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Systematic Review

Towards 4D BIM: A Systematic Literature Review on Challenges, Strategies and Tools in Leveraging AI with BIM

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Abstract: In moving toward the fourth dimension of building information modeling (4D BIM), this study systematically reviews the literature on challenges, strategies, and tools in 4D BIM-related research. To address the limitation of the static nature of knowledge represented in traditional building information modeling (BIM), 4D BIM incorporates the time dimension into BIM systems to anticipate potential delays, optimize workflows, and improve overall project efficiency in the architecture, engineering, and construction (AEC) industry. Although existing BIM research has covered various aspects, in-depth review studies specifically on 4D BIM remain scarce. Following a systematic search and data analysis, this work examines research contexts (building information models, lean systems, ontology frameworks, predictive strategies, and tools, software and techniques) in 4D BIM research and evaluates them qualitatively. The research and evaluation identified several key strategies for advancing 4D BIM, including the integration of lean methodologies, predictive strategies, and ontology frameworks. These approaches contribute to the automation of information sharing and the optimization of processes within AEC digital infrastructures. This review highlights the gaps in current research and emphasizes the importance of integrated digital solutions while also classifying the existing tools, software, and standards related to 4D BIM while presenting a foundation for future research on AI-driven solutions.

Keywords: 4D BIM; building information modeling; artificial intelligence; systematic literature review

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1. Introduction

Building information modeling (BIM) is a vital information technology infrastructure that serves as a knowledge database, collaborative tool, and virtual representation of construction operations [1,2]. Construction operations are constantly dynamic while knowledge databases and virtual representations remain static, thus being a limitation. Additionally, the overarching challenges affecting construction operations for a long period are time overruns, cost overruns, reworks, and health and safety issues [3,4]. Time overruns caused by ambiguity in scheduling, for instance, are heightened as the complexity of projects increases. At present, the level of complexity in awarded projects continually grows, and many contractors are not able to deliver construction projects on time or within the budget. In fact, despite the UK being a strong enabler of digitization efforts in construction, one-third of the UK's construction projects were deemed late, while about 70% of government projects in the United Kingdom were also delivered late [5]. The issue of time overruns is a key factor underscoring the importance of 4D BIM. Uncertainties in project scheduling can be effectively addressed through the implementation of 4D BIM, which includes features for production control, performance monitoring, risk management, visual simulations, and all modules existing in building information modeling (BIM) systems. This study is motivated by the need to advance from the current state of 3D BIM to 4D BIM, emphasizing the integration of time-related data. As shown in Figure 1, this study seeks to identify and leverage strategies, ascertain barriers, and review tools that facilitate the comprehensive integration of all aspects of BIM with time functions.

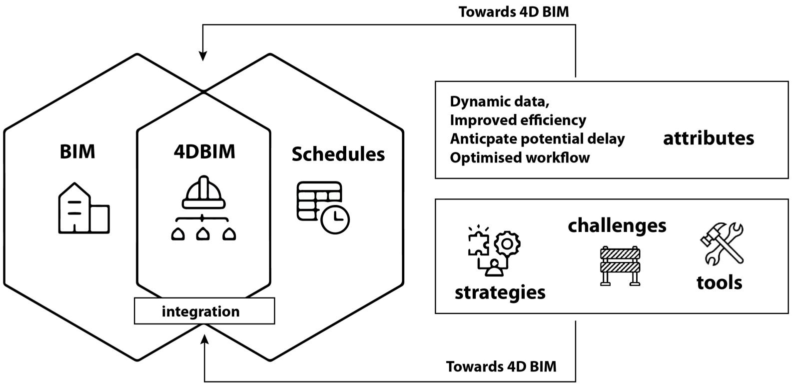


Figure 1. Towards 4D BIM: The additional dimension that incorporates time into existing BIM modules will assist in anticipating delay, improving efficiency, and optimizing workflows. This study identifies the strategic tools and barriers in 4D BIM research and developments.

Integrated BIM systems allow for seamless data sharing among construction digital infrastructures, which is vital, especially in circumstances where there are several technologies that have proven to develop the system's functional capacity. Aside integration of time with modules in BIM, other aspects that are beneficial in enhancing BIMs include lean, ontology, and predictive strategies [6–8]. These were discovered to be important aspects of integrated BIM. Lean reduces waste and improves collaboration, aligning with BIM's goals of streamlined processes. Ontology ensures standardized data and semantic interoperability, making information exchange seamless across BIM systems and various supportive technologies. Also, predictive strategies allow for data-driven insights, automating planning activities, and anticipating project risks. These aspects improve project outcomes, reduce costs, and support sustainable construction operations. Other technologies such as the Internet of Things (IoT), digital twins, blockchain, cloud computing, augmented reality (AR), and virtual reality (VR), etc., have also been identified as the next frontiers of digitization in the AEC sector [9]. In ensuring integrated 4D BIM systems, this study reviews related aspects and strategies towards 4D BIM implementation. The specific contributions of this review are highlighted in the following subsection. Finally, the structure of this paper is outlined in Section 1.2.

1.1. Study Contributions

This study's contributions aim to spur further research on 4D BIM. The following are its specific contributions: (1) A systematic literature review highlighting limitations in strategies and tools for 4D BIM development. (2) A classification of BIM modules, supportive technologies, and strategies towards 4D BIM as a digital construction initiative. (3) A taxonomy of tools, software, and techniques in 4D BIM development is presented. (4) A categorization of the key challenges associated with construction operations, thus providing a structured framework for understanding and addressing these issues.

1.2. Study Road Map

Figure 2 shows the review study road map, which indicates the order and structure to which this study is developed. This work begins with an introduction in Section 1, with the contribution and road map being highlighted in the same section. The methodology is presented in Section 2, which shows the detailed process of replicating this work. Section 3 showcases a background study of BIM regarding its definition, maturity, and structure of BIM. Section 4 contains BIM-related research studies on lean with BIM, 4D BIM, and ontology frameworks. Section 5 presents challenges in construction regarding construction information systems and presents the gaps and limitations. Section 6 presents strategic tools, techniques, and software used in 4D BIM-related research. Section 7 details existing research on predictive modeling strategies, including computer vision (CV), natural language processing (NLP), and general machine learning (ML). The evaluation of predictive modeling strategies is also presented in Section 7.5. A discussion of the entire work is presented in Section 8. Section 9 contains the open issues, providing a culmination of the gaps and limitations of this study. Section 10 outlines the conclusions, discussing the summary, findings, and further study opportunities for researchers in this field.

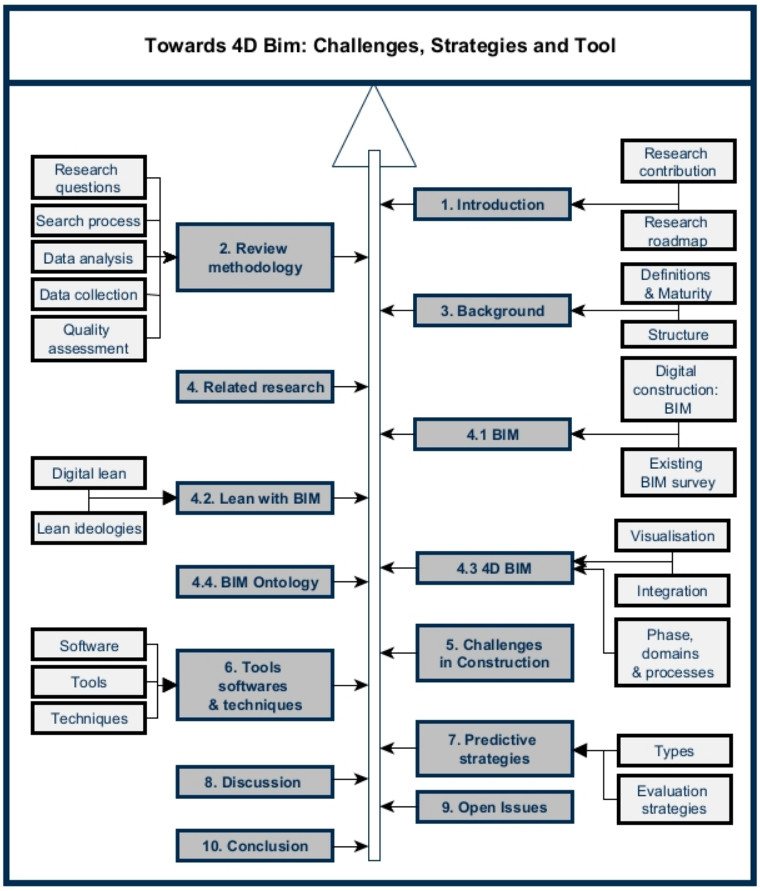


Figure 2. Systematic review study road map.

2. Review Methodology

This study reviews all research contexts (BIM, lean systems, ontology frameworks, predictive strategies, and tools, software and techniques) towards 4D BIM research and development. The section starts with explorations of research regarding BIM and lean strategies with BIM, leading to a review of 4D BIM, and a review of challenges in this context. Finally, this study concludes with a review of predictive strategies for an integrated and automated BIM system. Figure 3 shows clear links in connected subtopics discussed in this study. Throughout this work, the gaps and limitations of this study are highlighted and comprehensively summarized in Section 9.

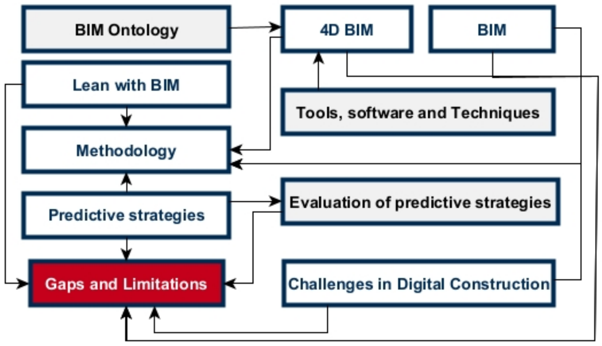


Figure 3. Review methodology.

2.1. Research Questions

To achieve the objectives of this study, the following research questions have guided the procedure, resolutions, and discussions in this study:

- RQ 1: What are the existing limitations in BIM?
- RQ 2: What challenges in AEC/digital construction have been addressed in the literature?
- RQ 3: What are the strategies that can be deployed towards 4D BIM?
- RQ 4: What tools, techniques, and software exist in the research for 4D BIM integration and 4D BIM related research?
- RQ 5: What are the predictive strategies applicable and how are they evaluated?

For research questions, RQs 1–5, existing related articles to each of the questions were searched using search strings, as outlined in Table 1, and a procedure as presented in the next section: Section 2.2.

Table 1. Study search strings.

SubTopic	Search String	Search Field
BIM	“3d bim” OR “bim” OR “building information modeling” OR “building information management” AND “survey” OR “literature review”.	Title
Lean systems in BIM	”lean” OR “lean construction” OR “lean methodology” AND “bim” or “building information modeling” or “digital construction” or “AEC *”	Title
Challenges in construction	”fragmentation” OR “Integration” OR “Adoption” OR “Implementation” OR “Cost” OR “Communication” OR “Collaboration” OR “Interoperability” OR “Sustainability” OR “Security” OR “Complexity” OR “Design” OR “Data” OR “Legal” OR “regulatory” OR “Standard” OR “Compliance” OR “Stakeholder” OR “Automation” OR “Skill” OR “Training” AND “Challenge” OR “Barrier” OR “Obstacle” OR “Issue” OR “Hurdle” OR “Limitation” OR “Problem” OR “Difficulty”	No field
	“construction *” OR “construction industry” OR “construction sector”	Subject
	“bim” OR “building information modeling” OR “building information *” OR “Information technology” OR “ICT” AND “Bim” OR “building information modeling” OR “building information *” OR “information technology” OR “ICT”	All text
4D BIM	4D BIM	Title
BIM Ontology	ontolog * AND “bim” or “building information modeling” or “digital construction” or “AEC *”	Title
Predictive strategies in 4D BIM	“Computer vision” OR “natural language processing” OR “NLP” OR “machine learning” OR “ML” AND OR “building information modeling” OR “AEC” OR “BIM”	Title

2.2. Search Process

The search procedure for this study follows a process specified by Kitchenham [10]. A set of search strings was carefully determined to present relevant works in the area of search while specifying the exact search field. For replicability purposes, further criteria for including and excluding papers were determined, and the order to filter and reach the final set of papers was determined. Using the search strings as in Table 1 and following exclusion and inclusion criteria as in Table 2, the articles selected in reviewing all topics and subtopics can be accessed. Figure 4 shows the PRISMA flow diagram, which details the total number of research articles reviewed for this study. This process is grouped as follows: (1) search entries which are the topics/subtopics, (2) search process which generates unfiltered numbers of articles, and (3) filters and total results of the articles reviewed are indicated at the lower end of the diagram.

The filters, including full-text availability, peer-reviewed articles, and year of publication, were all used at different points, with duplicates being removed and with exclusion and inclusion criteria being applied to choose articles. See Table 3 for the filters applied per subtopic. The complete process indicates that a total of 149 papers were reviewed for this article.

