IJISEM
INTERNATIONAL JOURNAL OF INNOVATIONS IN SCIENCE ENGINEERING AND MANAGEMENT

International Journal of Innovations In Science Engineering And Management

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OPEN ACCESS

Volume: 5

Issue: 4

Month: December

Year: 2026

ISSN: 2583-7117

Published: 21.11.2026

Citation:

Nilesh B. Korade, Vedanti Raut, Saachi Laturiya, Utkarsh Salunkhe, Vaidik Samarth "BuildSim – Virtual Construction Planning and Simulation Platform" International Journal of Innovations In Science Engineering And Management, vol.5, no.4, 2026, pp. 360-367.

DOI:

10.69968/ijisem.2026v5i4360-367

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BuildSim – Virtual Construction Planning and Simulation Platform

Nilesh B. Korade[1], Vedanti Raut[1], Saachi Laturiya[1], Utkarsh Salunkhe[1], Vaidik Samarth[1]

[1]*Computer Science, Artificial Intelligence Vishwakarma Institute of Technology, Pune, India*

Abstract

Digital technologies are increasingly leveraged by the construction industry to boost the efficiency of project planning, visualization, and decision-making during the life-cycle of a project. This paper discusses BuildSim, a web-based planning and simulation application for the construction industry which merges Building Information Model (BIM) technology, Critical Path Method (CPM) scheduling, and interactive 3D visualization capabilities into a single solution. The software employs modular architecture with React/TypeScript frontend, powered by Three.js technology for rendering, and a backend written in Python, which is responsible for parsing the models, project management and scheduling. With the help of BuildSim, users can import construction models, visualize the project components in an interactive 3D environment, create project schedules, and monitor the progress.

Keywords: *Construction Simulation; Critical Path Method (CPM); 3D Visualization; Building Information Modeling (BIM).*

INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry has seen a number of digital tools that aid construction planning and management emerge and evolve. Among such digital tools, Building Information Modeling (BIM) software has proven to be highly beneficial due to its ability to represent constructible projects digitally for improved collaboration, management, and construction planning. BIM has been shown to reduce design clashes, enable better communication, and improve project management compared to traditional approaches to construction planning [1]. Visualization technologies were also found to enable engineers and project managers to experience construction processes digitally [2].

More recently, researchers began exploring how best to combine BIM with construction scheduling and visualization in web-based software to improve construction management. Scheduling algorithms, such as Critical Path Method (CPM), were combined with 3D BIM models to produce 4D construction planning software that improves construction sequencing, progress monitoring, and managing of resources [3].

Similarly, recent advances in WebGL rendering and browser-based visualization have enabled the development of visualization tools that enable rendering of construction projects in browsers [4], [5]. Additionally, cloud-based BIM software has also enabled better storage, visualization, and scheduling of construction projects [6].

Despite the number of solutions available to date, many still involve the usage of disparate modeling, visualization, and project management solutions. Some require the use of desktop-based applications, which limits their flexibility [3], [6]. Others are not well integrated with project scheduling or other construction management processes [4], [7]. There is a need, therefore, for a more integrated solution that brings together BIM construction planning and management tools in a single software solution.

This paper describes BuildSim – a web-based construction planning and simulation platform that combines BIM model parsing, CPM scheduling algorithms, 3D model visualization, and project management into a single integrated solution. The solution is implemented using React, TypeScript, Three.js, and Python, providing an accessible web-based interface for construction planning and management.

The novelty of this approach stems from its ability to bring together BIM model parsing, project management, construction scheduling, and 3D model visualization in an accessible web-based application. The proposed construction planning and simulation platform will enable easier analysis of construction processes compared to existing solutions and will serve as a foundation for future improvements to digital construction planning and management solutions.

LITERATURE REVIEW

Buildings information modeling (BIM)has become a critical force in the Architecture, Engineering, and Construction (AEC) sector because it captures vital infor mation about construction projects' design and construction stages digitally. BIM allows for increased stakeholder information exchange, which leads to better project outcomes, including construction processes' visu alization, reduced design clashes,and improved project planning and performance. According to Azhar [1], the critical role of BIM is evident in the construction sector's adoption of this innovative teachnology to enhance project collaboration while minimizing the amount of human effort in the design process. Additionally, the review study conducted by Ivson et al.[2] revealed that BIM tools increase project efficiency through advanced visualization options, which improve design accuracy, construction, and information exchange.

