificial intelligence techniques in the AEC/ FM industry. Autom. Constr. 2022, 139, 104289. [CrossRef]


27. Han, C.; Tang, F.; Ma, T.; Gu, L.; Tong, Z. Construction quality evaluation of asphalt pavement based on BIM and GIS. Autom. Constr. 2022, 141, 104398. [CrossRef]


34. del Río-Barral, P.; Soilán, M.; González-Collazo, S.M.; Arias, P. Pavement Crack Detection and Clustering via Region-Growing Algorithm from 3D MLS Point Clouds. Remote Sens. 2022, 14, 5866. [CrossRef]


123. Wang, Y.; Roy, N.; Zhang, B. Multi-objective transportation route optimization for hazardous materials based on GIS. J. Loss Prev. Process Ind. 2023, 81, 104954. [CrossRef]
124. Debnath, P. A QGIS-Based Road Network Analysis for Sustainable Road Network Infrastructure: An Application to the Cachar District in Assam, India. Infrastructures 2022, 7, 114. [CrossRef]

236. Tang, F.; Ma, T.; Guan, Y.; Zhang, Z. Parametric modeling and structure verification of asphalt pavement based on BIM-ABAQUS. *Autom. Constr.* 2020, 111, 103066. [CrossRef]


241. Asghari, V.; Hsu, S.-C. An open-source and extensible platform for general infrastructure asset management system. *Autom. Constr.* 2021, 127, 103692. [CrossRef]


250. Aziz, Z.; Riaz, Z.; Arslan, M. Leveraging BIM and Big Data to deliver well maintained highways. *Facilities* 2017, 35, 818–832. [CrossRef]


267. Wang, H. Sensing Information Modeling for Smart City. In Proceedings of the 2015 IEEE International Conference on Smart City/SocialCom/SustainCom (SmartCity), IEEE, Chengdu, China, 9–21 December 2015; pp. 40–45. [CrossRef]


272. Álvarez, A.P.; Ordieres-Meré, J.; Loreiro, A.P.; de Marcos, L. Opportunities in airport pavement management: Integration of BIM, the IoT and DLT. J. Air Transp. Manag. 2021, 90, 101941. [CrossRef]


276. Han, T.; Ma, T.; Fang, Z.; Zhang, Y.; Han, C. A BIM-IoT and intelligent compaction integrated framework for advanced road compaction quality monitoring and management. Comput. Electr. Eng. 2022, 100, 107981. [CrossRef]


279. Rezaei, Z.; Vahidinia, M.H.; Aghamohammadi, H.; Azizi, Z.; Behzadi, S. Digital twins and 3D information modeling in a smart city for traffic controlling: A review. J. Geogr. Cartogr. 2023, 6, 1865. [CrossRef]


283. Renzi, E.; Trifarò, C.A. Knowledge and Digitalization: A way to improve safety of Road and Highway Infrastructures. Procedia Struct. Integr. 2022, 44, 1228–1235. [CrossRef]

284. Xu, J.; Shu, X.; Qiao, P.; Li, S.; Xu, J. Developing a digital twin model for monitoring building structural health by combining a building information model and a real-scene 3D model. Measurement 2023, 217, 112955. [CrossRef]


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