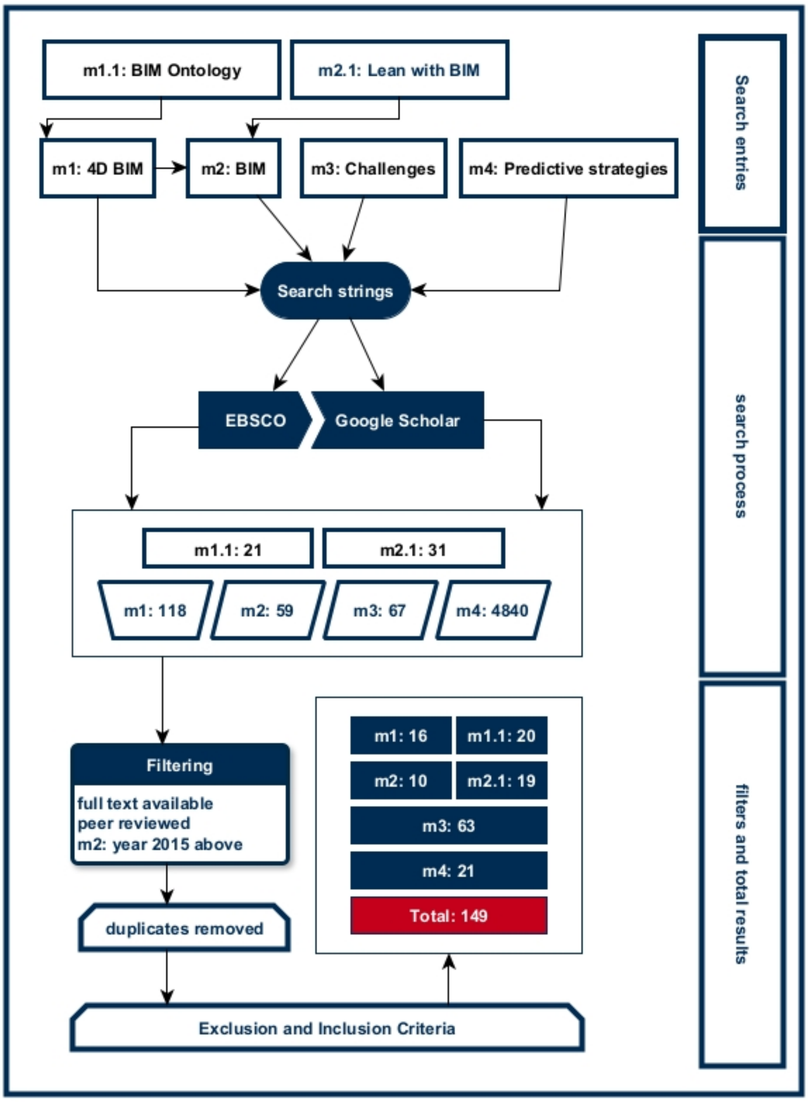


Figure 4. Review methodology PRISMA flow.

Table 2. Exclusion and inclusion criteria.

Subtopics	Exclusion	Inclusion
BIM	(1) Non-survey/review papers or case study application studies (2) Papers outside language scope (English)	(1) Survey or review papers regarding BIMs, its adoption, challenges, history, digital progression, etc.
Lean systems in BIM	(1) Articles not contributing to bridging the divide between lean construction and BIM (2) Studies including other technologies other than lean and BIM. (3) Paper outside language scope (English)	(1) Studies discussing on lean systems and application in AEC or BIM (2) Studies discussing existing products bridging the gap between lean BIM.
Challenges in construction	(1) Short paper columns that was published as article was excluded. (2) Papers from different fields/subject terms such as education, health user acceptance, microbial fuel cells, psychology, ecology, ethics were excluded (3) Surveys or review articles that did not have a specific challenge motivating research to achieve solutions and overcome such challenges were excluded (4) Articles with challenges not pertaining to construction or AEC were excluded (5) Articles written regarding other types of construction asides construction for built assets and physical building are not considered. Material construction, test construction, etc., are disregarded.	(1) Research work with a specific problem that spurs and motivates research (2) Research areas within subject area of construction and construction technology
4D BIM	(1) Articles without 4D BIM as main subject (2) Paper outside language scope (English)	(1) Studies discussing integration methods and frameworks (2) Studies detailing tools, software and techniques
Predictive strategies in 4D BIM	(1) Incoherent or poorly organized study documentation	(1) All studies showcasing AI-based technique in AEC phases, design, digital construction, BIM, etc. (2) All studies detailing evaluation basis

Table 3. Study using PRISMA filter.

Subtopic	Full Text	Peer-Reviewed	Language	Academic Journal	Ref. Available	Year	Total
BIM	x	x	x	x			10
Lean systems in BIM	x	x	x	x			19
Challenges in construction	x	x	x	x	x		63
Four-dimensional BIM	x	x	x	x		2015	16
BIM Ontology	x	x	x				20
Predictive strategies in 4D BIM	x	x	x			2020	21

Filters used in search process (x: filtered; blank: not filtered).

2.3. Quality Assessment

The tool employed in standardizing the outcome of this review encompasses detailed inclusion and exclusion criteria. This is important as the genuineness of findings and outcomes is only based on the quality of the reviewed articles, hence the need to ensure that existing articles selected for this review are relevant and unbiased. This study ensures quality outcomes by ascertaining the following quality assessment questions: Q1: Are the studies included or excluded in/from this study guided by the inclusion and exclusion criteria? Q2: Are the studies included free from any form of bias? Q3: Are the studies included relevant to the search topic or subtopic?

Through the selection process, the lead researcher ensured that each reviewed study followed the specified criteria, maintained relevance to the searched topic, and did not contain bias.

2.4. Data Collection

For each of the topics, data (as appropriate to the search area as possible) were extracted to be used in this study. These data included the following: (1) Source of data, including full references. (2) Geographical location of the origin of the paper. (3) Classification of methods used in the study. (4) Summary of the study extracted from abstracts, research questions, evaluations, and conclusions of the study. (5) Gaps in the existing literature and further research opportunities.

2.5. Data Analysis

An outlook of the search process outcomes is presented in charts. Table 3 contains the total papers per subtopic, including the search filters used to ascertain the articles used in this review. An analysis of publication by subtopics and quantity is given in Figure 5, while total publications by quantity for this research are presented in Figure 7b. Figure 6a indicates the regions and sources where articles in this review originated, while Figure 6b shows countries with more than four (4) articles reviewed in this study. Figure 7a also shows the number of publications per subtopic. Overall, the analysis of publication subtopics indicates that a greater number of papers reviewed was published in automation and control journals. However, notable exceptions were observed in the subtopics of "Challenges in Construction" and "Lean with BIM", where the majority of reviewed papers were published in engineering, construction, and architecture and advanced engineering informatics journals. The challenges in construction topic also had the most papers reviewed, as seen in Figure 7a. Lastly, as evident in Figure 6a, a larger number of the articles reviewed turned out to be from China, The United Kingdom, and The United States of America, revealing that more research activities concerning building information models are from these countries.

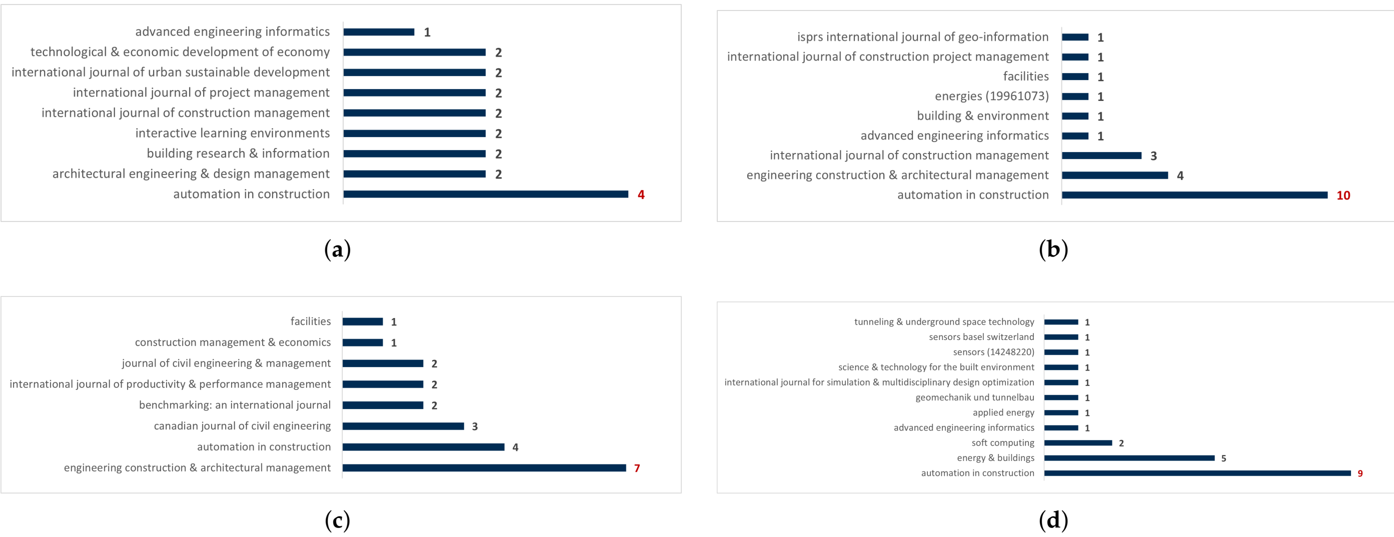
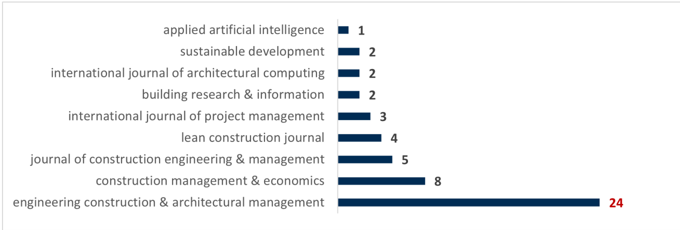
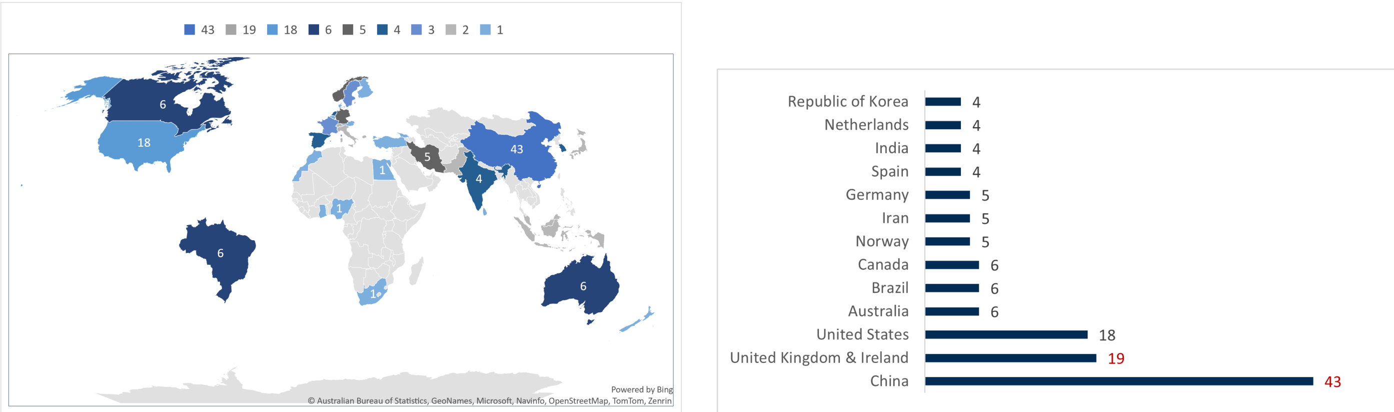


Figure 5. *Cont.*



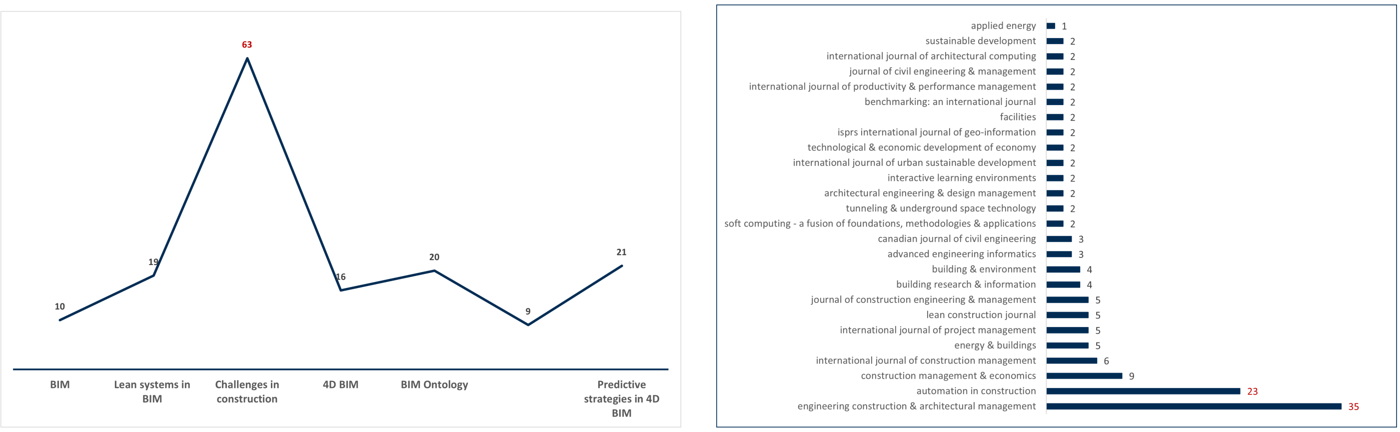
(**e**)

Figure 5. All Publication by subtopic analytics: (**a**) Publications on BIM analytics. (**b**) Publications on 4D BIM analytics. (**c**) Publications on lean with BIM analytics. (**d**) Publications on predictive strategy analytics. (**e**) Publications on challenges in construction analytics.



