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A design science framework for AI-driven 4D BIM-VR integration for construction planning and decision support

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Abstract—Construction projects are becoming increasingly complex due to multidisciplinary coordination, large-scale designs, and dynamic and uncertain planning environments. Although 4D Building Information Modeling (BIM) supports the integration of 3D models with construction schedules, current workflows remain dependent on manual processes, fragmented systems, and expert knowledge, which limit efficiency, interoperability, and decision-making. In addition, Virtual Reality (VR) applications are mainly used for visualization purposes, while Artificial Intelligence (AI) applications in construction are often isolated and lack integrated workflow automation. Therefore, this study proposes a Design Science (DS)-based semantic AI framework for integrating BIM, scheduling systems, and VR environments to support automated 4D BIM generation, intelligent construction planning, and decision-making. The research combines a structured literature review with comparative analysis to identify current limitations, research gaps, and opportunities for AI-enabled automation. The proposed framework integrates AI techniques, including Large Language Models (LLMs), Natural Language Processing (NLP), and Machine Learning (ML) methods, across different stages of the 4D BIM–VR workflow to support semantic reasoning, automated BIM–schedule linking, predictive analytics, and immersive VR simulations. The framework introduces a Semantic AI Layer that enables semantic interpretation of BIM information, automated element–activity matching, and adaptive planning support. The framework aims to improve efficiency, accuracy, interoperability, stakeholder collaboration, and decision-making in digital construction environments while establishing a foundation for future implementation and empirical validation of semantic AI-driven 4D BIM–VR workflows. The framework is conceptually evaluated through theoretical, logical consistency, comparative, and workflow validation.

Keywords— semantic AI; 4D BIM; large language models; virtual reality; construction planning; design science

I. INTRODUCTION

As construction projects become increasingly complex, Building Information Modeling (BIM) and Virtual Reality (VR) have emerged as valuable technologies for improving project visualization, planning, and stakeholder communication within the Architecture, Engineering, and Construction (AEC) industry. The fourth dimension of BIM (4D BIM), which links 3D models to schedule, enables simulation of construction activities throughout the project lifecycle and provides a more comprehensive representation of project execution. When 4D BIM models are integrated into VR environments, users can navigate and review construction scenarios and sequences in an immersive setting. Such capabilities can improve project understanding, facilitate communication among stakeholders, and support more effective planning decisions.

Several studies have reported the benefits of integrating BIM with VR integration in construction projects. Immersive environments have been shown to improve communication among project participants, support design reviews, and facilitate construction planning activities. Johansson and Roupé (2024), for example, demonstrated the use of VR for applications such as site monitoring and client interaction [1]. Similarly, Khorchi and Boton (2024) presented an OpenBIM-based VR environment designed to support coordination meetings and collaborative project reviews [2].

In parallel with the growing use of VR in construction, Artificial Intelligence (AI) in BIM-based workflows has attracted increasing attention. AI techniques have been applied to a range of tasks, including schedule analysis, resource allocation, design support, and error detection [3]. While BIM–VR and AI-based approaches have generally evolved along separate research paths, recent developments indicate that combining these technologies could strengthen construction planning processes. The integration of AI-driven analysis with immersive 4D BIM environments may enable more automated workflows while providing stakeholders with richer project information for planning and decision-making.

Despite ongoing developments in 4D BIM, many existing workflows continue to depend on manual configuration and predefined linking rules. The integration of BIM models with construction schedules often requires considerable user intervention, particularly when different software platforms and data formats are involved. Automated and semi-automated approaches have reduced some of this effort; however, issues related to interoperability, data exchange, and platform compatibility remain unresolved.

A similar situation can be observed in BIM–VR applications. Most VR implementations are designed to improve visualization and project communication rather than support planning or decision-making activities. At the same time, AI applications in construction are commonly developed for specific purposes such as scheduling, safety monitoring, or model analysis. As a result, fully integrated workflows connecting BIM, AI, and VR remain limited. Rehman et al. (2025) further identified challenges associated with workflow standardization, software compatibility, and real-time synchronization between BIM platforms and game engines [4].

Although 4D BIM technologies have advanced considerably, many practical implementations still require manual setup and predefined relationships between model elements and schedule activities. Integrating information across different software platforms remains difficult, particularly when data must be transferred between multiple systems. While automation has improved in recent years,

interoperability and data consistency continue to be recurring concerns.