Moreover, the application of BIM has evolved from computer-aided design software to a digital prototype of building construction projects that are designed to incorporate project scheduling databases and visualize project's time-phased construction processes. The 4D construction planning systems enable construction planners to organize the work process according to the schedule while adhering to building design specifications. Park et al. [3] presented a 4D BIM framework that enables the visualization of day-by-day progress of construction projects as well as stakeholder coordination through a database supported BIM-based framework. The construction planning system aids in expediting project planning by enabling construction planners to assess activity sequence and identify potential construction process conflicts and issues through an improved project's spatial and temporal analysis. This demonstrates that there has been an increase in research studies focused on the application of project's scheduling frameworks in combination with BIM to improve construction project's management, planning, and control.

Besides the traditional methods of BIM application, construction project management tools have embraced web technologies to offer more accessible visualization options. For instance, Zhou et al. [4] developed an open BIM visualization framework that enhances model processing, rendering, and navigation within web browsers using WebGL technology. The study by Wang [5] introduced a web-based framework that allows for effective presentation and systematic analysis of IFC data to enable model exchange and project stakeholders access to a model database through internet browsers. Another study conducted by Chen et al. [6] resulted in developing a cloud-based BIM system that supports model storage, visualization, and collaborative management in a web-based platform. Additionally, the research study by Delgado et al. [7] revealed that applying BIM in combination with geospatial information and construction management processes improves project's information management and stakeholder coordination throughout the project's delivery period. The researchers argue that these BIM-based systems increase the efficiency of managing construction projects because they remove the need for powerful hardware required by traditional BIM software. This shows that web-based BIM visualization frameworks are efficient in enhancing project delivery and management and replacing conventional desktop applications.

Despite the many benefits of the BIM-based system and the recent developments in applying the BIM technology for construction project planning and construction process visualization, most of the available solutions have limited features, such as web-based BIM processing, project scheduling, and collaboration tools. The majority of the researchers have focused on the application of one aspect of BIM in construction projects, such as visualization, project's scheduling, and project collaboration [3], [6], [7]. This implies that researchers have overlooked the potential of developing a system that merges the following features: project planning and scheduling, BIM model processing, visualization of both the project and model in a web-based system, and project management. Table I below compares some of the related studies reviewed and the proposed BuildSim platform. From the table, it is evident that although previous research efforts have significantly enhanced BIM visualization and project's scheduling, little attention has been paid to developing a cloud-based, modular, and accessible platform that can be used in construction project management to visualize, plan, and simulate a complete construction project.

The motivation and significance of this study stem from the need to provide a more accessible and integrated platform for construction project planning and management using BIM.

Table 1 Comparison with Existing Studies.

Study	Primary Focus	Technology / Methodology	Research Gap / Limita
Azhar [1]	Adoption and benefits of BIM	Building Information Modeling	Focuses on BIM adoption and benefits; does not provide an integrated implementation platform.
Ivson *et al.* [2]	BIM visualization techniques	Systematic review of visualization methods	Reviews visualization approaches without proposing an integrated construction management system.
Park *et al.* [3]	4D BIM for construction planning	BIM integrated with scheduling	Limited emphasis on modular web-based project management and browser accessibility.
Zhou *et al.* [4]	OpenBIM visualization	WebG L-based BIM rendering	Primarily focuses on model visualization rather than scheduling and workflow management.
Wang [5]	IFC visualization	Web-based BIM model analysis	Supports interactive visualization but lacks integrated scheduling and project management.

METHODOLOGY

The proposed BuildSim platform is designed using a modular client-server architecture that employs building information modeling (BIM) processing, construction scheduling, project management, and interactive three-dimensional (3D) visualization for construction planning purposes. The platform aims to provide a web-based application that enables users to upload BIM models, develop a project schedule, view construction components using 3D visualization, and manage project information using an interactive web interface. The front and end of the application are decoupled to ensure extensibility, ease of maintenance, and modularity while also facilitating communication between the modules.