(**a**) (**b**)

Figure 6. All Publication by subtopic analytics: (**a**) Total publication by geographical location. (**b**) Publication by country analytics.



(**a**) (**b**)

Figure 7. Total publications analytics for review and per subtopic: (**a**) Number of publications reviewed per subtopic. (**b**) Total publications analytics for review.

3. Background

The shift from the existing 3D BIM to 4D BIM is long overdue, particularly in the context of increasing industrialization and the growing complexity of modern construction projects. The potential and prospects of 4D BIM are immense, as it addresses ambiguity and uncertainty by providing a time-based visual twin of projects, encompassing resources and other critical aspects. BIM coupled with predictive strategies and other supportive technologies will enhance the usability, adoption, and adaptability of the digital infrastructure in practice. This section discusses the varying descriptions of BIM based on different contexts.

The descriptions and definitions of BIM vary significantly across different sources. These variations often reflect the geographical context of the article, the background of the authors, or the specific functional aspects of BIM relevant to the focus of the report. BIM differs in meaning based on the context outlined below, with Table 4 indicating the different descriptions of each BIM context:

- As a knowledge and information resource;
- As a collaborative tool;
- In terms of content;
- In terms of location;
- As a 3D digital representation, as well as other contexts.

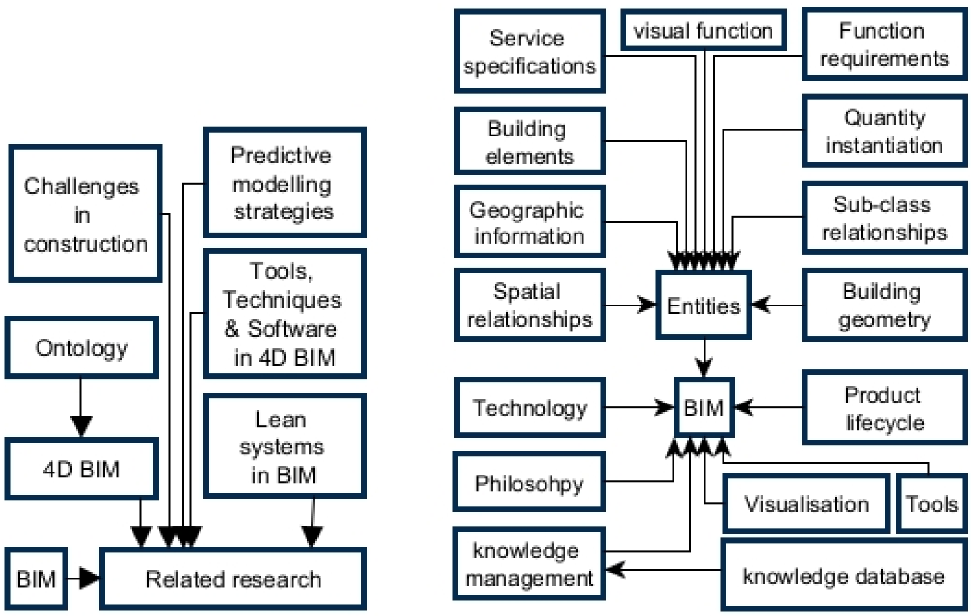
Table 4. Description and definition of building information modeling.

Context	Building Information Modeling Description	Citations
Knowledge resource	NBIMS-US defines BIM as a digital representation of physical appearance and functional capability of a built asset	[2]
Collaborative tool	BIM is a virtual system that encompasses all aspects, disciplines, and elements of a facility within a single virtual workspace allowing team members to collaborate more accurately and efficiently than using traditional processes	[1]
Content	A BIM comprises the location, geometric details, spatial relationships, quantities and properties of building components with schedules, resource availability, and cost estimates	[1]
Geographical location	In the UK, BIM is regarded more as a process than a technology or software. BIM is described as the process of designing, constructing, and operating a building or infrastructure using an object-oriented information system (The British Standards Institution, 2015)	[1,11]
Other contexts	Three-dimensional digital representation (model), coordination of design activities, supply chain management system, management method for planning, and life cycle monitoring of products	[11]

BIM is often regarded as a shift in paradigm for construction processes when it emerged in the construction information system scene as a technical support system to the digital or virtual representation of built assets. BIM maturity as can be observed in Figure 8, and it follows a functional progression. BIM started out at level one as an improvement to paper or manual drawings. Moving through to level 3 entails continuous improvement from 2D drawings with partial collaborations through 3D CAD, which allows for full collaboration of all stakeholders, including quantity surveyors, architects, structural engineers, and mechanical and electrical engineers. Now, intensified research and attention are on ensuring workability, effectiveness, and adoption of level 3 (integrated systems), which introduces time, cost, and sustainability analysis.

BIM is a tool, technology, and philosophy that offers a simulated multidimensional model that enhances quality, reduces time and cost risks, and boosts productivity [12–14]. BIM is also utilized for lifecycle support of a product, facilitating continuous use and update with relevant information throughout its lifecycle [15,16]. The BIM research domain has grown exponentially with a change from data collection to knowledge management. The BIM framework, as discussed in [17–19] contains a range of entities. The entities include building geometry, spatial relationships, geographic information, quantities and properties of building components, functional requirements, service specifications, and structured, three-dimensional data capturing the physical and dynamic functional characteristics. The framework also encompasses authorization requirements for regulating access to the structured data within BIM and to external systems and data repositories. The functional structure showcasing the associated entities and essence of BIM is depicted in Figure 9. Additionally, it includes knowledge components, maturity stages, implementation steps, and visual knowledge models.

Figure 8. BIM maturity order.



(**a**) (**b**)

Figure 9. Related research classification and functional structure: (**a**) Related research classification. (**b**) BIM: functional structure including classification as philosophy, tool and technology.

4. Related Research

In this section, results of this review are highlighted for all subtopics, including building information modeling (BIM), lean with BIM, 4D BIM, BIM ontology, challenges in construction, tool software and techniques, and finally, predictive strategies. Figure 9a displays the order for related research, and Figure 9b presents a classification of digital construction highlighting the strategies towards 4D BIM.

4.1. Digital Construction: BIM

Digital construction is a term that describes the virtual representation of the existing physical built assets and can be synonymous with building information models (BIMs) [20–22]. However, more technologies currently operating independently from BIM are sub-components of digital construction. Such supportive technologies include digital twins, clouds, blockchains, augmented and virtual reality (AR-VR), Internet of things (IoT), artificial intelligence (AI), etc. These technologies are often integrated into BIMs, with Figure 10 showing the taxonomy of digital construction. The taxonomy shows the strategies that can be employed to improve interoperability within BIM. The major aspects of the taxonomy outline various aspects of digital construction, starting with domains, which include inter-related nodes spanning fields such as design, engineering, architecture, and more [23,24]. Lean construction is divided into lean ideologies and digital lean systems, and a further expansion is given in Section 4.2. Construction management involves areas such as planning, cost, risk, logistics, and quality management [25–27]. Phases refer to project life cycles from conceptualization to decommissioning, with significant interactions with management processes [28]. BIM levels describe the increasing maturity levels of building information modeling, and further details are presented in Figure 8. Ontology, software and tools, and challenges are also included in Sections 4.4, 5 and 6. Technologies such as digital twins, robotics, and AR/VR are highlighted for their potential in construction, requiring interoperability with BIM. Lastly, predictive strategies are referred to in Section 7. Table 5 summarizes research articles, most of which employed systematic literature reviews to identify, interpret, and analyze key research topics.

In this review of BIM, as evident in Table 5, adoption and implementation studies are the most common focus in BIM research, with key enablers identified for the AEC industry [29–34]. Additional studies explore factors influencing adoption in cloud-based systems, productivity tracking, and the integration of BIM with emerging technologies such as AR, VR, and machine learning [6,35–37].

The identified limitations—modeling complexities, high data volumes, and poor data quality—underscore a significant gap in 4D BIM research, particularly given the scarcity of systematic literature reviews in this area [35,36,38,39]. This highlights the need to explore how lean systems in BIM can address these challenges.

Table 5. Existing surveys on BIM.

Citations	Review Topic	BIM Type	Application Area	Research Method	Gaps and Limitations
Mesároš et al. [38]	The fifth dimension of BIM—implementation survey	5D BIM	• Cost modeling including budget monitoring and cost analysis; perception analysis, 5D BIM software comparison and geographical implementation dispersion	survey	• Five-dimensional modeling processes face limitations, particularly due to the risk of significant financial errors and the complexities associated with managing and integrating large volumes of financial data
Abbasnejad et al. [34]	• Building information modeling (BIM) adoption and implementation enablers in AEC firms: a systematic literature review	BIM	• Identification and classification of BIM adoption and implementation enablers in AEC	SLR	• Unclear implementation guidelines leading to inability to realize BIM benefits
Zhao and Taib [35]	• Cloud-based building information modeling (cloud-BIM): systematic literature review and bibliometric-qualitative analysis	Cloud-BIM	• Cloud-BIM influencing factors.	SLR	• Unavailable research assessment on cloud-BIM; exclusion of non English, Chinese or Korean language; cloud-BIM adoption level; lack of universal standards
Bastem and Cekmis [39]	Development of historic building information modeling: a systematic literature review	HBIM	• Heritage building information modeling H-BIM aids IP protection and also facility management. HBIM is used in documentation, restoration, and preservation of heritage buildings, and enterprise BIM (E-BIM) is applied in sustainability, repair, and facility management.	SLR	• Study limitations include unreliable collected point cloud data; non-standardized point cloud data collection method; general complexity of 3D object modeling; etc.
Alankarage et al. [40]	Organizational BIM maturity models and their applications: a systematic literature review.	BIMMM (BIM maturity model)	• This study ascertains the current research status concerning BIMMMs in organizations whilst identifying the BIMMM selection factors and application areas. The research discovered that maturity models were identified based on the capability maturity model integration CMMI. The essence of this research was to ensure less confusion in maturity models and providing distinct classification	SLR	• BIM maturity level descriptor is not robust and not standardized. There is a lack of in-depth research documentation highlighting trends, frontiers using bibliometric and scientometric analyses.

Table 5. *Cont.*

Citations	Review Topic	BIM Type	Application Area	Research Method	Gaps and Limitations
Abanda et al. [41]	A literature review on BIM for cities distributed renewable and interactive energy systems.	BIM-Energy	• This study reviews the challenges posed at the integration of BIMs with DRIES (distributed renewable and interactive energy systems) with a goal of attaining net-zero-energy buildings (NZEBs).	SLR	• Studies focusing on energy system for cluster of building are scarce. Also, standard measurement and indicators in ensuring NZEBs are not yet developed
Wang and Meng [37]	Transformation from IT-based knowledge management into BIM-supported knowledge management: A literature review	BIM-KM (knowledge management)	• This study evaluates BIM features such as virtual visualization and parametric modeling. The study also provided a conceptual framework for the combination of BIM with knowledge management	SLR	• Limitations in BIM where BIM features such as parametric and object-oriented modeling, collaborative working and digital visualization is lacking support towards Knowledge management.
Zabin et al. [6]	Applications of machine learning to BIM: A systematic literature review	BIM-ML (machine learning)	• This research discussed and demonstrated how machine learning can be a tool for automating workflow and data in BIMs. The review focused on projects in the AEC industry and highlighted the gaps and future trends	SLR	• Inefficient data retrieval. BIM is currently not intuitive and insight generation require a time-consuming data process. Unreliable data, etc.