Similar limitations can be found in BIM–VR research. In most cases, VR is used to visualize project information and support communication among stakeholders. AI applications, on the other hand, are often developed independently to address specific construction tasks. Consequently, seamless workflows that combine BIM, AI, and VR within a single planning environment are still uncommon. Rehman et al. (2025) highlighted related issues, including the absence of standardized workflows, limited compatibility between BIM tools and game engines, and challenges in achieving real-time synchronization [4].

Previous studies have explored BIM–VR integration and AI-assisted BIM workflows separately. However, these research works have largely evolved independently, with relatively few studies examining the combined use of AI, 4D BIM, and VR for construction planning. Existing workflows also continue to face challenges related to real-time responsiveness, predictive analysis, and interoperability across software platforms [5]. More recently, advances in semantic BIM interpretation and Large Language Models (LLMs) have opened new possibilities for extracting construction knowledge, understanding BIM semantics, and improving information integration processes [6,7]. Despite these developments, the use of semantic AI techniques for automated BIM–schedule linking and 4D BIM generation has received limited attention in the literature. As a result, there remains a need for a semantic AI-driven framework capable of integrating BIM data, scheduling information, and immersive VR environments within a unified workflow for automated construction planning and decision support.

This research proposes a Design Science (DS)-based semantic AI framework for integrating BIM, scheduling systems, and VR environments to support automated 4D BIM generation and construction planning. The framework introduces a Semantic AI Layer that combines LLMs, Natural Language Processing (NLP), and Machine Learning (ML) techniques to automate BIM–schedule integration, support predictive planning functions, and improve the interpretation of construction information.

The objective of this research is to develop and validate a semantic AI framework that connects BIM data, scheduling systems, and VR environments within a unified workflow. Particular attention is given to the use of LLMs and semantic reasoning techniques to interpret BIM information and automatically associate building elements with construction activities. By reducing reliance on manual linking procedures, the proposed approach aims to improve the efficiency and consistency of 4D BIM generation.

The framework also extends the resulting 4D BIM model into an immersive VR environment that supports interactive visualization, collaborative planning, and decision-making. Its evaluation follows DS artifact assessment principles, including theoretical, logical consistency, comparative, and workflow validation. Accordingly, this study addresses the following research question: “How can a semantic AI-based integration of BIM, scheduling systems, and VR environments support automated 4D BIM generation, construction planning, and collaborative decision-making in digital construction environments?”

II. RELATED WORK

BIM has become an important digital approach for managing and exchanging project information in AEC industry. BIM integrates geometric, topological, and semantic information describing building elements, materials, and their relationships, thereby supporting collaboration throughout the building lifecycle [8]. The concept has gradually expanded beyond 3D modeling to include additional dimensions such as time (4D), cost (5D), and sustainability-related information, enabling more effective project planning, management, and delivery [9].

4D BIM refers to the integration of 3D BIM-based models and the time dimension. It links 3D models with scheduling or planning data to support better coordination and decision-making [10-14]. Several studies have highlighted the advantages of 4D BIM applications in improving progress tracking, risk and resource management, scheduling, safety planning, and waste reduction [10,15]. However, despite the growing adoption of 4D BIM tools in the AEC industry, further research is still required to fully integrate design models with project schedules and workflows [11,15]. Existing approaches also face challenges related to automation, interoperability, data quality, adaptability, and scalability across different project types and contexts.

To better understand current 4D BIM implementation practices, a comparative review of academic studies was conducted, as presented in Table 1. The table summarizes the major categories of existing 4D BIM workflow approaches, including traditional 4D BIM systems, automated BIM workflows, BIM–VR integration, AI-assisted scheduling, and semantic BIM applications.

Table 1. Comparative Analysis of Existing 4D BIM Workflow Approaches.

Category	Typical Methods	Common Tools	Main Limitation	References
Traditional 4D BIM	Manual or ID-based BIM–schedule linking	Revit, Navisworks, MS Project	High manual effort and limited adaptability	[10-11], [16-17]
Automated 4D BIM	APIs, scripts, and rule-based automation	Revit API, Dynamo, C#, SQL	Platform dependency and limited interoperability	[16], [18-19]
BIM–VR Integration	Model export and immersive visualization	Unity, Unreal Engine, Oculus	Primarily visualization-oriented	[2], [20-21]
AI-Assisted Scheduling	ML and optimization algorithms	ML models, Genetic Algorithms	Fragmented and task-specific applications	[3], [22-23]
Semantic BIM & AI	Semantic interpretation and knowledge extraction	LLMs, Semantic Web technologies	Limited application to 4D BIM automation	[6-7]

The review indicates that most approaches rely on manual, ID-based, or rule-based linking between BIM elements and schedule tasks, often supported by APIs, scripts, plugins, or database integrations. Although these methods improve automation and visualization capabilities, they still require significant technical expertise and remain limited in flexibility, interoperability, and intelligent decision-support functionality.

