Enhancing Construction Simulation with Building Information Modelling and Game Engine-based Visualization

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Abstract- *Construction simulation has been widely used in academia for research purposes. However, it has been neglected by the industry for various reasons, including the amount of data, skills, effort, and time required to develop complex simulation models, the difficulty of model reuse, and the abstract and confusing way in which simulation results are usually presented. This article demonstrates how BIM can be employed to facilitate the development of a construction simulation model that considers constraints related to resource allocation and task interdependencies. Furthermore, it shows how a game engine can be used as a platform to implement the proposed framework for the integration of BIM and construction simulation and to produce animations from simulation results.*

The feasibility of the framework is demonstrated through a case study on masonry construction, where crew composition optimization played a significant role in project duration. Another case study showcases the successful integration of simulation technology into industrial construction processes, enhancing planning and scheduling accuracy. The third case study evaluates the impact of muscle fatigue on construction operations, emphasizing the importance of ergonomic considerations in planning. Results of implementing the framework reveal that BIM-based simulations can reduce the skills, effort, and time required to develop simulation modelsand enable model reuse. The integration of simulation-based animations provides a model verification and validation mechanism and a means to communicate model results to stakeholders unfamiliar with simulation.

Keywords- BIM; discrete-event simulation; simulation-based animation; game engine

I. INTRODUCTION

Construction simulation is a computational method employed to model and understand the intricate behaviour of construction systems. It offers a digital sandbox where construction processes can be meticulously analyzed and experimentally manipulated. In the context of our research, we focus on a particular facet of construction simulation—modeling the construction process itself at the operational level.

These operational-level construction simulation models are designed to encapsulate the intricate sequence of tasks and activities that define a construction operation or project. Within these models, key performance indicators, such as the duration and cost of various project components, are carefully tracked and analyzed. Furthermore, they account for the dynamic utilization of different resources, including materials, equipment, skilled labour, and spatial allocations,throughout the execution of these tasks.

Historically, discrete-event simulation (DES) has stood as the dominant approach for simulating construction systems. DES employs a modeling paradigm where a system's state variables undergo instantaneous changes at distinct points in time, representing events that occur during the simulation. This enables the dynamic modeling of complex construction processes, providing valuable insights into project performance.

Building Information Modeling (BIM) stands out as a transformative innovationin the realm of architecture, engineering, and construction. At its core, BIM technology involves the creation of a highly accurate and comprehensive virtual model of a building or infrastructure project. This model is digital in nature but encompasses precise geometry, intricate details, and relevant data that collectively represent a holistic view of the project.

The primary intent of BIM is to facilitate and streamline various phases of a construction project's lifecycle, from initial design and procurement to fabrication and construction activities. BIM models serve as rich repositories of information, providing project stakeholders with a centralized and consistent source of data. This data can include architectural, structural, and mechanical details, material specifications, cost estimates, and scheduling information.

II. OBJECTIVES

- **Develop an Integrated Framework:** Create an integrated framework that combines Building Information Modeling (BIM) with construction simulation to enhance planning and decision-making in the construction industry.
- **Improve Simulation Accessibility:** Make construction simulation more accessible to industry professionals by reducing the complexity and skills required to develop and use simulation models.
- **Enable Model Reuse:** Design the framework to promote model reuse, allowing construction companies to adapt and apply simulation models to various projects.
- **Enhance Crew Composition Optimization:** Investigate the impact of crew composition on construction project performance and develop optimization techniques to determine the most efficient crew compositions for different tasks.
- **Evaluate Ergonomic Factors:** Assess the influence of ergonomic factors, such as muscle fatigue, on construction operations, and integrate ergonomic considerations into planning and decision-making processes.
- **Validate Simulation Results:** Develop simulation-based animations that serve as a validation and communication tool for stakeholders unfamiliar with simulation, ensuring the accuracy and reliability of simulation results.
- **Streamline Planning and Scheduling:** Utilize the framework to streamline construction project planning, scheduling, and visualization, improving accuracy and efficiency in these areas.
- **Enhance Resource Allocation:** Optimize the allocation of construction resources, including labour and equipment, by considering task complexity and resource availability.
- **Facilitate Real-time Adjustments:** Implement a system for making real-time adjustments to construction plans and crew compositions in response to unexpected delays, resource fluctuations, or emerging ergonomic issues.
- **Promote Sustainability:** Explore how the integration of BIM and simulation can contribute to environmentally sustainable construction practices through optimized resource utilization and reduced waste

III. METHODOLOGY

This chapter briefly explains the methodology adopted in this work.