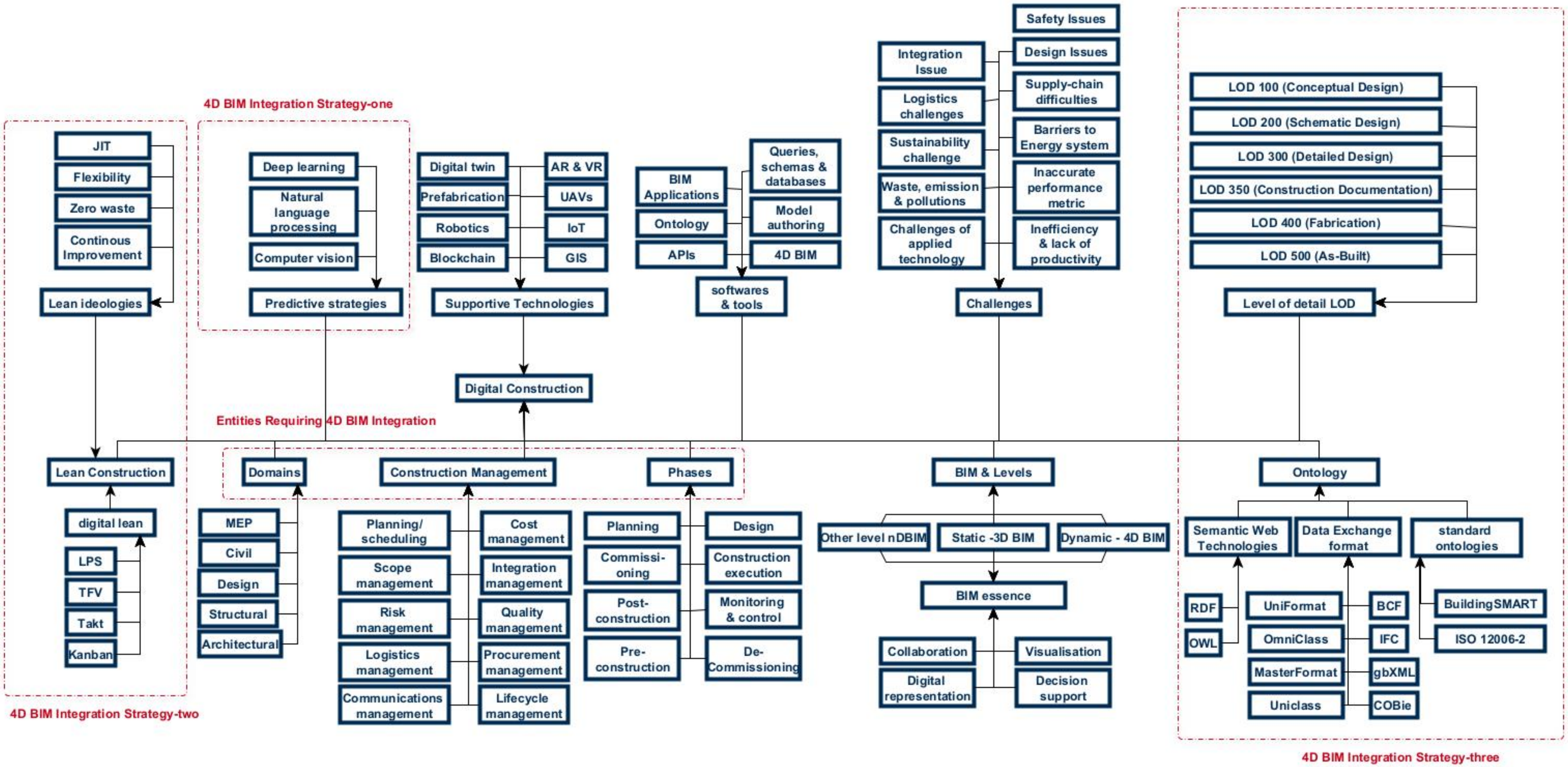


Figure 10. Towards 4D BIM: The digital construction taxonomy presents strategies towards BIM integration and highlights the domain entities requiring integration particularly towards dynamic BIM development.

4.2. Lean Systems in BIM

Lean approaches have been applied to construction using lean ideologies, which are applicable in either digital aspects of construction and during field implementation processes [42,43]. Lean ideologies are basically process improvement and waste removal methods that originated from Toyota manufacturing process ideologies, also known as Kaizen. The ideologies have been earmarked and applied in different ways with the aim of continuous improvement and development of digital lean systems [44,45]. Lean systems in construction can be categorized into two distinct groups:

1. Digital lean systems;
2. Traditional lean ideologies.

Digital lean systems include various methodologies, such as Takt, value stream mapping, and Kanban, which are applied through digital platforms. In contrast, traditional lean ideologies encompass concepts like just-in-time (JIT) and flexibility. This classification underscores the dual nature of lean systems in the BIM environment, incorporating both advanced digital tools and foundational lean principles.

The integration of lean methodologies and BIM gained significant importance as both systematic approaches evolved independently to address product, process, and organizational challenges in distinct ways. However, persistent errors, failures, and communication issues within the AEC industry highlight the need for a convergence of lean with BIM methods to provide more comprehensive solutions. Early studies in this area discussed transformation-flow-value theory as an early shift in construction practices leading to lean construction [7]. Additionally, the initial prototype of the last planner system (LPS), developed based on lean principles, addressed the limitations of the critical path method (CPM). CPM was considered inadequate for managing project variability and was often viewed as counterproductive, particularly in handling complex projects with increased variability [46]. LPS, which is a BIM-lean-based approach to planning, partially solved the problem of uncertainty preventing smooth production flow [44]. After LPS, other prototypes of construction information systems such as OurPlan, LEWIS, and KanBIM were developed [7,47].

The confluence of BIM with lean construction research focus is necessary for showcasing synergy nodes between BIM and lean construction. In discussing and analyzing their correlation, Sack et al. [48] presented 56 nodes of interactions between these two systematic approaches. The interacting nodes from a lean standpoint include just-in-time (JIT), pull management, making the process transparent to all, reduced inventory, improving quality (reducing product variability), striving for single-piece flow, visual management, etc., while interacting nodes from a BIM standpoint include collaboration, rapid design generation and object-based communication [7]. Lean techniques such as automated work package creation, resource leveling, and value planning are supported in BIM, and this allows for the placing of two different concepts ("lean system" and BIM) in tandem to each other because they both achieve the same end goal of reduced waste, cost and improved efficiency [49]. Overall, it is evident that several lean principles, such as Transformation flow value TFV, 5s, Kanban, value stream mapping, Takt, pull, etc., are all applicable in construction processes including digital construction support systems and the AEC industry as a whole. Nonetheless, the interaction between lean principles and 4D BIM, as well as 4D visualization, represents an unexplored area for further research, particularly in light of the significant benefits observed from implementing lean methodologies in second-level BIM.

4.3. 4D BIM

The fourth dimension of building information modeling (4D BIM) is the technology that integrates the time dimension into existent BIM modules, such as design, communication, planning and other management processes, domains and phases. According to research, the term 4D BIM describes the system where 3D BIMs are linked with plans or schedule-based information [5,50–53]. Four-dimensional BIM is quickly becoming noticeable because of its ability to demystify ambiguity and uncertainty in complex construction projects by providing trend analysis and goals for planning and schedule coordination, and risk-based simulations for actual versus planned visualizations, among other use cases. Researchers have discussed the vast application and benefits of 4D BIM, which include progress monitoring, risk management, scheduling, safety management, waste management planning, resource management, etc. [5,54,55]. On the other hand, many AEC operators have begun to reap the early benefits of the 4D BIM tool available in the market, the integration of the cores of design and schedules still requires further research and implementation. This section discusses 4D BIM-related research classified by their application areas (including visualization, performance, safety, progress monitoring, scheduling, decision making, and integration).

Firstly, Park and Cai [56] presented a web framework that allows for project monitoring and visualization in an automated manner, leveraging the advancements in database management technologies. The article probed and provided answers to the research question: how the 4D BIM environment can be used to monitor or capture construction project progress? The framework prototype details how information from daily reports and updates from sites is extracted for use to update and visualize progress automatically. The prototype was developed and validated under real construction project data. As an advancement, Park et al. [57] were motivated to determine effective methods to visualize and communicate plans and progress using 4D BIM, proposing a method that analyses information in an activity diagram of how the users, viewer, and database interact seamlessly to find an improved solution. The solution was based on real project case studies, bringing some credibility to the methods used. Overall, the main benefits of 4D BIM were noted as task- flow visualization, component spatial visualization, task and component timeline simulation, and improved understanding of plan [54,55].

Vtt et al. [58] researched safety management use cases for AEC site project planning. They found that integrating 4D BIM technology into the project planning phase can significantly enhance site safety. By incorporating safety considerations early on, 4D BIM facilitates clearer visualization and communication of safety measures, ensuring that these protocols are effectively conveyed and adhered to as the project progresses. However, it was mentioned that there has been no fully tested and validated case studies for this study.

Montaser and Moselhi [59] worked on a method for bringing 4D BIM technology to life. With the purpose of creating a correlation, they created a framework and software that automatically extracted group names of the building elements and attempted to map them with schedule details, including each task's dependencies. Similarly [60] highlighted the potential of AI and ontology in 4D BIM integration studies. Although the software and tools used included Visual C# .NET, Autodesk Revit, Revit API, and Microsoft Project, it was noted that documentation on 4D BIM is quite limited and needs further research and regulation to improve impacts in AEC. Moreover, while acknowledging that a prototype has been implemented, it was concluded that further development and testing are necessary, particularly to ensure its generalizability across various types. Likewise, Raut [61] also discussed how the generalizability of the findings of their 4D BIM-related research are limited to the case study in their research only.

Decision making is an integral aspect of construction project management, which requires a data-driven approach. Bolshakova et al. [62]'s research focused on developing a supportive decision-making system as a use case for 4D BIM technology. Decisions are apparent through the lifecycle of a product or project. Therefore, the research phased the possible decision in the design, pre-construction, and construction implementation phases. Some of the decision points include decisions related to 4D scheduling/planning, 4D clash detection, 4D safety management, 4D constructability management, 4D layout and environment management, and 4D project monitoring. Being a gap in the study, other decision points not mentioned in the existing research include decisions regarding the closure or continuation of projects, as well as decisions regarding earned value management to determine if benefits would still be realized regardless of the status or complexity of projects.

In terms of adoption, Gledson and Greenwood [51] attempted to determine the adoption levels of 4D BIM between awareness to first use. The findings indicate that there is an increase in adoption in the UK construction industry and that there was a lag between awareness and first use. However, in India and other developing countries, Charlesraj and Dinesh [54] highlighted that, despite the growing awareness of 4D BIM, its adoption remains low due to the high initial costs and challenges faced by clients and contractors in utilizing and adapting to 4D BIM technology. Also, quantifying the influence of the implementation of 4D BIM as a tool in construction projects is important to justify its usefulness and impact on successful or unsuccessful projects [5]. In a study by Gledson and Greenwood [51], the inability to generalize results was also noted as a limitation, as well as the need for an investigation into ways of inculcating 4D BIM in decision-making processes. Other related research studies evaluated 4D virtual design and construction (VDC) and 4D BIM's impact on construction projects [63–65].

Overall, the study that is visible in Table 6 indicates that 4D BIM uses/cases span different modes, including project monitoring, scheduling, safety management, performance, visualization, and integration, whereas the adoption of the technology is noted to be impacted by different reasons based on location. The classification of use cases shows that scheduling, visualization, and progress monitoring have the largest impact in terms of research. However, other modules within BIMs, such as safety, communication, etc., have been applied and researched sparingly. As indicated in Figure 11, the related research articles reviewed in this section have been classified as modeling, simulation, framework, case study-based works, and others. Most of the studies used a couple of these techniques in their study, while "others" contained research articles that are qualitative or utilized statistical approaches in evaluating and documenting research. A common 4D BIM limitation is the inability to generalize solutions for all types of projects regardless of the size or type of project.

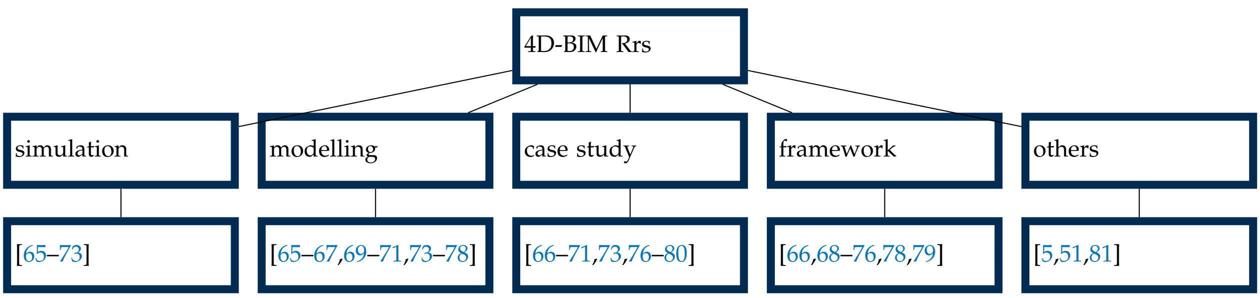


Figure 11. A visual representation of 4D BIM-related research studies (RRSs) categorized into simulation, modeling, case study, framework, and others [5,51,65–81].

Table 6. Four-dimensional BIM-related research application areas.

Citations	Field-Topic	Vis	Perf	Saf	Prom	Sch	Decm	Itgn
Charlesraj & Dinesh [54]	Status of 4D BIM Implementation in Indian Construction	x			x	x		
Umar et al. [55]	4D BIM Application in AEC Industry: Impact on Integrated Project Delivery	x			x	x		
Park & Cai [56,57]	(1) Framework of Dynamic Daily 4D BIM for Tracking (2) Database-Supported and Web-Based Visualization for Daily 4D BIM	x			x	x		
Vtt [58]	4D-BIM for Construction Safety Planning			x		x		
Montaser & Moselhi [59]	Methodology for Automated Generation of 4D-BIM							x
Raut [61]	Improve the Productivity of Building Project using BIM Based 4D Simulation Model					x		
Doukari et al. [60]	The Creation of Construction Schedules in 4D BIM: A Comparison of Conventional and Automated Approaches							x
Bolshakova et al. [62]	Identification of relevant project documents to 4D BIM uses for a synchronous collaborative decision support			x	x	x	x	
Crowther & Ajayi [5]	Impacts of 4D BIM on construction project performance		x		x	x		
Salman & Hamade [63]	The Integration of Virtual Design and Construction (VDC) With the Fourth Dimension of Building Information Modeling					x		
Harris et al. [64]	4D Building Information Modeling and Field Operations: An Exploratory Study	x				x		
Martins et al. [65]	Evaluation of 4D BIM tools applicability in construction planning efficiency						x	x

x: includes, blank: does not include; Vis: visualization; Perf: performance; Saf: safety; Prom: progress monitoring; Sch: scheduling or planning; Decm: decision making; Itgn: integration.