Recent studies also emphasize the integration of BIM with immersive VR technologies to improve construction visualization, coordination, and stakeholder collaboration. VR has been explored in the AEC industry since the 1980s, but recent advances in hardware and software have enabled more practical implementation in construction projects [24].

BIM-VR integration transforms BIM data into immersive virtual environments that improve spatial understanding, communication, and collaborative design review [25-26]. In addition, immersive 4D BIM environments enhance stakeholder engagement, project coordination, and workflow communication [1-2].

To analyze existing BIM to VR workflows, a comparative analysis of software platforms and transfer methods was developed and summarized in Table 2. The review shows that transferring 4D BIM models into VR environments commonly involves direct BIM exports, game engine-based integration, OpenBIM workflows, and collaborative VR platforms. Popular platforms include Unity, Unreal Engine, Twinmotion, and Enscape. The reviewed studies also reveal several technical challenges, including interoperability issues, schedule integration, automation limitations, and limited support for intelligent decision-making and collaborative multi-user environments.

Table 2. Comparative Analysis of BIM to VR Transfer Approaches.

Approach	Typical Workflow	Common Platforms	Main Challenges	Ref.
Direct BIM to VR Export	Export BIM models directly into VR environments	Twinmotion, Enscape	Limited schedule integration and interactivity	[27-28]
Game Engine-Based Integration	Transfer BIM models through FBX, IFC, or glTF into game engines	Unity, Unreal Engine	Data loss, geometry optimization, interoperability issues	[29-31]
OpenBIM-Based Workflows	Use IFC and open standards for BIM–VR integration	Unity, BIMXplorer	Complex data mapping and schedule synchronization	[1-2], [21]
Collaborative VR Environments	Multi-user immersive design review and coordination	Unity-based VR platforms	Limited automation and decision-support capabilities	[2], [32-33]
AI-Enhanced BIM–VR Systems	Integration of BIM, VR, and intelligent analytics	Unity, ML-enabled platforms	Limited end-to-end BIM–AI–VR integration	[29, 34]

Alongside BIM–VR developments, AI is playing a more active role in construction-related BIM workflows. Several studies report that AI can improve design productivity. It is also being used to reduce clashes and improve the reliability of scheduling and resource planning [3], [35-36].

Some recent systems, such as Generative AI BIM and BIM-GPT, show a shift in how users interact with BIM environments. Instead of working through complex tools or manual queries, users can now use natural language to access and manipulate BIM data [35, 37]. At the same time, AI is being applied in more technical areas like model checking, safety monitoring, predictive analytics, and schedule optimization [38-39]. More recently, attention has moved toward combining AI, 4D BIM, and VR in a single workflow. Rehman et al. (2025) developed a synchronized 4D BIM–VR system that links scheduling data with immersive environments, making construction planning more interactive [4]. In a similar direction, Amani and Akhavian (2024) proposed an AI-based framework where ML and sensor data are integrated with 4D BIM to better predict tasks and understand on construction sites [23].

Overall, the direction is quite clear. The field is moving away from isolated tools toward more connected systems that can support not just visualization, but also prediction and decision-making.

Research Gaps:

The literature review reveals that significant progress has been made in BIM, VR, and AI technologies; however, their integration within construction planning workflows remains limited. Current 4D BIM implementations continue to rely heavily on identifier-based and rule-based linking approaches that require predefined rules, manual configuration, and substantial expert intervention. As a result, the creation and maintenance of 4D BIM models remain time-consuming and difficult to scale across complex projects.

Furthermore, although AI technologies have demonstrated strong potential for schedule optimization, predictive analytics, automated reasoning, and information management, most existing applications remain fragmented and task-specific. Current AI implementations typically address isolated functions such as safety monitoring, scheduling optimization, clash detection, or BIM querying rather than supporting end-to-end construction planning workflows. Similarly, VR technologies have significantly improved construction visualization, stakeholder communication, and spatial understanding. However, most BIM–VR systems continue to function primarily as visualization environments with limited capabilities for intelligent planning, predictive analysis, or collaborative decision-making. Interoperability challenges between BIM platforms, scheduling systems, AI tools, and VR environments further restrict the effectiveness of existing solutions.