PROPOSED FRAMEWORK

Framework Design

This research adopted a design-science methodology to create an artefact that facilitates the development of construction simulation models using BIM. The conceptual framework was implemented in a game engine-based artefact and demonstrated through case study.

The five modules of the proposed framework were designed based on the following requirements:

- Reuse of simulation models.
- Simulation modelling flexibility.
- Decision-making mechanism.
- BIM-based.

The simulation approach that underpins the proposed framework (shown as an example in Figure 3.1) is based on the distributed simulation paradigm. Sub models representing different construction activities (white squares in the figure) are composed together through hierarchical control units (black rhombuses in the figure) with parameter-based rules (white ovals in the figure) that determine the conditional behaviour of the model. Resources (white circles in the figure) and factors that affect construction, such as equipment breakdown, weather, procurement delays, and absenteeism (black hexagons in the figure) can be modeled independently.
The control unit of each construction activity submodel subscribes to the parameters published by these other models. Implementing a hierarchical control structure to control entity flow in a distributed simulation provides a mechanism to allocate shared resources among tasks of different construction activities and to comply with project-specific decision-making rules. Moreover, the federated simulation model can be scaled by parameters that represent project-specific constraints prevalent in construction. Such parameters modify directly one or more submodels or the control units that determine their behavior. These modifying parameters may be related to the product of the construction (product parameters) or the constraints of the project (project parameters).

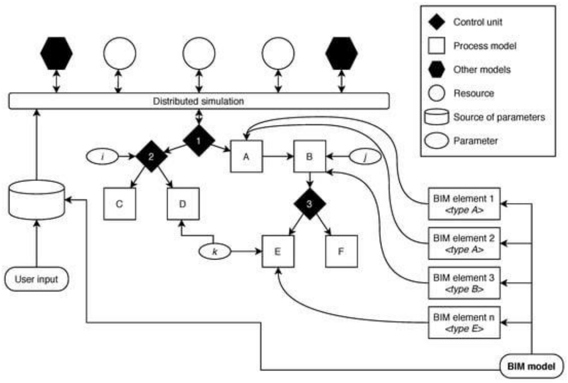

Figure 3.1. Adopted simulation approach.

Simulation-Based Animations

In the proposed framework, a game engine is used to visualize an animation of the simulation results. The approach used to generate the simulation-based animation is to adopt post-processing visualization. A collection of chronologically ordered trace files indicating the position and state of materials, workers, and equipment during each step of the simulation is generated for each simulation run following an object-oriented approach.

When a simulation event occurs, the attributes of the game objects that represent the different resources involved in the event are modified, and a new trace file is published. The new trace file saves the attributes of the relevant game objects at the corresponding simulation time. During the animation, the trace files are "played back." The resulting animation shows the interaction between the different resources involved in the construction process of the element. The animations can be visualized in a 3D environment that domain experts unfamiliar with simulation can easily interpret.

Proposed Framework

In this section, we delve into the proposed framework that aims to seamlessly merge construction simulation and building information modeling (BIM). Figure 3.2 provides a visual overview of this comprehensive framework, which is structured around five main modules. These modules are meticulously designed to empower construction professionals in enhancing their project planning and decision-making processes.

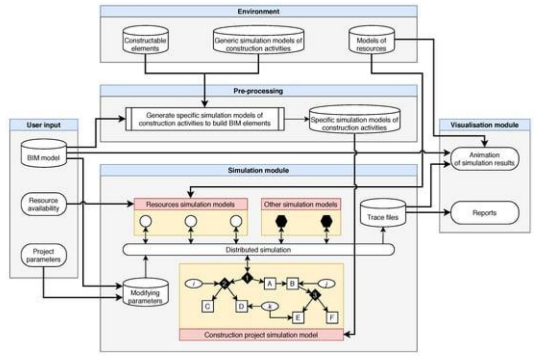

Figure 3.2. Overview of the proposed framework.