4.4. BIM Ontology

Ontology is regarded as a knowledge representation of class entities with attributes and relationships used for data integration frameworks [82]. It is a system of representing "globals", defined as classes and the inter-relations between and among them by defining the terms, axioms, rules, and constraints. Basic formal ontology BFO which is the industry standard (ISO/IEC 21838-2) [83] is popularly used in many domains as the backbone of the ontological structure [82]. Also, resource description framework (RDF) and web ontology language (OWL) are the main semantic ontology languages developed; other classification systems include Uniclass, MasterFormat, OmniClass, and UniFormat. Existing AEC-related ontologies include the Information reference model for AEC (IRMA), building project model (BPM), construction operation building information exchange (COBie), industry foundation class (IFC), BIM collaboration format (BCF), and green building XML schema (gbXML). Widely accepted standard ontology languages include ISO 12006-2 [84] and BuildingSMART. The process of developing ontology was presented by Zheng et al. [85], where they amalgamated two (2) existing processes for developing an ontology for varying scopes and purposes. The process includes [85] the following steps: (1) identify the purpose and scope; (2) specify requirements; (3) review existing models, data, and sources; (4) define and order entities and attributes by hierarchy; (5) develop the ontology using development tools; (6) integrate terms, entities, attributes, and relationships (7) review existing ontology; and (8) evaluate constructed ontology. Overall, this process adheres to a systematic approach that involves the specification, conceptualization, acquisition of knowledge, implementation, and evaluation. Also, the techniques used in implementing new ontology can include expert workshops, criteria- and task-based evaluations, and automated systems, which can, in turn, be evaluated based on clarity, usability, coverage, consistency, and extensibility [85].

BIM Ontology-Related Research

Current BIM-related ontologies can be categorized based on the domain or process in which they are applied. Although a review study in this area by Pauwels [86] exists within subdomain ontologies, such as environmental ontology, maintenance ontology, skill ontology, digital construction ontology, etc., continuous digital developments increase the amount of unexplored ontology areas giving reasons for additional reviews that can be carried out to expose further gaps in ontology research. Other related 4D BIM ontology analyses expand more on logistics and 4D collaboration ontology, which outlines the collaborative and communication enhancement aspects of 4D BIM [87–90]. The processes' and domains' categorization with existing ontology research or applications include maintenance, risk management, quality, resource planning, communication, cost management, design, knowledge management, integration, monitoring and compliance.

In maintenance-related ontology research, Gourabpasi and Bakht [8], when diagnosing faults in heating, ventilation, and air conditioning (HVAC) systems, developed an ontology termed AFFDonto, which was developed for the integration of BIM with maintenance parameters and insights from machine learning. This ontology is aimed at automated fault detection diagnostics. The developed ontology, which integrates BIM with BAS (building automation system), is determined to monitor workflows and changes, visualizations, and serve as a digital twin [8]. Another research article noted that the duo of BIM and semantic web technologies (SWT) could help to integrate systems and products throughout their lifecycles. The article was driven by the identified gap in the lack of a general systems' theory for the SWT representations of HVAC systems. To address this, the TUBES System ontology (TSO) was developed [91].

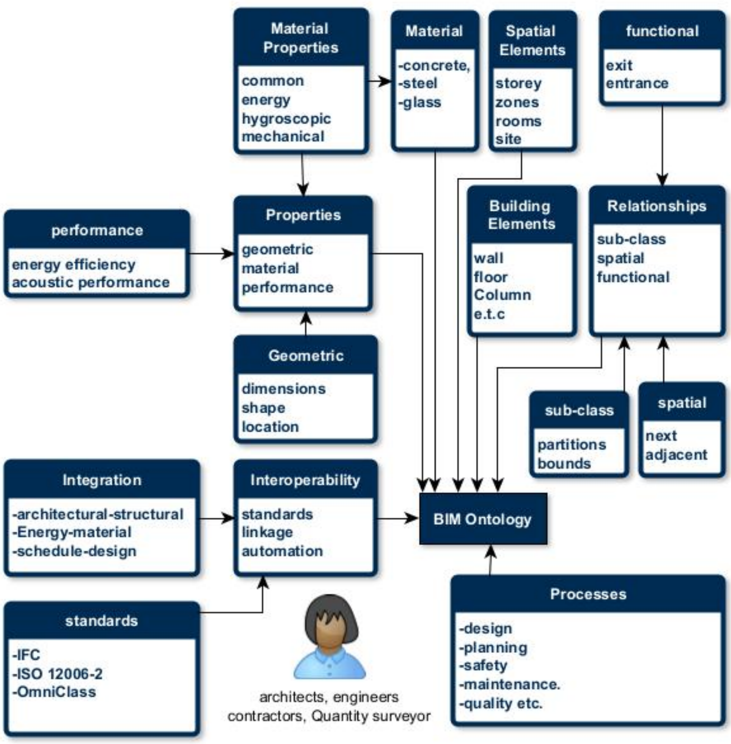
Unique ontologies are also being developed for the safety applications of regulations in process areas with BIM. Dam safety monitoring systems (DSMSs) are vital in determining dam operation performance. A study proposed OntoDSMS, which collects a knowledge base from dam information models and BIM using rule-based reasoner and SPARQQL queries. The study was able to attain integration for the DSMS, although it was limited by the not including geometrical attributes [92]. Also, the visual data available in BIM present a rich context for determining construction risks. Another research study created an ontology framework for linking the safety knowledge base with specific BIM objects semantically using OWL and semantic web rule language (SWRL) rules to present a risk map [93].

Most quality management systems are normally processed in silos away from the processes or procedures themselves, and because the records are mostly in an unstructured format, a study sought to merge heterogeneous data in defect management data with BIM information. The study arrived at the development of defect ontology, which is a product that extracts BIM data in an RDF format merged with stemming data from the defect management domain using SPARQL queries [94,95].

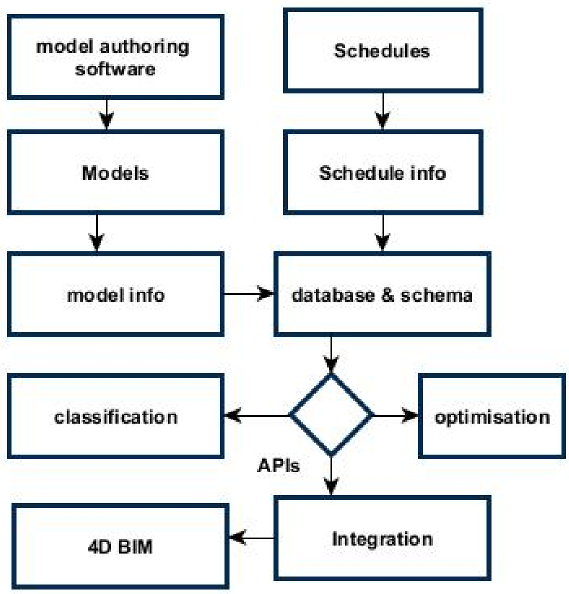
Some specific resource and planning frameworks have been introduced in the literature. A resource planning framework for the ontological representation of the knowledge base used semantic reasoning techniques for drawing insights and supporting collaborative data-driven decisions [96,97]. Other research efforts focused on ontological databases for enabling value for money (VFM) in supporting public projects. VFM ontology integrates project and finance management semantics, develops a data exchange policy process map, and facilitates term mapping and model instantiation for entity representation, though heterogeneity remains a key challenge for construction workflow integration [98,99]. Another research study presents an ontology system for integrating CW data. The CW ontology developed included six modules using the BFO concept, and they included entities, processes, information, agents, variables, and contexts [85].

Other existing ontology studies on integration include design, scheduling and procurement data integration ontology called BIMSO; Geographic information system (GIS) and BIM integration ontology called UIM (urban information modeling); BIM and sensor network integration ontology; and integration ontology for BIM-GIS-IoT [100–104]. Ontology built for automation existing in research includes building code compliance-checking system ontology, a visual layer and application layer with material estimate ontology called BIM-R, and communication/collaboration ontology [105–107]. The related research studies highlight existing process applications of ontology themes, and Table 7 showcases studies that match specific ontology categories with identified processes.

Overall, a BIM ontology will usually include entities, as given in Figure 12a. The figure, albeit on a high level, shows how the entities, relationships, and configuration systems interrelate. Major entities in any given BIM ontology will include properties (material, geometric, and performance), relationships (spatial, subclass, functional), building elements, spatial elements, and integration, enabling interoperability through multiple BIM modules. It was discovered that processes such as quality management, facility management, and planning usually have parameters and attributes existing in basic structured formats, like XML. This results in heterogeneity when mapping these processes to other domains, such as BIM. Additionally, while certain areas and subdomains within the AEC industry—such as GIS, safety, quality, planning, and time management—have been developed independently, it is important to note that many integrated or linked ontologies, such as safety-schedule-BIM ontologies or schedule-BIM ontologies, remain underdeveloped.



(a)



(b)

Figure 12. (**a**) High-level BIM ontology. (**b**) Step flow for 4D BIM integration.

Table 7. Construction process application of ontology themes.

Processes	Citations	Krs	Std	Sch	Infr
Communication	Kwofie et al. [108]				x
Cost management	Lee et al. [97]; Ren et al. [98]	x		x	x
Design	Ma and Liu [106]	x	x	x	x
Integration	Tchouanguem et al. [82]; Shi et al. [103]	x	x	x	x
Knowledge management	Lee and Jeong [107]; Niknam and Karshenas [100]; Zhou et al. [92]	x		x	x
Maintenance	Mignard and Nicolle [101]; Hosseini Gourabpasi and Nik-Bakht [8]; Pauen et al. [91]	x	x		x
Monitoring and compliance	Zhong et al. [102]; Jiang et al. [105]	x	x	x	x
Planning	Tavakolan et al. [96]; Zheng et al. [85]	x			x
Quality management	Park et al. [95]; Lee et al. [94]			x	x
Quantity (multiplicity)	Liu et al. [99]	x		x	
Risk management	Ding et al. [93]	x			

Krs: knowledge representation semantics, Std: standard ontology applied, Sch: schema applied, Infr: information retrieval.

5. Challenges in Construction

The construction industry, as one of the most vital sectors globally, faces numerous challenges that are commonly encountered by organizations operating within the sector across various regions [33,109]. Broadly, a construction project commonly experiences one or more combinations of issues, such as cost overruns, delays, increased defects, constant need for rework, health and safety issues, and production inefficiency [3,4,110]. As shown in Figure 13, these issues also contribute to more detrimental challenges, including profit losses, unending legal suits, unreliable built assets, loss of business, etc. The rapid urbanization and increase in the need for complex mega projects fuels the spiraling uncertainty and unpredictability, leading to the previously raised challenges. Effective management and planning are often seen as the solution to these challenges. Construction field situations limit managers from proper deliberation, analysis, and planning. Thus, they are constrained to depend on instincts, experience, and tacit knowledge in making decisions, leading to previously raised challenges.

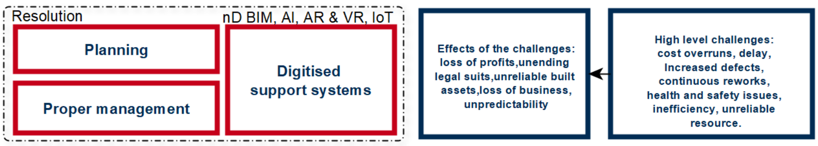


Figure 13. High-level challenges, effects and solutions [3,4,110,111].

While experienced and great managers are important to the success of some projects, technological insights and support are increasingly needed to ensure the success of highly complex mega projects. The utilization of technology has been proposed as a potential solution to the challenges confronting the AEC industry, although many of the technologies are reported to be riddled with more challenges [29]. The prospects of the fourth industrial revolution, which is expected to support existing information system infrastructure with an integrated internet-enabled cyber-physical system in a network-like fashion, indicate potential resolutions regarding the generation of insights and support for construction projects in real time. Despite these prospects, construction is reported to be behind in digitization efforts across the board and different regions of the world when compared to other sectors, such as manufacturing, finance, etc. [112]. Construction adoption of technology in the UK is increasing due to policies and incentives put in place to ensure the adoption of technology, such as 3D BIM, but it is met with even more challenges that then do not motivate all-around acceptance of technological support to construction processes. Dave [111] elaborated on the shortcomings experienced in each phase and stage of construction projects, especially touching information and communication systems. Figure 14 shows the identified challenges in a categorized cause-and-effect pattern. These challenges are highly inter-related and causal to overall issues of cost overruns, delay, defect, safety, and sustainability across the different phases and processes.