System Architecture

The BuildSim system architecture consists of two main components, namely, the front end and back end servers. The front end is developed using React, TypeScript, and Vite to provide an intuitive graphical user interface (GUI) for model visualization, project management, and user authentication. The back end is developed using Python and offers services such as user authentication, project management, BIM parsing, and construction scheduling. The front end communicates with the back end using Representational State Transfer (REST) API to share information and facilitate interaction between the modules. The application is designed in a modular manner to ensure that each component can be developed, maintained, and updated independently while also ensuring seamless integration.

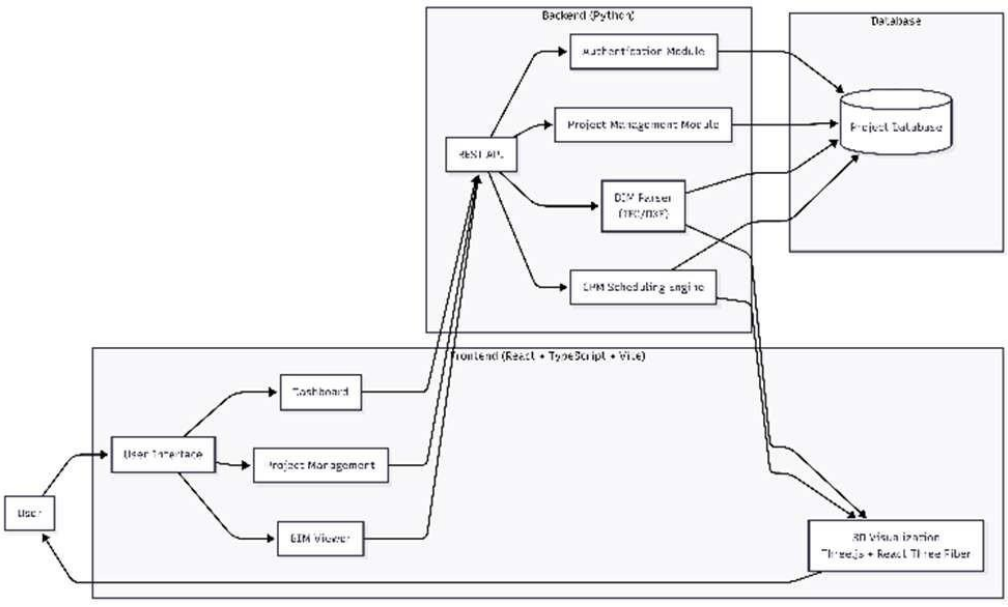


Figure 1. System Architecture

Bim Model Processing

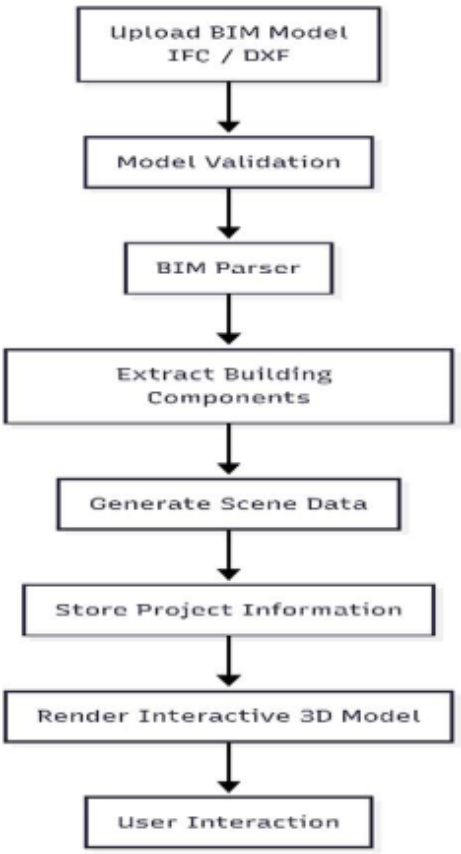


Fig 2. BIM model import and processing workflow

Project Scheduling

The project scheduling component uses the critical path method (CPM) to develop the construction schedule for the project. This component enables users to enter the construction activities and their relationships before generating a schedule that can be used to analyze the construction process. In addition to developing the construction schedule, the CPM algorithm can also be used to identify the critical activities that determine the project's overall duration. The construction scheduling information can then be combined with the BIM visualization to help users manage the project and understand the relationship between the activities and built elements.