Recent advances in semantic BIM interpretation and LLM-based reasoning suggest new opportunities for automated BIM–schedule integration and intelligent information processing. Nevertheless, the application of semantic AI techniques for automated activity and element matching, 4D BIM generation, and VR-supported decision-making remains largely unexplored.

Consequently, a significant research gap exists in the development of a unified semantic AI-driven framework capable of integrating BIM data, scheduling information, AI reasoning mechanisms, and immersive VR environments within a single interoperable workflow. Addressing this gap forms the primary motivation for the framework proposed in this study.

III. METHODOLOGY

This research follows a DS methodology to develop an AI-driven 4D BIM–VR framework for construction planning and decision support. In the field of Information Systems (IS), DS is recognized as an appropriate framework for conducting technology-oriented research because it supports the development of innovative and useful artifacts while contributing to scientific knowledge [40-41].

According to Peffers et al. (2007), the DS research methodology consists of five main steps: (1) problem identification and motivation, (2) objectives definition, (3) artifact design and development, (4) solution evaluation, (5) results communication [41].

The primary artifact developed in this research is a semantic AI-driven framework integrating BIM models, construction scheduling systems, and VR environments within a unified workflow for construction planning and decision support.

The research methodology is organized into three main phases aligned with the DS framework, as illustrated in Figure 1 and 2. The three phases include:

1) Pre-AI-driven 4D BIM–VR Integration
2) AI-driven 4D BIM–VR Integration for Construction Planning
3) Evaluation for Project Planning and Decision-Making.

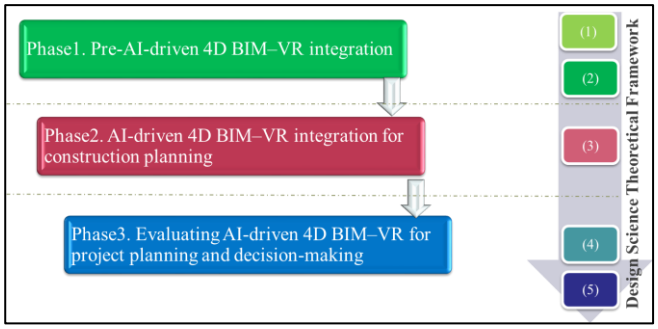


Fig. 1. Three-phase AI-driven 4D BIM–VR methodology aligned with DS.

This three-phase structure ensures a systematic process from problem identification and artifact development to evaluation and knowledge dissemination.

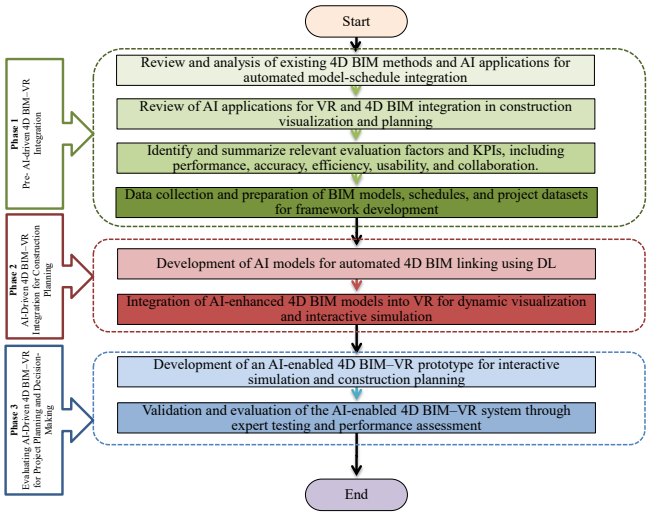


Fig. 2. Structure of the proposed research approach

Phase 1 – Pre-AI-driven 4D BIM–VR Integration

The first phase focuses on identifying current limitations, inefficiencies, and research gaps in existing 4D BIM, BIM-VR, and AI-assisted BIM workflows. A structured literature review is conducted to critically analyze 4D BIM generation methods, BIM to VR conversion workflows, AI applications in construction planning, interoperability limitations, scheduling integration techniques, and intelligent decision-support approaches. The findings established the theoretical and technical foundation for the development of the proposed framework.