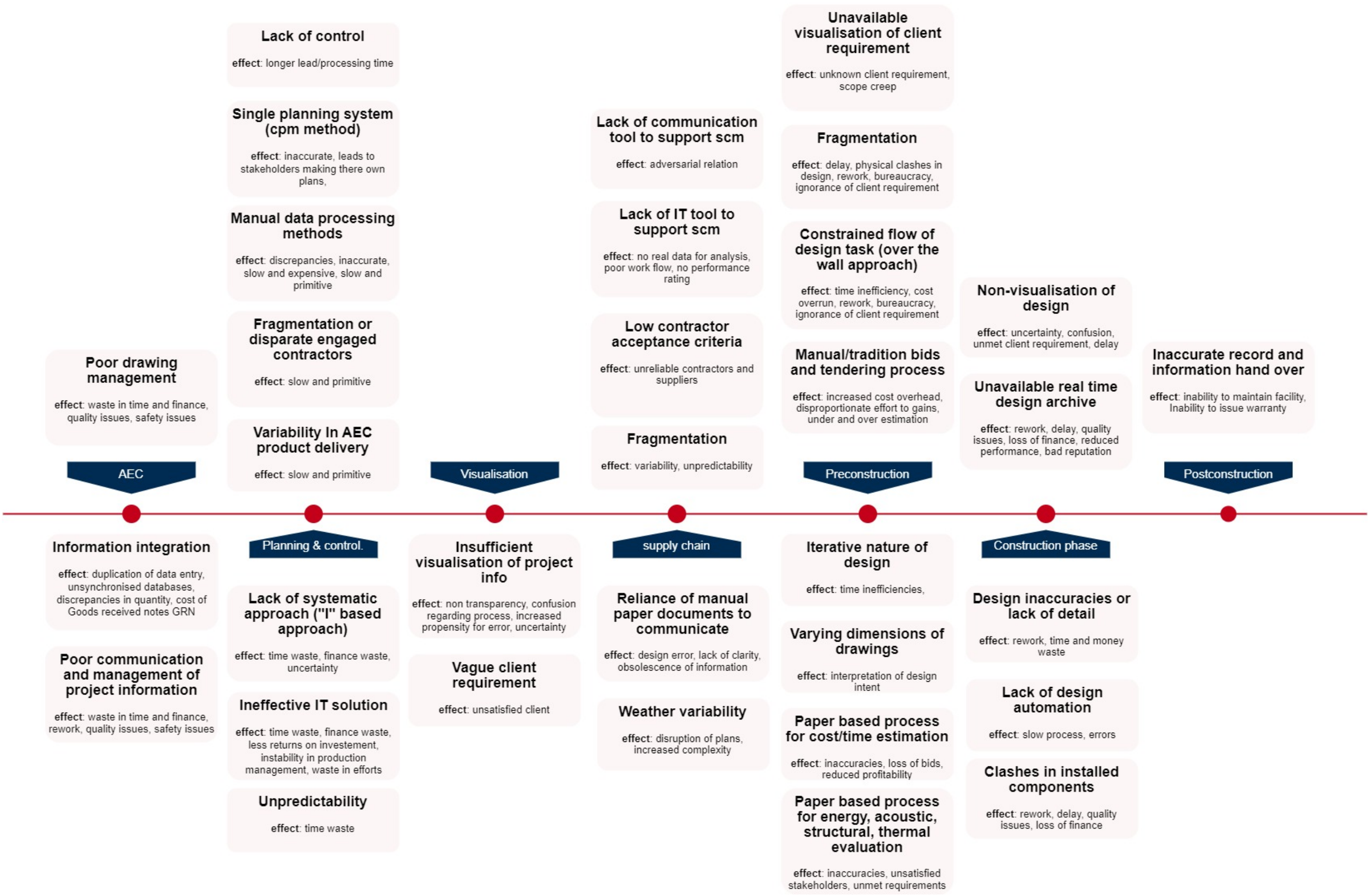


Figure 14. Granular challenges in AEC phase stages [111].

The challenges faced by digital construction and new technologies in the AEC industry are enormous [1,33,113–115]. As detailed in Table 8, these challenges also span different phases and stages within the AEC industry. The highlighted challenges, as discovered in the literature, are coined from operational circumstances. For instance, in construction projects, projects are oftentimes fast-tracked to meet specified contract objectives and avoid delay. However, this leads to digital barriers, such as uncoordinated operations, incomplete design documents, unending design developments, and continuous changes in scope, etc. [1]. Saka et al. [116] also identified barriers in digital communication in the AEC industry. These barriers include those relating to privacy, security, ethics, and data quality. Overall, the review identifies the challenges existing in the literature that affect the construction industry.

Table 8. Digital issues in construction phase stages.

Phase/Stage	Related Digital Challenges	Citations
General AEC	• Interoperability in existing software uses across regions, companies, and projects; • Data ownership; • BIM adoption across board; • Unavailable integration support; • Security; • Communication and information exchange issues; • Cost of training; • General unawareness of BIM/CAD models; • Challenges in automated communication systems in AEC include development and data barriers, cultural barriers, ethics, privacy and security, scalability and expertise.	[1,33,113,114,116]
Digital construction	• Collaboration-based cloud computing security system; • information sharing boundaries; • Trust and prevention.	[117]
Planning and control	Fast-tracked project issues include • Incomplete designs and documents; • Uncoordinated events; • Unending design development; • Frequent scope changes.	[1]
Visualization	• Inadequate expertise; • Initial cost of digital technology; • Complexities of 3D systems.	[9]
Supply chain	• Unstructured path to procurement; • No flexibility in projects; • High cost of digital technologies; • Rarity of materials.	[118]
Pre-construction	• Irregular geometry; • Interoperability between XML-based software and traditional model authoring software like Revit; • Spatial incompatibility; • Process integration; • Multidisciplinary design; • Non-automation of processes.	[119,120]
Construction phase	• Design-related errors; • Incorrect performance metrics; • Non-automated decision support using project data.	[121]
Post-construction	• Data quality; • Data ownership.	[115]

6. Tools, Techniques and Software in 4D BIM

A review of software used in 4D BIM research indicates common tools, techniques, and software utilized in evaluating, analyzing, and computing within the AEC industry. To achieve the seamless integration of 3D model elements with schedule information, a workflow is established for retrieving information from both models and schedules. Application programming interfaces (APIs) enable efficient data retrieval from both models and schedules, supporting the synchronization of scheduling information. The information obtained through APIs can then be leveraged for tasks such as optimization, classification, and various predictive modeling applications. A view of the order of this flow is indicated in Figure 12b.

Table 9 shows the classification and list of model authoring software, 4D BIMs, scanners, schedule software, API, databases, and classifiers used in studies related to 4D BIM.

Autodesk Revit is a common industry standard tool in businesses and in research. Autodesk Naviswork and Syncro Pro are the major 4D BIM implementation tools that have 3D models with timelines or durations received from schedules. Studies has used a combination of different techniques to resolve the integration of data in 4D BIM [71,73,122]. A classification of the tools, techniques, software, methods, file types, and integration technique is shown in Figure 15, and a description of each item in the classification is discussed in Section 6.1.

Table 9. Software and tool classification used in 4D BIM-related studies.

Classification	Software/Tools	Citations
Model authoring software	Revit, Bentley MicroStation, Tekla, Solibri Model Checker, ArchiCAD	[65–67,69,73,75,122–124]
4D BIM software	Synchro Pro, Naviswork, Fuzor	[65–67,75,77,123–126]
Modeling and Design	Autodesk Maya, Autodesk 3ds, Blender SketchUp, McNeel Rhinoceros (Rhino)	[65,66,73,75,125]
Scanners (data capturing)	Faro Focus, Recap	[66,122]
Schedulers	Microsoft project, primavera p6, Excel	[65,67,68,71,75,77,123,124,126]
API	Autodesk Forge, Trimble Connect, Dynamo, Revit API, BIM 360 API, COMSOL API	[65,66,68,69,73,124]
Databases	ODBC, structured query languages SQL, schemas	[66,122]
Classifiers and Algorithms	RANSAC, NSGA-II algorithm, multiobjective optimization using GA	[68,71,76,122,123]

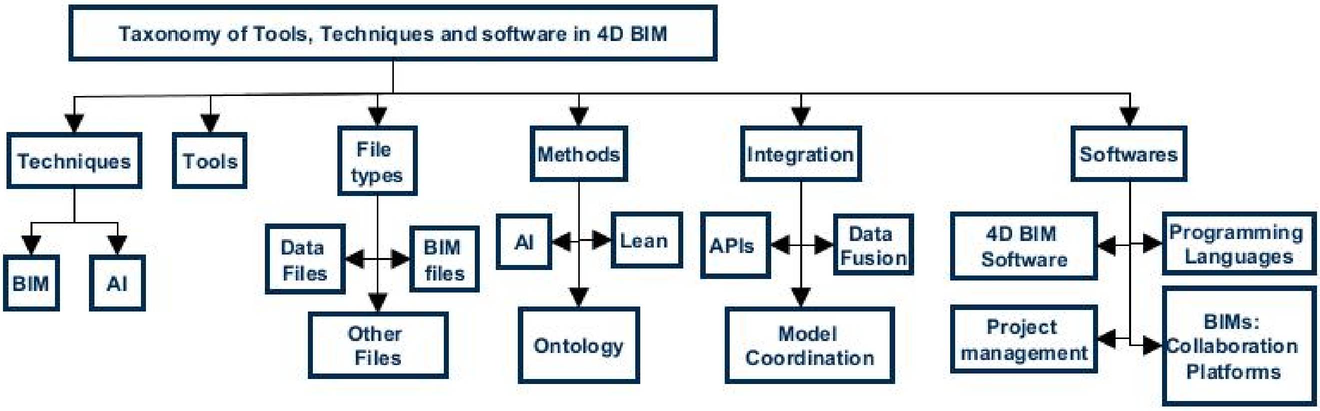


Figure 15. Tools' and techniques' taxonomy in 4D BIM.

6.1. Classification of Instruments in 4D BIM

This section provides a description of 4D BIM instruments within this study. The classifications examined include tools, techniques, software, integration methods, and file types pertinent to this field of research, with a further elaboration on their applications and relevance.

6.1.1. Tools

These are objects that deliver the ability of a user to modify features of work environments and help complete tasks. Digital construction tools include 3D scanners, workstations, VR/AR devices, sensors, cameras, barcode scanners, etc.

6.1.2. Techniques

Techniques indicate the systematic procedure for carrying out digital tasks. Different techniques exist for planning and scheduling, such as the last planner system, Takt, location-based scheduling, simulation, and visualization, such as clash detection and other analysis, quantification and estimation techniques, etc. Also, artificial intelligence techniques such as deep learning (DL), machine learning (ML), natural language processing (NLP), and computer vision (CV) are categorized here.

6.1.3. Software

These are digital programs that perform tasks or serve as a system where tasks can be performed. Existing software in the construction industry is classified as 4D BIM (Naviswork, SynchroPro, Bentley ProjectWise, Tekla structures, Vico office), 3D BIM collaborative tools (Visilean, PlanGrid, procore, BIM 360), programming languages (R, Matlab, python), planning/scheduling (Microsoft projects, Primavera p6), model authoring software (Revit, Tekla, Bentley), etc.

6.1.4. Integration

Digital model coordination is important in all phases, domains, and management processes, and data fusion tools such as databases, schema, and reports (SPARQL) are required. Application programming interfaces (APIs) allow for the data extraction and modification of elements and relationships in model authoring software (e.g., Dynamo, SynchroPro API, Naviswork API, BIM360 API, Forge).

6.1.5. Methods

In this study, methods can be viewed as strategies that are used to improve existing tools and techniques such as lean systems such as JIT, LPS, Kanban, 5S, etc., ontology and ontology tools (RDF-Resource description framework, OWL-Ontology web language, protege), and AI methods such as neural networks, supervised and unsupervised learning, and reinforced learning.

6.1.6. File Types

This is the structure or format housing data. File types include BIM files such as RVT (Revit), IFC (Industry foundation classes), artificial intelligence data files such as (CSV (comma-separated values), JSON (JavaScript object notation), HDF5 (Hierarchical data format), etc.

7. Predictive Modeling Strategies

The application of predictive modeling strategies is now more prevalent than ever before [127,128]. This is the case as data are growing at unprecedented rates, and projects are constantly becoming more challenging and complex [129]. Predictive modeling has now found a use in more phases in construction, from idea conception through design, implementation, commissioning of built assets, sustainability, demolition, and consequent lifecycle of the product. Insights on processes, projects, and products are increasingly demanded by managers and stakeholders in real time to cater to the growing uncertainties and unpredictability that arise from large, complicated, and complex construction projects. Predictive modeling strategies are artificial intelligence techniques classified as computer vision (CV), natural language processing (NLP), general machine learning (ML), and other subdomain techniques. The subsequent section categorizes the relevant research articles based on the AI techniques and algorithms employed at different stages or nodes within construction processes, projects, or products.