3d Model Visualization

The 3D model visualization component uses Three.js and React Three Fiber to visualize construction models using web browsers. The component offers several interactive modules, including camera controls, object viewing, navigation, and timeline visualization, to enable users to view project models from different angles and perspectives. In addition, the 3D model viewer is integrated directly into the web browser, negating the need for users to rely on other desktop visualization tools to interact with the model. This feature is particularly essential since it enables users to make more informed decisions during the construction planning process by offering an immersive visual environment for analyzing and reviewing the project details.

Project Management

The project management component enables users to organize their projects, upload BIM construction models, and manage construction activities in a web-based platform. The component offers a dashboard where users can store and manage project data and activities and view them in the 3D model viewer. In addition, the project management dashboard also enables users to authenticate themselves and access their projects. Other aspects of this component include user authentication services, project management tools, and APIs that facilitate information exchange between the front end and back end of the application.

Software Implementation

The proposed Buildsim platform can be implemented using a combination of web technologies that enable the development of scalable and modular applications. The front end of the application can be developed using React, TypeScript, and Vite framework. The interactive 3D component can be developed using Three.js and React Three Fiber. On the other hand, the back end can be developed using the Python programming language. The implementation component should be developed in a modular manner so that the project management, visualization, and backend components can be maintained and updated independently.

EQUATIONS

The scheduling component of the proposed BuildSim platform is based on the Critical Path Method (CPM), which is a deterministic network scheduling algorithm commonly used in construction project management to define a set of activities that form the critical path of a construction project. The CPM algorithm estimates the earliest and latest possible times for each activity by representing a construction project as a directed network, where nodes correspond to activities and edges represent precedence constraints. By estimating early and late start times for all activities in the project, the algorithm identifies the project's critical path.

Activity Network Representation

A construction project is represented as a directed graph,

$$G = (V, E)$$

where

V denotes the set of construction activities,

E represents the dependency relationships among activities.

Each activity i is associated with a duration di.

Earliest Start and Earliest Finish

The earliest start time of an activity is determined from the completion times of all its predecessor activities.

$$\boldsymbol{ESi} = \boldsymbol{max}(\boldsymbol{EFj}), \forall \boldsymbol{j} \in \boldsymbol{Pred}(\boldsymbol{i})$$

where $\boldsymbol{Pred}(\boldsymbol{i})$represents the set of predecessor activities. The earliest finish time is calculated as

$$\boldsymbol{EFi} = \boldsymbol{ESi} + \boldsymbol{di}$$

These values are obtained during the forward pass of the CPM algorithm.

Latest Start and Latest Finish

The backward pass computes the latest allowable execution times without delaying project completion.

The latest finish time is given by

$\boldsymbol{LFi} = \boldsymbol{min}(\boldsymbol{LSk}), \forall \boldsymbol{k} \in \boldsymbol{Succ}(\boldsymbol{i})$ where $\boldsymbol{Succ}(\boldsymbol{i})$denotes the successor activities. The latest start time is

$$\boldsymbol{LSi} = \boldsymbol{LFi} - \boldsymbol{di}$$

These values determine the scheduling flexibility available for each activity.

Total Float Calculation

The total float represents the permissible delay for an activity without affecting the overall project completion time.

$TF\text{i} = LS\text{i} - ES\text{i}$

or equivalently,

$TF\text{i} = LF\text{i} - EF\text{i}$

Activities with zero total float are classified as critical activities.

Critical Path Identification

The critical path is defined as the longest path through the project network and determines the minimum completion time of the construction project. It consists of activities satisfying

$TF\text{i} = 0$

The project completion time is therefore computed as

$T\text{project} = \max(EF\text{i})$

where the maximum earliest finish corresponds to the terminal activity of the project network.