Phase 2 – AI-driven 4D BIM–VR Integration for Construction Planning

Based on the identified research gaps, a semantic AI-driven framework integrating BIM, scheduling systems, and VR environments was designed as the primary DS artifact.

The framework integrates BIM data, scheduling information, semantic reasoning mechanisms, ML techniques, and immersive VR environments within a unified architecture for construction planning and decision support.

A feedback mechanism was incorporated to enable planning decisions and simulation outcomes generated within the VR environment to inform subsequent optimization processes, thereby supporting adaptive and iterative decision-making.

Phase 3 – Evaluation for Project Planning and Decision-Making

Since the framework has not yet been implemented, evaluation was limited to conceptual DS validation, including theoretical grounding, logical consistency, comparative analysis, and workflow validation.

These evaluation perspectives were selected to assess the theoretical grounding, internal consistency, functional completeness, and potential contribution of the proposed framework to intelligent construction planning and decision support.

IV. DISCUSSION

This section presents and discusses the proposed AI-driven semantic framework developed using the DS methodology described in the previous section.

This framework introduces a semantic AI-driven architecture for integrating BIM, construction scheduling systems, and VR environments into a unified workflow for construction planning and decision support. It is structured into three interconnected layers: (1) a Data Layer, (2) a Semantic AI Layer, and (3) a VR Decision Layer. Together, these layers support automated 4D BIM generation, immersive simulation, and intelligent decision-making.

Data Layer: The Data Layer represents the primary information sources required for construction planning. It includes BIM models. The models developed in software, such as Revit and exchanged through Industry Foundation Classes (IFC) standards. It also includes scheduling data from tools, such as Microsoft Project and Primavera P6.

In addition, the layer brings together key project information such as cost data, resource availability, risk factors, and site conditions. These datasets provide the foundation for subsequent AI-driven processing and decision-support functions.

Semantic AI Layer: The Semantic AI Layer constitutes the core research contribution and the main source of innovation within the framework. This layer integrates LLMs, NLP, and ML techniques to automate BIM–schedule integration and support intelligent construction planning.

LLMs are used to interpret BIM semantics and understand relationships among BIM objects, construction activities, and scheduling information. Through semantic reasoning, the models can identify links between BIM elements and schedule tasks without relying exclusively on predefined identifiers or rule-based mappings. NLP techniques support the extraction and interpretation of activity descriptions and project information from schedules, reports, and textual documents. ML algorithms are incorporated to support schedule prediction, duration estimation, resource optimization, and risk analysis.

The outputs of this layer include automated BIM–schedule linking, activity to element mapping, and generation of 4D BIM models. By reducing manual intervention and improving semantic understanding, the AI layer aims to increase efficiency, consistency, and scalability in 4D BIM creation.

VR Decision Layer: The VR Decision Layer transforms AI-generated 4D BIM models into immersive and interactive planning environments. This layer can be implemented using platforms such as Unity or Unreal Engine and includes a 4D simulation engine capable of visualizing construction sequences, project progress, and alternative planning scenarios.

Beyond visualization, the VR environment supports collaborative planning, constructability analysis, stakeholder communication, and decision-making. Multiple users can interact with project information within the same immersive environment, facilitating review and evaluation of construction strategies.

An important feature of the framework is the feedback mechanism between the VR and AI layers. User interactions, planning decisions, simulation results, and scenario evaluations generated within the VR environment are fed back into the Semantic AI Layer. This feedback enables continuous optimization of schedules and planning strategies, allowing updated 4D BIM simulations to be generated dynamically. Consequently, the framework facilitates an iterative and adaptive decision-support process rather than a static BIM to VR workflow.

Expected Outcomes: This framework is expected to improve planning accuracy, reduce manual effort in 4D BIM generation, enhance interoperability among BIM, scheduling, and VR platforms, and support predictive analytics for construction planning. Furthermore, the integration of semantic AI and immersive VR technologies is expected to improve stakeholder collaboration, facilitate scenario-based evaluation, and strengthen decision-making in digital construction environments.

Figure 3 illustrates the proposed three-layer semantic AI-driven 4D BIM–VR framework, including the data sources, AI processing components, VR decision-support environment, and the continuous feedback loop that enables adaptive planning and optimization.