7.1. Computer Vision

Computer vision is the branch of AI that allows recognition, detection, classification, tracking, and segmentation of objects in images or videos. This strategy is applicable in different processes and project stages, such as safety, project planning and control, logistics, material management, quality management, waste management, project documents, etc. Kulinan et al. [130]'s study, which offers a framework for workforce safety monitoring, identifies that the potential for integration between computer vision and BIM platforms is lacking or unexplored and offers a linkage by monitoring onsite activities through installed CCTV cameras as data sources and a relational database management system (RDBMS) for linking data and BIM platforms for visualization. Likewise, Yan et al. [131] synthesized images of a set of data on safety systems, materials, logistics, and machine objects and used deep learning-based instant segmentation for automating process tasks.

Another aspect where prediction strategies have been utilized includes progress monitoring for project planning and control duties. A study by Wei et al. [132] investigated the tracking of foundation activities on a construction site. Similarly, a study by Yang et al. [133] presented a framework for action recognition of work activities such as laybrick, transporting, cutplate, drilling, tie-rebar, nailing, plastering, shoveling, bolting welding, and sawing [134]. Behnam et al. [135] also reviewed activity-tracking-related articles drawing and inspecting limitations of the technique. Quality management systems in the construction domain have utilized predictive strategies in the detection of cracks and defects in built assets. Tan et al. [136] presented a framework comprising BIM and AR devices for detecting crack defects in built assets for quality management and automated inspection processes. In other processes, such as waste and process documentation, Lu et al. [137] created, pre-processed, and annotated their own dataset to which DL techniques were applied for waste material composition recognition tasks, while Lucio and Jiawe [138]'s research systematically classified tasks for separating construction documents.

7.2. Natural Language Processing

Natural language processing (NLP) is a branch of AI that enables the interpretation, comprehension, and generation of human language by computers in a manner that is meaningful and useful. NLP has been applied to digital construction in different forms, such as large project document text summarization, communication text reasoning, scheduling and activity listing, sequencing, design, safety quality, and even in lifecycle assessments (LCAs). In construction project communication processing, Ding et al. [139] and Jung and Lee [140] researched text reasoning and text classification, respectively. Ding et al. [139]'s study attempts to process human language used in construction modes of communication, such as word documents, excel files, emails, extensible markup language (XML), portable document format (PDF), computer-aided design (CAD), etc. However, the study stated that data sources were not available and that researchers did not offer datasets as open source. Consequently, the study only used data from published articles in the review.

In schedule management, Singh et al. [141] presented an overview of the prospects and the potential NLP's use for automating construction scheduling. Kim et al. [142] also completed a study that indicated how predictive strategies can be applied in the following areas: design (bid and tendering, error analysis, changes analysis), supply chain, and maintenance. In the safety domain, growing complexities in construction inspired an automatic safety identification and mitigation mechanism using NLP and ontology science [142]. Also, in quality management in construction, Shooshtarian et al. [143] attempted to identify the causes of building defects by analyzing court proceeding texts that dealt with building-related issues using NLP techniques. Finally, Forth et al. [144] considered the lifecycle assessment of built assets, with their study linking data from BIM with LCA databases to automate the manual processes of drawing information to enrich processes in both LCA and BIM.

7.3. General Machine Learning

Machine learning techniques are being increasingly applied to more processes within the construction sphere. Zabin et al. [6] noticed that ML applications to BIM and construction are still in the initial stage. Their study reviewed commonly utilized areas, such as schedule creation, performance monitoring, cost estimation, risk identification, knowledge-based BIM systems, energy management systems, localization, and maintenance prediction. McArthur et al. [145] focused on the maintenance and facility management domain, on which they used ML algorithms to predict work order sub-categories for unstructured work orders. Tixier et al. [146] and Lee et al. [147] were motivated to determine safety assessments during the event of an accident. They used a ML algorithm to analyze safety systems to mitigate accidents and remove hazards. In the risk domain, PourRahimian et al. [148] introduced a proof-of-concept framework for the simulation of construction project risk monitoring in a game-like manner using machine-learning-based classifiers. Also, in applying predictive strategies in lifecycle safety analysis, quality, and the performance monitoring domain, Mirzaei et al. [149]'s review analyzed the process of achieving quality, productivity, and safety improvements using processed point cloud information.

7.4. Summary of Predictive Modeling Strategies

The predictive strategies used in this research utilized different types of base algorithms. From Table 10, it was noted that different variants of DL architectures and models (such as convolution neural networks (CNNs), Mask R-CNN, Cascade Mask R-CNN, You Only Look Once Version 8m (YOLOv8m), Segmenting Objects by Locations Version 2 (SOLOv2), PointRend, You Only Look at cCefficients (Yolact&DeepLabv3+), YOLOv5 + DeepSORT (Simple Online and Real-time Tracking with a Deep Association Metric), Graph Convolutional Neural Networks (GCNs), Fully Convolutional Networks (FCNs), Multiview Convolutional Neural Networks (MVCNNs), Dynamic Graph CNNs (DGCNNs), and Recurrent Neural Networks (RNNs)) have mostly been applied in CV and general ML-related applications, while Transformer models such as bidirectional encoder representations from transformers-BERT, generative pretrained transformer-GPT, KeyBERT, BERT-Base, robustly optimized BERT-RoBERTa-Base and other variants have been touted as next-level for NLP applications. It is also noted that region-based CNNs, Fast R-CNNs, Mask R-CNNs, Cascade Mask R-CNNs, and many other variants have been used in tracking and classifying objects, with which their localization or position within the search space is a feature [131,132]. From Table 10, support vector machines (SVMs) happen to be the most commonly applied supervised learning algorithm in this domain of research and [138] in their over two-decade-old publication, which used shallow learning algorithms encompassing naïve Bayes, decision trees, k-nearest neighbors (KNN), random forest (RF), multiple linear regression for project document classification. Overall, this review indicates that DL algorithms and transformer models will be highly resourceful in generalizing and recording high accuracy during training and testing operations of an ML, CV, or NLP data syntheses and evaluations. On the other hand, in applications where localization is important, region-based neural network should be considered.

Table 10. Prediction strategies.

Technique Domain	Technique	AEC Domain/Processes	Citations
Computer vision	Stochastic gradient descent (SGD), YOLOv8m	Safety (workforce safety monitoring)	Kulinan et al. [130]
	SOLOv2, PointRend, Yolact, Cascade Mask R-CNN, Mask R-CNN	Status (Progress Monitoring)	Wei et al. [132]
	Mask R-CNN, Cascade Mask R-CNN, CNN	Logistics, Safety, material	Yan et al. [131]
	YOLOv5 + DeepSORT	Quality (crack defects detection for inspection)	Tan et al. [136]
	DeepLabv3+	Waste (construction waste)	Lu et al. [137]
	Review study; ANN, SVM, CNN, etc.	Performance monitoring: equipment and worker activity recognition	Behnam et al. [135]
	Support Vector Machines—SVMs; Histograms of Oriented Gradients—HOGs; Histograms of Optical Flow—HOFs; Motion Boundary Histogram—MBH	Action recognition	Yang et al. [133]
	SVM, Naı¨ve Bayes, decision trees, k-nearest neighbors, regression, neural networks, boosting algorithms	Document classification	H et al. [138]
Natural Language Processing	Systematic scientometric analysis; BERT, GPT, Neural networks	Communication: Text reasoning	Y. Ding et al. [139]
	Overview paper; Long Short-Term Memory Recurrent Neural Network LSTM-RNN, Graph Convolutional Neural Network (GCN), Transformer machine learning model	Schedule management	Singh et al. [141]
	Support vector machine (SVM) , latent semantic analysis (LSA) and latent Dirichlet allocation (LDA)	Text classification	Jung & Lee 2019 [140]
	SVM, SVO tagging, PRINCO (Principal Component Analysis) and Random Forest	Design (Bid and tendering, error analysis, changes analysis), Supply chain, Maintenance	Kim et al. [142]
	Ontology, Text summarization	Safety	Kim et al. [142]
	Review paper, BERT, GPT, LSA, LDA, Word2Vec and its variants (e.g., Sentence2Vec, Doc2Vec), GloVe, and FastText	Construction	Chung et al. [150]
	KeyBERT algorithm, BERT-Base, RoBERTa-Base, and fastText	Quality (building defect analysis)	Shooshtarian et al. [143]
	GermaNet, SpaCy, or BERT.	Design, Sustainability (GHG)	Forth et al. [144]
Machine Learning	Review paper, ML, RDF, ANN, SVM, CONVNETS, GA, DT	Schedule creation, performance monitoring, cost estimation, risk identification, knowledge-based bim system, energy management system, localization, maintenance prediction	Zabin et al. [6]
	Random forest classifier, decision trees, frequent item set analysis 'FIA'	Facility management	McArthur et al. [145]
	Random Forest (RF) and Stochastic Gradient Tree Boosting (SGTB),	Safety (injury prediction)	Tixier et al. [146]
	CNN, SVM, RF	Risk monitoring	PourRahimian et al. [148]
	SVM, KNN, RF. Ensemble techniques, CNN, FCN, WNN, DGCNN, RNN, MVCNN, RANSAC, PCA	Lifecycle safety analysis, quality, performance monitoring	Mirzaei et al. [149]
	Multiple linear regression, multi-layer perceptron (MLR)	Design (implication of design changes)	Abdulfattah et al. [151]

7.5. Evaluation Methods

In terms of evaluation, accuracy is commonly used metric in classification tasks to assess deep learning (DL) algorithms' ability to generalize effectively across specific datasets. However, accuracy as a metric may be insufficient in datasets with class imbalances, necessitating the use of alternative metrics, such as the F1 score, precision, and recall. These metrics provide a more nuanced evaluation of model performance by addressing issues related to class distributions. As seen in Table 11, accuracy is used across different types of predictive strategies. However, mean average precision (mAP) is mostly used for CV tasks, such as object recognition. Other ML tasks use precision, F1 score, and accuracy in determining performance and comparing with other existing studies. Table 11 presents the advancements and current progress in applying predictive modeling techniques across diverse datasets within the construction domain. The evaluations included in Table 11 are not intended for a direct comparison; rather, they serve to assess the progress in implementing predictive strategies. This approach is necessary due to the varied datasets and distinct subdomains represented in each referenced study.

In related works, Rogage and Doukari [152] used models from open source national BIM library NBL for training, while datasets of models with disparate origins were used for the testing and classification of components in models created for actual projects. The research highlighted 3D deep learning algorithms, such as PVCNN, as having potential for superior performance, along with other algorithms listed on the Princeton modelnet leaderboard. Several models from the Princeton modelnet leaderboard were used in the analysis of applications of geometrically oriented DL algorithms, which classify different components in the large open source dataset [153–158]. The evaluation of these models mostly considered accuracy [153–156], while others used mAP as a metric for evaluation purposes, and some causal papers from the 'leaderboard' used precision–recall curves in their evaluations [157]. Other related works and their evaluation techniques discussed applications in object recognition, productivity prediction, integration, and classification tasks [70,130,140,159].

Overall, it is evident that the evaluation of DL techniques on different datasets and varying technique domains requires specific and strategic evaluation methods. For instance, mAP is mostly used in evaluating CV tasks, and accuracy is wildly used in all domains. Precision–recall curves, which show the trade-offs between precision and recall in a classification task, are also standards for the comparison of performances of different algorithms or models. ML tasks often use accuracy, precision, and F1 score in evaluating how well a model performs. They are used along with the mean squared error (MSE) and mean absolute error (MAE) to analyze the data with regard to where the model performs suboptimally. Figure 16 shows the prediction strategy pathway from data sources through data types, with different learning algorithms being used for various tasks and evaluated using analyzed methods.

Table 11. Predictive strategies used in existing research with performance results.

Ref	Domain	Prediction Strategy	Cm	mAP	PR Curve	Acc %	Precision %	Recall %	F1 Score %
[152]	CV–CAD object classification	convolutional deep belief network (CDBN)	no	-	no	-	42–62	-	-
[130]	CV–worker/ safety object classification	YOLOv8m	no	92.3	yes	-	88.3	89.3	-
[70]	ML-work productivity prediction	MLP (adam), Histogram based gradient boosting, stacking MLP SGD,	yes	-	no	86.2, 93.8, 90.8	86.2, 93.9, 91.1	86.2, 93.8, 90.8	86.2, 93.85, 90.95
[159]	CV-progress monitoring	Mask R-CNN	no	92.6	yes	-	-	-	-
[140]	NLP case study classification	LSA, LDA, SVM					100	27	41.82
[157]	CV-Princeton modelnet leaderboard-volumetric/ geometric classification	Convolutional Deep Belief Network	yes	68.26	yes	83.54	-	-	-
[155]	CV-volumetric/geometric classification	LP-3DCNN	no	-	no	94.4	-	-	-
[154]	CV-Multiview recognition	pairwise	no	-	no	0.907	-	-	-
[156]	CV-Varied orientation recognition	Orions	no	-	yes	89.7	-	-	-
[153]	CV-Voxel-based representation for object recognition	VRN ensemble	no	-	no	97.14	-	-	-

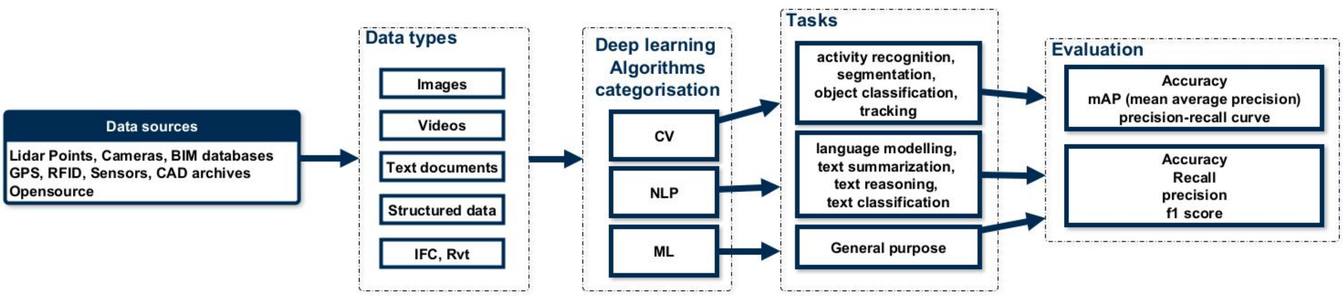


Figure 16. Predictive strategies flow (from data acquisition (sources) to evaluation methodologies).