Table 1 CPM Parameters used in Buildsim

Symbol	Description
(d_i)	Duration of activity (i)
(ES_i)	Earliest Start time
(EF_i)	Earliest Finish time
(LS_i)	Latest Start time
(LF_i)	Latest Finish time
(TF_i)	Total Float
(T_{project})	Total project completion time

RESULTS

The proposed BuildSim platform was designed as a browser-based construction planning and simulation solution that leveraged building information modeling (BIM) processing, critical path method (CPM) scheduling, project management, and three-dimensional model visualization. The application was built using React and TypeScript framework with Three.js and React Three Fibers libraries as its visualization engine, while Python was used to develop the server-side components. The application design allowed it to be a highly modular system that seamlessly integrated all the construction planning and management processes into a single platform.

The BIM processing module allowed for importing and converting construction models into a desired format and extracting geometric and project-related information for visualization and CPM scheduling calculations. Having been processed, the construction models were visualized using the browser-based model viewer that allowed users to review, navigate the construction model, and interact with it. As such, there was no need to use third-party desktop-based applications for model visualization, which is the common practice in the construction industry.

The CPM scheduling module utilized the activities entered by the user to create a schedule that displayed the activities' earliest and latest start and finish dates along with the critical path. The results of the CPM scheduling module were then visualized within the context of the project model, enabling construction planners to see how various project activities related to project models.

In addition to the construction planning and scheduling capabilities, the proposed BuildSim platform offered robust project management capabilities and dashboards for project users. It was possible to log in to the dashboard, manage, and organize projects, and store and view construction data. Overall, the proof-of-concept prototype was able to showcase the potential of the proposed approach and the integration of different aspects of the construction process within a browser-based framework.