Environment Module

The Environment Module serves as the foundation of the framework, encompassing three fundamental components: Constructable Elements, generic simulation models of construction activities, and resource models. Together, these components enable the semi-automated creation of BIM-based construction simulation models and facilitate the production of simulation-based animations. Each element within the environment module can be viewed as a container, housing loadable elements that are essential for developing simulation models and animations.

User Input Module

Comprising three integral components, the User Input Module plays a pivotal role in the framework's operation:

1. **BIM Model**: This component incorporates BIM elements, from which the Constructable Element interface extracts essential information needed to develop the simulation model. This includes element type, unique identifiers, spatial coordinates, and element geometry.
2. **Resource Availability and Constraints**: This component captures critical details concerning resource availability and constraints. It includes information about the number of available workers, their skills, the types and quantities of available equipment, and details about material storage sites such as location, capacity, and restocking frequency.
3. **Project-Specific Parameters**: Users have the flexibility to input project-specific parameters, including working shifts, limits on the number of workers on-site simultaneously, and explicit interdependencies between submodels based on the preferred construction strategy, among others.

Pre-Processing Module

The Pre-Processing Module streamlines the development of the simulation model for a construction project based on its BIM model. It accomplishes this by instantiating specific submodels corresponding to the construction activities required for each BIM element. These submodels are configured with values extracted from BIM elements using the Constructable Element interface. Figure 3.3 provides a visual representation of the workflow within this module.

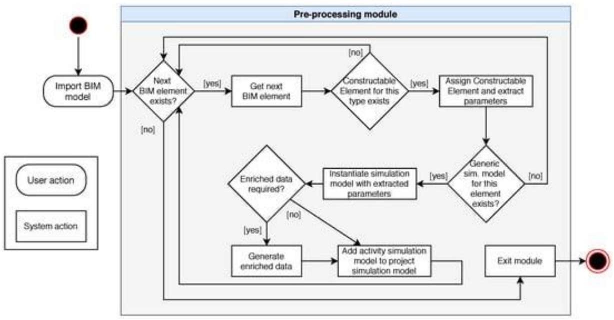

Figure 3.3. Flow diagram of the pre-processing module.

Visualization Module

The Visualisation Module, presents simulation outputs through two main channels: reports and animations.

Implementation

The practical implementation of our proposed framework was realized within the Unity game engine, providing a robust platform for construction simulation and BIM integration. To achieve the desired functionality, we harnessed several key game engine concepts and libraries. This section details the implementation steps and components of our framework:

Game Engine Fundamentals

We began by leveraging core game engine concepts:

- **Game Objects**: In Unity, game objects are fundamental entities representing characters, props, and scenery. They serve as the building blocks of our simulation, encapsulating various elements within the virtual construction environment.
- **Game Components**: Game components define the functionality of game objects. These components are essential for implementing specific behaviors, interactions, and attributes. Within our framework, they play a vital role in modeling construction elements.
- **Scripts**: Scripts, a type of game component, are pieces of code that developers use to implement custom features and logic. Our application primarily relies on scripts written in C# to extend Unity's functionality and create tailored simulations.
- **Reusable Assets**: Unity supports reusable assets, which are templates of game objects and their associated components. These templates enable us to efficiently create new instances of game objects. This capability is particularly useful when modeling repetitive construction elements.

Distributed Simulation Component

At the heart of our simulation module lies the distributed simulation component, a critical orchestrator that manages various aspects of the simulation. This component was implemented as a script game component using C#. The distributed simulation component is composed of three primary SharpSim events:

- **Run Event**: This event marks the beginning of the simulation.
- **Control Unit Event**: Serving as the highest control unit in the project's control structure, this event manages critical aspects of the simulation.
- **End Event**: This event signifies the conclusion of the simulation.