8. Discussion

This survey presents the results of a review of the literature regarding the tools, strategies, and challenges in moving toward 4D BIM. This study illustrates the process of data collection and analysis, highlighting the journals with the highest number of published articles and identifying the regions with the most significant volume of research in this field.

Additionally, this work provides an in-depth discussion of research contexts (building information models, lean systems, ontology frameworks, predictive strategies, and tools, software and techniques) whilst integrating and synthesizing key ideas from the existing literature. Research in 4D BIM has been steadily expanding, with various researchers focusing on the analysis of its impact on key operational areas, such as performance measurement, safety, operations and management, design processes, and lifecycle assessments. Similarly, the application of lean methodologies, ontology, and artificial intelligence within this field has gained increasing attention from researchers, leading to diverse reviews that spur further development and implementation. This review study synthesizes existing research to determine the status quo and understand the prospects of 4D BIM in construction. The outcome indicates the gaps and limitations that exist in the literature whilst detailing the method of research; step flow procedure for the integration of 4D BIM; tools' and techniques' classifications that indicate standards, file types, etc.; and predictive strategies presenting its classification and evaluation methods. The context in this research is derived from research questions mentioned in Section 2.1, with the following comprising the discussed answers to the research questions asked in this study:

8.1. RQ 1: What Are the Existing Limitations in BIM?

BIM is noted as a major digital construction tool in research and practice. However, digital technologies and strategies have been suggested as techniques for a more robust BIM. Based on this research, it is evident that the static nature of BIM data with respect to time fails to accurately represent physical assets, which constitutes a significant limitation of this study. From Table 5, it is also apparent that BIM research studies and reviews have covered different aspects based on the limitations of the existing system. For instance, potential errors in manual cost analysis have motivated automated implementation surveys, difficulty in comprehending BIM implementation guidelines, and inability to realize BIM benefits have stimulated research in this domain. Moreover, the lack of intuitiveness and generation of automated insights in existing systems are some of the reasons and motivations behind the applications of artificial intelligent techniques in construction production planning, progress monitoring, and workflow systems. Other limitations can be viewed in Table 5, which shows some of the existing surveys within the literature on BIMs.

8.2. RQ 2: What Challenges in AEC/Digital Construction Have Been Addressed in the Literature?

Section 5 provides a comprehensive response to this research question, and Table 8 directly indicates the challenges discovered in the digital construction and AEC industry simultaneously. This study adopted a problem-centered framework to identify key directions and pathways for this survey. The highlighted challenges, as discovered in the literature, are coined from operational circumstances. For instance, in construction projects, projects are oftentimes fast-tracked to meet specified contract objectives and avoid delays. However, this leads to other barriers, such as uncoordinated collaborative operations, incomplete design documents, unending design developments, and continuous changes in scope, etc. [1]. Saka et al. [116] also identified barriers to digital communication in the AEC industry. These barriers include those that are related to privacy, security, ethics, and data quality.

8.3. RQ 3: What Are the Strategies That Can Be Deployed Towards 4D BIM

As in the taxonomy for digital construction (BIM) shown in Figure 15, 4D BIM development would require strategies such as lean approaches, predictive strategies, and ontology frameworks generated specifically for 4D BIM. Section 4.2 discusses lean construction ideologies and digital lean systems which are being deployed for BIM processes. Related research indicates that several lean systems and nodes intersect with BIM, effectively bridging the gap between the two methodologies. Furthermore, this review study has introduced various BIM-compatible methods for scheduling, including Kanban, LPS, location-based scheduling, Takt, 5S, value stream mapping, and pull.

As in Section 4.4, the second strategy discusses BIM ontology while showcasing how ontologies are developed. This strategy showcases that several ontologies exist, and these ontology standards can be combined with new ones to create a new data exchange system. Several research studies have discussed new ontology frameworks and standard ontologies, such as COBie, IFC, BCF, BFO, gbXML, and the following widely accepted standard ontologies: ISO12006-2 and BuildingSMART. Related ontology researchers have developed construction management ontology for processes such as communication, cost management, design, integration, knowledge management, maintenance, monitoring and compliance, quality, risk management, and estimation. Research gaps indicate that most processes, like quality, facility management, planning, etc., experience similar limitations as they have process parameters and attributes that exist in basic structured formats, such as XML, indicating heterogeneity when needing mapping with other domains, such as BIM. Through this review, it was also discovered that ontology development software, such as protégé and World Wide Web Consortium (W3C), have standard ontologies for major domains used in practice and can be reused for consistency. However, protégé can be used to develop non-existent ontologies. Also, querying packages SPARQL and others have been used to build reasoners and automate processes.

Finally, Section 7 indicates the three categorized predictive strategies that can be used to achieve intuition and automation in 4D BIM developmental processes. Application areas encompass design analysis, with a focus on predictions related to design elements, spatial and 3D geometric data, and construction process data, including safety, planning, documentation, logistics, material management, quality control, and waste management. This review highlighted that the primary sources of data utilized in the literature include LiDARs, cameras, BIM databases, global positioning systems (GPSs), radio frequency identification (RFID) technologies, sensors, CAD archives, and open source datasets. Furthermore, the predominant data types used in 4D BIM studies are images, videos, text, and structured formats such as XML, JSON, IFC, Revit, and point cloud data. This study highlighted the effectiveness of deep learning algorithms and transformer-based models in enhancing automation and intuitive processes across various applications. In model evaluation, accuracy, mean average precision (mAP), and precision–recall (PR) curves were predominantly utilized in computer vision (CV) tasks. In contrast, accuracy, precision, recall, F1 score, and other evaluation metrics were more commonly employed for natural language processing (NLP) and other general machine learning tasks. Additionally, for region-specific tasks where spatial reference is crucial, region-based neural networks were deemed the most appropriate.

8.4. RQ 4: What Tools, Techniques, and Software Exist in the Research for the Integration of 4D BIM?

Section 6 and Table 9 discuss classified existing tools that have been used in 4D BIM-related studies. The tools and techniques in 4D BIM presented a comparison and classification of all software, tools, and techniques, showcasing groupings, use cases, and functionalities. It was discovered that Revit, in comparison with other model authoring software such as Bentley Microstation, Tekla, Solibri model checker, ArchiCAD, etc., is most commonly used in the industry and in research. Also, 4D BIM solutions that were discovered in the literature include Synchro Pro, Naviswork, and Fuzor.

9. Open Issues

The ascertained status quo of BIM and the prospects of 4D BIM indicate further research and developments. This section discusses the necessary future directions in terms of limitations and gaps discovered throughout this literature review.

1. Adoption and implementation of BIM is generally determined to be a limitation in BIM research. The barriers associated with the adoption of 4D BIM software should be further analyzed to achieve a consensus on how advancements in AI can facilitate automation, enhance training, and improve usability [160,161].
2. Existing use cases of 4D BIM are visualization, performance monitoring, safety, progress monitoring, scheduling and planning, decision making, and integration [5,50,51]. However, in construction, there are other unexplored aspects such as instant risk insights, project continuation/closure, and evaluation, project benefit evaluation-earned value analysis, project securing (i.e., automated bid and tendering), etc. These areas should be further explored with real project pilot case studies for validation.
3. Discussions regarding digitized support and combination of technologies such as AI, IoT, Cloud storage, AR, and VR are common [162,163]. However, there is not enough analytical research detailing the outcomes of each of the combinations and their importance for the sustainability and progress of digital construction.
4. Other gaps in 4D BIM-related research:
    (a) Inability to generalize 4D BIM solutions: This is a recurrent limitation in most 4D BIM studies across different projects, contexts and organizations. Factors leading to such limitations include complexities and uniqueness of projects embarked on in construction, tailored schedules that do not match 3D BIM information, software compatibility, and inconsistent data standards, leading to data losses and nonquality data [51,58–61].
    (b) Lack of Integrated Decision-Making Support in 4D BIM Systems: The majority of businesses in AEC, projects, processes, and domains operate with siloed data that comprise different formats and types; for example, schedules and 3D drawings are created independently without collaborative efforts between designers, engineers, and planners. These disparate data sources only lead to fragmented information, making it difficult to draw instant project or business insights. Thus, analytical capabilities are limited and can be prone to undue errors and inconsistencies [51,62].
    (c) Limited research documentation and regulation in 4D BIM: The small amount of research documentation of 4D BIM, coupled with unavailable standardized protocols that are non-existent in many regions of the world, are determined as additional limitations in this regard. Going forward, it is important to promote academic research in this area and enhance the promotion of using standardized data formats alongside APIs [59,60].
    (d) Lack of automation (AI) in 4D BIM: The manual method of data integration and lack of automation in 4D BIM is a major limitation that impedes accuracy, consistency, and effectiveness in project management. Without AI, it is impossible to take a proactive approach and generate actionable insights instantly. It is, however, important to take an AI-driven approach to building 4D BIM solutions [5,60].
5. BIM ontology reviews indicate the need for further research and development. Although several BIM modules have standardized and validated ontological, structures such as time, dimension, GIS, safety, quality, planning, and other modules that are

developed and validated by standard regulatory bodies, there are other lower-level modules or domains such as predictive maintenance systems for energy systems, predictive failure modules, automated machinery systems and other relatively new models which require integration with BIM to function. Also, other linkages, such as safety-schedule-BIM ontology, schedule-BIM ontology, etc., are still unexplored. This shows that there is a need for further research to overcome the continuous integration challenge experienced across the board in digital construction.

6. The level of detail (LOD) in 4D BIM is unexplored [164–166]. There is a need for the analysis of LOD in 4D BIM solutions for entity integration, data extraction, design and implementation workflow analysis, automation, production control, visual management, etc. It is important to systematically and analytically determine the level of detail for all process steps regarding 4D BIM and all integrated digital construction systems.

10. Conclusions

The increased ambiguity, uncertainties in AEC and its processes, generating time and cost overrun, and other risks have motivated this research to aim at overcoming the static nature of BIM systems. This gives rise to the need to have a time dimension included or linked with all BIM modules, including design, communication, production control and monitoring, safety, quality, logistics, etc. The goal is set towards achieving 4D BIM, which is a foundation for the automation of systems for the instant generation of insights, automation, and correctness of virtual representations of knowledge when compared with physical situations. This review of existing BIM surveys indicated that 4D BIMs were sparingly researched as no in-depth SLRs existed in the research repositories that were investigated.

Research into challenges in AEC indicated that delays, cost overruns, and other risk events are only effects of granular causal challenges experienced in the AEC field operations, as illustrated in Figure 14. These challenges include poor communication, variability in products, fragmentation, and many others. It was identified that while proper management and planning are commonly suggested solutions, the implementation of an integrated digitized support system is recognized as a more vital approach going forward. Despite digitized solutions, such as BIM and other supportive technologies, related digital challenges have also been discovered, as shown in Table 8.

While moving towards 4D BIM, lean approach, predictive strategies, and ontology structures were identified as major strategies that are deployed in 4D BIM development studies. Lean systems are used digitally in current BIM with underlying principles solutions, such as TFV, LPS, Kanban, location-based scheduling, Takt, etc., which have been employed by major BIM solutions as well as traditional lean approaches, such as JIT, flexibility, etc. This has indicated the existence of potential correlations between lean approaches in 4D BIM scenarios. Also, it is certain that predictive strategies are unequivocally imperative in the development and integration of BIM with time. Based on the research, AI algorithms such as DL neural networks and transformers have shown increased potential through evaluations for resolving the integration challenge and automating BIM processes, especially when combined or integrated with newer supportive technologies. It is also evident that the ontology structures of existing base modules, which are reusable and validated by regulatory bodies, serve as a foundation for the development of new ontologies for 4D BIM, as well as for emerging supportive technologies and programs.

Finally, this study included the tools, techniques, and software classifications utilized in 4D BIM-related research developments. The classification showed the methods and integration software used, including APIs, file types, and other software, for 4D BIM-related research, as illustrated in Figure 15. This was important in serving as a basis for prompting and encouraging research studies to be carried out with regard to 4D BIM development. Overall, based on the findings of this study, further research is essential and has the ability to be carried out in multiple directions. The ontology structures for new artificial intelligent models should be built for different phases, domains, management processes, machines, and operations within AEC, while predictive strategies using DL algorithms, transfer learning, and transformers should be utilized for integrating and automating systems within the AEC industry. Also, the level of detail (LOD) for 4D BIMs and validated AI models should be specified and configured through further research.

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