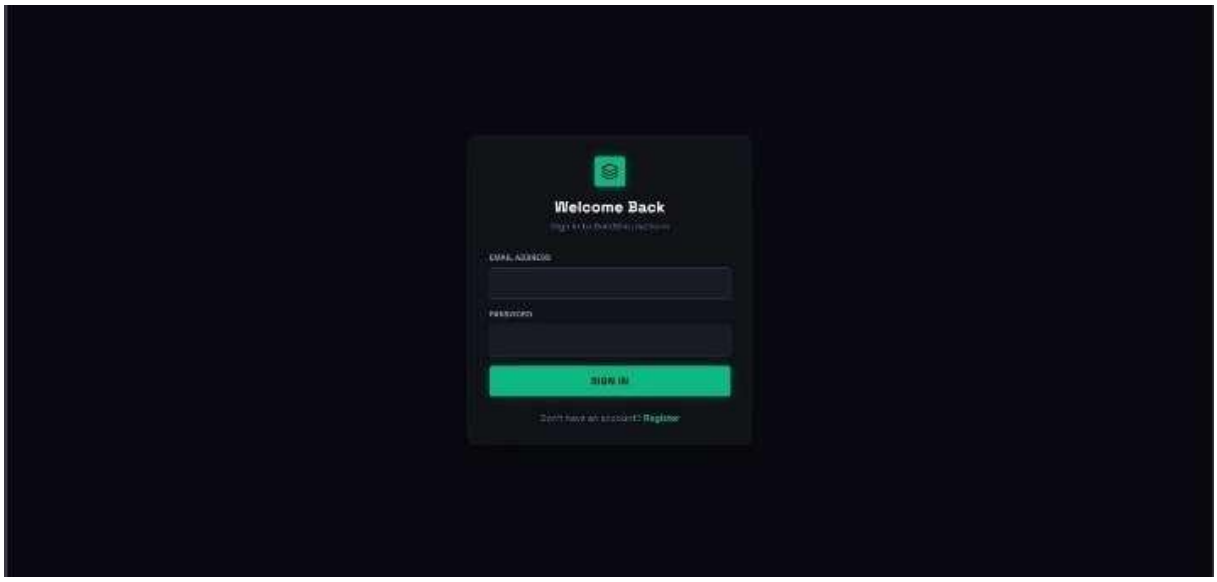


Fig 3. Login Page

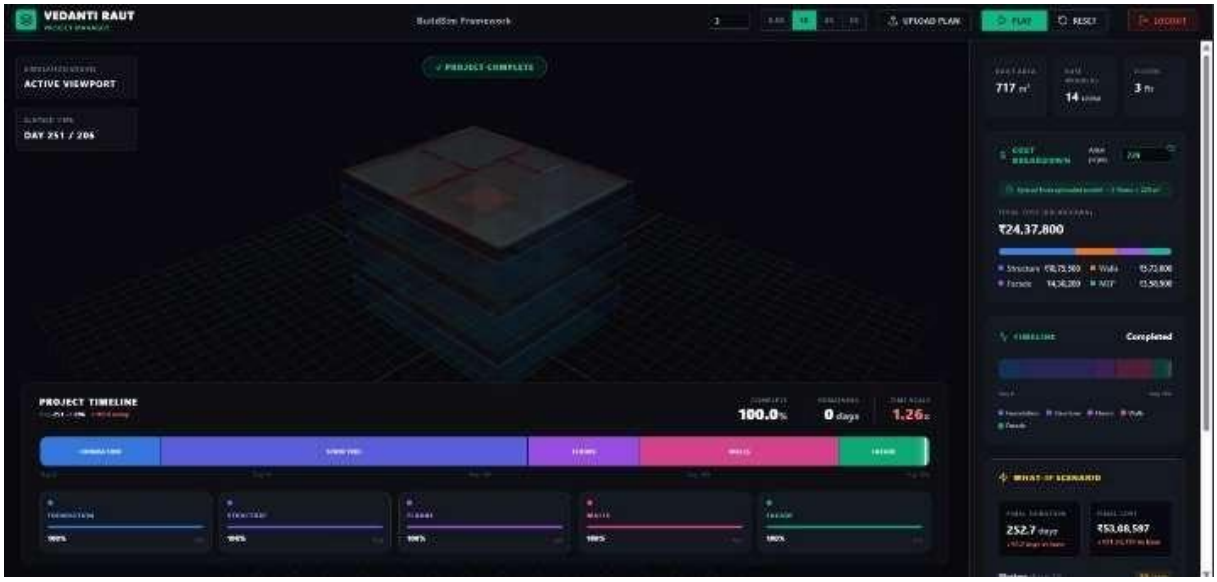


Fig 4. Project Dashboard

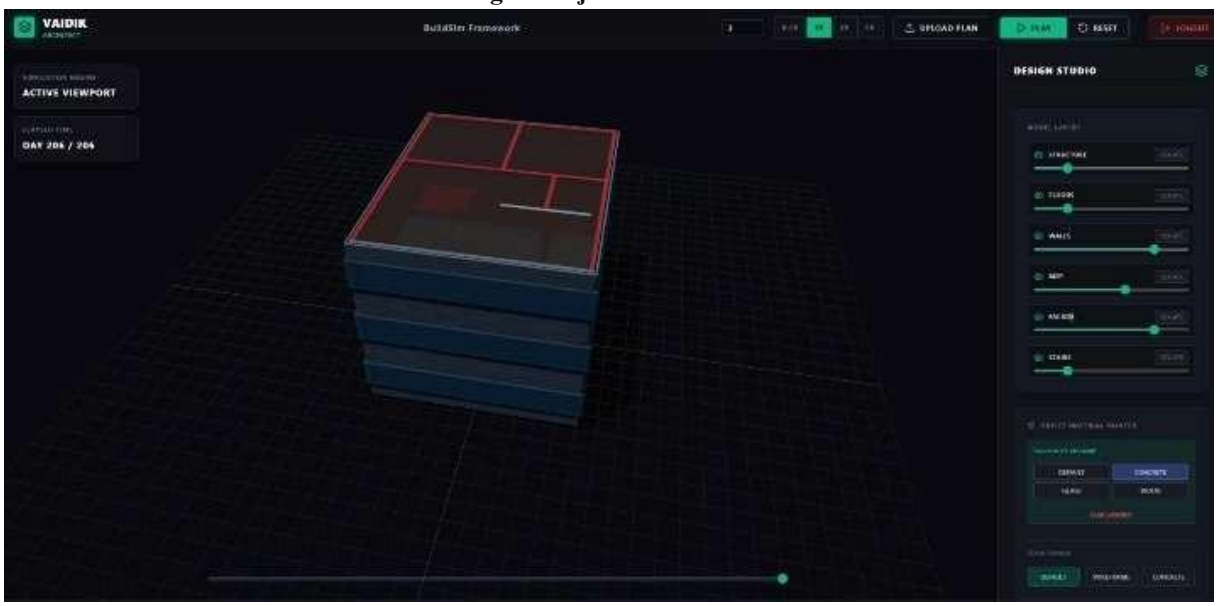


Fig 5. BIM Model Visualization

Table 3 Functional Implementation of BuildSim

Module	Implemented Functionality	Status
User Authentication	Secure login and user management	✓ Implemented
Project Management	Project creation and organization	✓ Implemented
BIM Model Processing	IFC/DXF parsing and validation	✓ Implemented
CPM heduling	Construction schedule generation	✓ Implemented
3D sualization	Interactive Three.js visualization	✓ Implemented
Dashboard	Project monitoring and management	✓ Implemented

DISCUSSIONS

The results prove that the idea of using BIM processing, CPM scheduling, project management, and browser-based three-dimensional visualization is possible and appropriate for construction planning. Contrary to the traditional method of construction planning, which includes using many different software systems for visualizing, scheduling, and managing projects, BuildSim provides all of these functions through one web platform. It allows to optimize and simplify the management process.

The given approach, which was chosen for developing the system, proved to be beneficial for the construction planning task. The separated structure of the application, based on which the client-server interaction was built, allowed to organize the work properly and make the system easily scalable and maintainable. The choice of the browser as an interface to the application made the developed system more portable and appropriate for use in collaborative work or education.

Compared to the solutions described in the literature, the developed approach implements in one system such functions as construction planning, management, visualization of building objects, and critical path scheduling. However, the previous works only offer to visualize BIM objects within a web application, manage BIM data in the cloud, or develop 4D projects. Moreover, the described concept is implemented in a light version of the software, which does not include such components as collaborative work management tools or cost estimation and scheduling.