Resource Modeling

Resource management is essential in construction simulation, and within our framework, we modeled resources as 3D models accompanied by scripts containing a set of attributes. By combining these elements into a single game object, we created reusable assets.

BIM Model Integration

Our framework seamlessly integrates BIM models into the Unity environment, enhancing the synergy between BIM and construction simulation. When imported, each BIM element within the model becomes a game object within Unity. We attached scripts of the Constructable Element and generic simulation model classes to these BIM element game objects based on their type. Through a scripted process, we identified BIM elements within the scene, assigned the relevant instantiated scripts, executed methods to extract and enrich BIM data, and provided this data to the generic simulation models. Consequently, simulation models within the scene transformed from generic representations into construction activity models, closely aligned with the associated BIM elements.

Trace Files

To capture critical information during the simulation, we implemented trace files as script-based components following an object-oriented approach. Each instantiation of a trace file class contains all the essential data required for generating reports and animations. These trace files serve as a detailed log of events within the model, facilitating post-simulation analysis and visualization.

Animation and Visualization

The animations can be replayed from various viewpoints, enhancing the understanding of resource behavior and construction progression. The framework leverages Unity's capabilities, allowing users to visualize simulations in immersive virtual reality environments, potentially improving workflow efficiency within the construction context.

CASE STUDY

Case Study 1

Project Description

In this section, we will delve into the case study that demonstrates the application of the proposed framework and its components for masonry construction in a housing project. A typical masonry crew consists of two types of workers, skilled workers (masons) and unskilled laborers (helpers). The crew composition can vary depending on the specific job requirements. This case study aims to analyze various crew compositions involved in the construction of masonry walls using concrete blocks within a large housing project. While the primary focus of this case study is project duration, it's worth noting that the same approach can be adapted to study other key performance indicators, such as cost, by incorporating relevant criteria into the simulation model.

The selected project involves the construction of 746 one-story houses as part of a larger housing development in South East Mexico. To optimize crew composition and workflow, this case study focuses on determining the number of helpers required by a mason to maintain a continuous workflow. The determination is based on the distance between the house under construction and the material storage site. For this purpose, the construction site has been divided into four distinct zones, as illustrated in Figure 3.4.

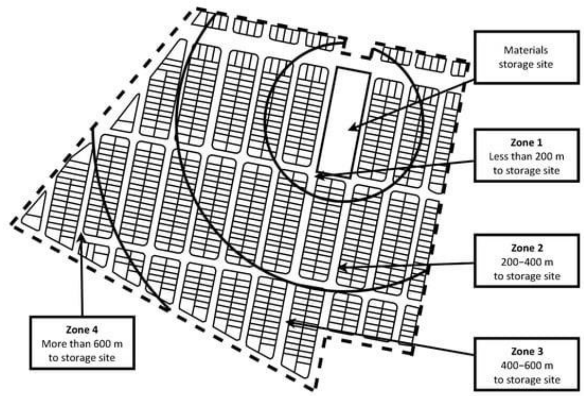

Figure 3.4. Case study site layout.

Generic Simulation Model

The federated simulation model for this project comprises instances of a generic submodel representing the selected construction activity for each masonry wall of the house prototype. This submodel is implemented as a C# script game component.

BIM Model

For this case study, we developed a model of a sample house using Autodesk Revit (Version 2018) and imported it into the scene as an FBX file. Subsequently, scripts of the Constructable Element and generic simulation model types were attached to each game object representing masonry walls.The generic simulation models utilize the geometry and location data extracted from the BIM model. The geometry information is crucial for calculating the required materials, while the location data helps determine distances between each wall and the material storage sites defined in the environment. Additionally, it assists in placing concrete blocks and workers correctly during animations.