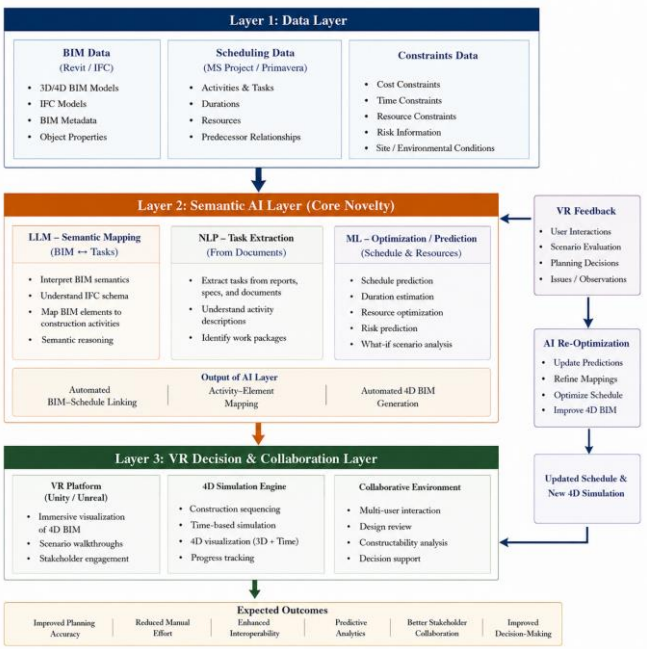


Fig. 3. Three-layer semantic AI-driven 4D BIM–VR Framework.

The need for semantic AI in BIM–VR integration becomes evident because rule-based BIM–schedule linking is insufficient. Existing 4D BIM workflows primarily rely on predefined rules, object identifiers, and manual linking processes to associate BIM elements with construction activities. Although these approaches improve project visualization and scheduling capabilities, they remain limited when project information becomes heterogeneous, incomplete, or distributed across multiple software environments. The Semantic AI Layer is grounded in recent advances in AI, NLP, ML, and LLMs. Previous studies have demonstrated the capability of AI techniques to support schedule optimization, predictive analytics, risk assessment, and automated information processing in construction management [42-43].

Recent advances in LLMs have demonstrated their potential to support semantic interpretation and natural-language querying of IFC-based BIM data, enabling more flexible information retrieval and interaction with BIM models [44]. In parallel, semantic mapping approaches have improved interoperability and information exchange across BIM environments through structured representations and rule-based mapping techniques [45].

Unlike conventional BIM–schedule integration methods that rely on predefined mappings, semantic AI enables contextual understanding of BIM data, construction activities, and project constraints. Through semantic reasoning, LLMs and NLP techniques can support automated BIM–schedule linking, intelligent information extraction, predictive analysis, and improved interoperability across BIM, scheduling, and VR platforms.

The proposed framework contributes to construction informatics by integrating BIM, scheduling systems, semantic AI, and VR within a unified conceptual architecture for automated 4D BIM generation and construction planning. From a practical perspective, it is designed to reduce manual effort, improve interoperability, enhance planning accuracy, and support collaborative decision-making.

V. CONCLUSION AND CONCEPTUAL VALIDATION

Since the proposed artifact represents a conceptual DS framework rather than an implemented software system, the evaluation focuses on conceptual validation rather than empirical performance assessment. The framework was assessed using four complementary validation perspectives, including theoretical, logical consistency, comparative, and workflow validation.

Theoretical Validation

Theoretical validation aims to determine whether this framework is grounded in established theories, concepts, and prior research within the domains of BIM, AI, and VR.

The Data Layer is supported by extensive research demonstrating the value of BIM and 4D BIM for construction planning, scheduling, coordination, and visualization. Previous studies have shown that integrating scheduling information with BIM models improves project understanding, construction sequencing, and communication among stakeholders [46]. Furthermore, BIM has become a widely accepted digital information management platform within the AEC industry [47].

The proposed Semantic AI Layer builds upon recent advances in LLM-based BIM research and semantic mapping approaches to support semantic interpretation and BIM–schedule integration within a unified workflow for automated 4D BIM generation [44,45]. These studies provide the

theoretical foundation for the semantic reasoning and automated BIM–schedule linking mechanisms proposed in this research.

The VR Decision Layer is supported by a growing body of literature demonstrating the effectiveness of immersive environments for construction visualization, stakeholder communication, constructability analysis, and collaborative project review [1, 33]. Previous research has shown that VR environments improve spatial understanding and facilitate interaction with complex project information. The developed framework extends these capabilities by integrating VR with AI-generated 4D BIM simulations to support collaborative planning and decision-making.