Nevertheless, the described solution has some shortages that need to be considered. The current version of the platform is still under development, and more features are needed to make the application suitable for managing large-scale projects. These features include collaborative real-time editing of projects, optimizing resources, scheduling, and estimating costs, tracking the construction progress, and synchronization with cloud storage.

Fig 5. BIM Model Visualization

Table 2: IV : Comparative analysis of Buildsim

Parameter	Existing Approaches	BuildSim
BIM Visualization	Standalone/Desktop	Interactive Web-Based
Project Scheduling	External Tools	Integrated CPM Module
Project Management	Separate Applications	Unified Platform
Accessibility	Platform Dependent	Browser-Based
Workflow	Fragmented	Integrated
Modularity	Moderate	High
Extensibility	Limited	Easily Extendable

CONCLUSION AND FUTURE SCOPE

This paper introduced BuildSim – a web-based construction planning and simulation platform that unifies building information modeling, critical path method scheduling, project management, and 3D visualization in a single software environment. The developers created the application using React, TypeScript, Three.js, Python programming languages, and the open-source BIM library IfCJS. The application allows construction participants to manage projects, process building information models, create schedules, and visualize constructs in a simplified manner. The article highlighted that the unified approach to construction planning based on BIM and CPM technologies and implemented in a web browser can make the construction process more transparent, manageable, and efficient, and serve as a useful tool for construction education.

While the software demonstrated impressive results in terms of unifying the major aspects of construction planning, there are still some ideas that could be implemented in the future development of the application. Those include the addition of real-time project management and collaboration tools, cloud storage, project estimations, and 4D construction planning, among others. In addition, the ability to leverage more BIM standards and expand the application's capabilities beyond construction planning could be beneficial for the construction industry as it would allow participants to rely on a single source with powerful digital tools.

ACKNOWLEDGMENT

We would like to express our gratitude to the peer reviewers for their fruitful insight. We would like to express our gratitude to our guide for their experienced guidance.

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