In addition, the feedback mechanism incorporated within the framework is supported by concepts from adaptive decision-support systems and iterative planning processes. By enabling user interactions and simulation outcomes generated within the VR environment to inform subsequent AI-based optimization, the framework promotes continuous improvement and adaptive construction planning.

Overall, the proposed framework is theoretically grounded in established BIM, AI, and VR research streams. Each layer is supported by prior studies, while their integration addresses limitations identified in existing literature regarding automation, interoperability, semantic understanding, and collaborative decision support.

Logical Consistency Validation

Logical consistency validation examines whether the proposed framework follows a coherent and internally consistent information flow from data acquisition to decision support. Figure 3 demonstrates a logically structured architecture in which information progresses through three interconnected layers: the Data Layer, the Semantic AI Layer, and the VR Decision Layer.

The Data Layer provides BIM models, scheduling information, and project constraints that serve as the primary inputs to the framework. These inputs are subsequently processed within the Semantic AI Layer, where LLM, LP techniques, and ML algorithms could facilitate semantic interpretation, activity extraction, BIM–schedule linking, and predictive analysis. The outputs generated by this layer, including activity–element mappings and automated 4D BIM models, become the direct inputs to the VR Decision Layer.

The VR Decision Layer utilizes these outputs to support immersive visualization, collaborative planning, constructability analysis, and decision-making. This sequential relationship ensures that each processing stage receives the information required from the preceding stage without disrupting data continuity or workflow integrity.

Furthermore, the feedback loop connecting the VR Decision Layer to the Semantic AI Layer strengthens logical consistency by enabling planning decisions, user interactions, and simulation outcomes to be incorporated into subsequent optimization processes. This iterative mechanism supports adaptive planning and continuous improvement rather than a static one-way workflow.

Thus, the framework maintains clear and logically consistent progression from data acquisition and semantic processing to immersive decision support and feedback-driven optimization.

Comparative Validation

Comparative validation was conducted by comparing the proposed framework with representative categories of existing approaches, including traditional 4D BIM systems, BIM–VR integration platforms, and AI-assisted scheduling systems. The comparison focuses on key capabilities identified in the literature, including automated BIM–schedule linking, semantic reasoning, predictive analytics, collaborative VR environments, adaptive feedback mechanisms, and end-to-end system integration.

Table 3 compares the proposed framework with representative studies selected from the literature review. These studies represent major research streams in 4D BIM visualization, BIM–VR integration, AI-assisted scheduling, and semantic BIM interpretation.

As shown in Table 3, existing studies typically address specific aspects of construction planning and digital project management. For example, Boton (2018) and Khorchi and Boton (2024) demonstrate the benefits of immersive VR environments for visualization and coordination, while Fazeli et al. (2024) and Wefki et al. (2024) introduce automation and optimization capabilities within scheduling workflows [2, 18], [22-33]. More recently, Jin et al. (2026) demonstrated the potential of semantic interpretation of IFC-based BIM information using advanced AI techniques [6]. However, none of these studies provides a unified environment that combines semantic reasoning, automated BIM–schedule linking, predictive analytics, immersive collaboration, and adaptive planning within a single workflow. To provide a broader perspective, Table 4 compares the proposed framework against major categories of existing solutions. This comparison highlights the overall technological capabilities of traditional 4D BIM systems, BIM–VR integration platforms, and AI-assisted scheduling systems relative to the approach.

As shown in Table 4, traditional 4D BIM approaches primarily support visualization and construction sequencing but rely heavily on manual BIM–schedule linking and predefined rule-based relationships. BIM–VR systems improve stakeholder communication and immersive visualization; however, they generally lack intelligent automation and predictive decision-support capabilities. Similarly, AI-assisted scheduling systems provide optimization and predictive analytics but are often disconnected from BIM and VR environments. In contrast, this framework combines LLM-based semantic reasoning, automated BIM–schedule integration, ML-driven predictive analytics, and immersive VR collaboration within a single architecture. Furthermore, the framework introduces a feedback mechanism that enables planning decisions and simulation outcomes to continuously inform subsequent optimization processes.

As a result, the proposed framework extends existing approaches by providing a unified BIM–AI–VR ecosystem capable of supporting automated 4D BIM generation, adaptive planning, enhanced interoperability, and collaborative decision-making. Comparative validation demonstrates that the proposed framework addresses several limitations identified in previous studies and offers a more comprehensive solution for intelligent construction planning.

Table 3. Comparative analysis of the proposed framework and existing approaches.

Capability	4D BIM Visualization	VR Integration	Automated BIM–Schedule Linking	AI / ML Integration	LLM-Based Semantic Reasoning	Activity–Element Semantic	Predictive Analytics and Optimization	Collaborative Decision Support	Dynamic Feedback Loop	Unified BIM–AI–VR Integration
Boton (2018) [33]	✓	✓	✗	✗	✗	✗	✗	Partial	✗	✗
Ur Rehman et al. (2023) [48]	✓	✓	Partial	Partial	✗	✗	Partial	Partial	✗	✗
Khorchi & Boton (2024) [20]	✓	✓	Partial	✗	✗	✗	✗	✓	✗	✗
Fazeli et al. (2024) [18]	✓	✗	✓	Partial	✗	✗	✓	✗	✗	✗
Wefki et al. (2024) [22]	✓	✗	Partial	✓	✗	✗	✓	✗	✗	✗
Jin et al. (2026) [6]	Partial	✗	Partial	✓	✓	Partial	Partial	✗	✗	✗
Proposed Framework	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Contribution Addressed	Advanced visualization	Immersive collaboration	Reduced manual linking	Intelligent automation	Semantic understanding	Automated mapping	Planning optimization	Multi-stakeholder	Adaptive planning	End-to-end integration

Workflow Validation

Workflow validation evaluates whether the proposed process can support the intended functions of automated 4D BIM generation, AI-assisted planning, and VR-based decision support. The proposed framework demonstrates the feasibility of an integrated workflow connecting BIM data acquisition, semantic processing, automated BIM–schedule integration, 4D BIM generation, immersive simulation, and feedback-driven optimization.

Table 4. Comparative validation of the proposed framework.

Capability	Traditional 4D BIM	BIM-VR Systems	AI Scheduling Systems	Proposed Framework
Automated BIM–Schedule Linking	No	No	Partial	Yes
Semantic Reasoning	No	No	Partial	Yes
LLM Integration	No	No	No	Yes
Predictive Analytics	No	No	Yes	Yes
VR Collaboration	Limited	Yes	No	Yes
Adaptive Feedback Loop	No	No	No	Yes
End-to-End Integration	No	Partial	Partial	Yes

The workflow establishes a clear progression in which BIM models, scheduling information, and project constraints are first collected and processed through semantic AI techniques, including LLM, NLP, and ML algorithms. The outputs generated during semantic interpretation and predictive analysis are subsequently used to automate BIM–schedule linking and generate 4D BIM simulations. These simulations are then transferred to the VR environment, where stakeholders can visualize construction sequences, evaluate alternative scenarios, and support collaborative decision-making. The workflow further incorporates a feedback mechanism that allows user interactions and simulation outcomes to inform subsequent optimization processes within the Semantic AI Layer. By defining explicit inputs, processing stages, outputs, and feedback relationships, the workflow demonstrates a coherent and implementable process that aligns with the objectives of intelligent construction planning. Therefore, the proposed framework provides a theoretically coherent basis for supporting integrated BIM, AI, and VR operations within a unified decision-support environment.

This paper presented a semantic AI-driven DS framework for integrating BIM, scheduling systems, and VR technologies within construction planning processes.

The proposed framework addresses limitations associated with manual BIM–schedule integration, fragmented AI applications, and visualization-oriented VR systems. By combining semantic reasoning, ML, automated 4D BIM generation, and immersive decision-support environments, the framework establishes a unified intelligent planning ecosystem.

The study contributes both theoretically and practically by introducing a novel architecture for AI-enabled construction planning. The study demonstrates the potential of semantic AI to serve as an enabling layer connecting BIM, scheduling systems, and immersive VR environments within an intelligent construction planning ecosystem.

This study presents a conceptual framework and therefore does not include software implementation, real project deployment, experimental validation, or quantitative performance analysis. The proposed Semantic AI Layer and BIM-VR workflow remain to be implemented and evaluated through case studies and expert assessment.

Future research will focus on implementation and empirical validation using real construction projects, as well as integration with Digital Twins, IoT technologies, and real-time construction monitoring systems.

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