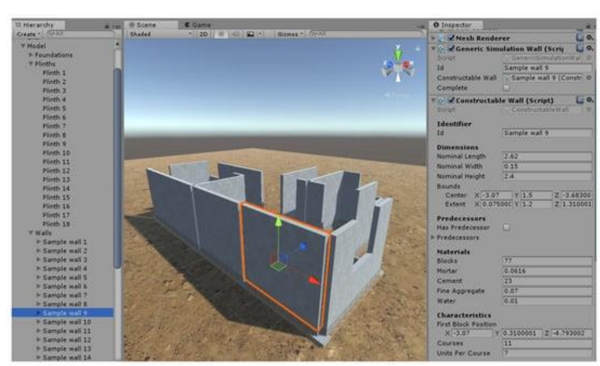

Figure 3.5. BIM model of masonry walls loaded into scene.

Simulation Model

The simulation model for the selected construction project comprises 21 wall submodels. Each submodel is linked to the Main CU event of the distributed simulation component, representing the highest control unit in the control structure hierarchy. When this event occurs, it triggers a signal to each incomplete wall submodel. All the necessary materials are instantiated as game objects at the beginning of the simulation, with predefined storage locations in the environment.

The simulation involved different scenarios for a random house from each zone, using crews consisting of a mason and varying numbers of helpers. Table 3.5 outlines the scenarios simulated to achieve the objectives of the case study. Scenarios where additional helpers did not significantly reduce the average duration of the activity were not considered. The evaluation focused on three key outcomes: (1) the duration of the construction activity, (2) the waiting time of the mason, and (3) the daily walking distance covered by helpers. Each scenario underwent fifty simulations, and the results were compared to derive recommendations.

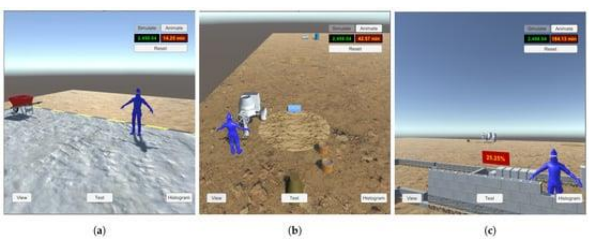

Figure 3.6. Resources at different points in time in Scenario 2. (**a**) Mason idle at time 14.25. (**b**) Mason preparing mortar at time 42.57. (**c**) Mason laying block at time 184.13.

Case Study Results

Figure 3.7 illustrates the activity durations obtained from the scenarios in Zone 3. The left side of each subfigure displays the frequency distribution of durations observed throughout the simulation runs. On the right side, a comparison is made between the empirical cumulative distribution function (ECDF) of observed results and the normal cumulative distribution function (CDF). A Kolmogorov–Smirnov goodness-of-fit test was applied to the obtained duration datasets, indicating that all duration datasets follow normal distributions with a significance level of α=0.05.

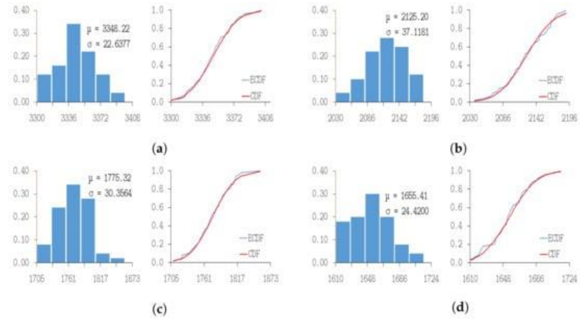

Figure 3.7. Simulation results from the scenarios of zone 3. (**a**) Scenario 6. (**b**) Scenario 7. (**c**) Scenario 8. (**d**) Scenario 9.

Case Study 2

PCL, a leader in construction within the buildings, civil infrastructure, and heavy industrial markets in Canada and the United States, has successfully implemented advanced simulation technology to improve its construction processes. With an annual work volume exceeding $6 billion, PCL is at the forefront of innovation in the construction industry.

Module Yard Facility and Industrial Module Construction

PCL's commitment to innovation extends to its module yard facility, a crucial part of its industrial construction operations. This facility specializes in industrial module construction, a method that involves extensive offsite prefabrication and preassembly (Fig. 3.8). The modules produced are large, often measuring approximately 20 ft wide, 60 to 120 ft long, and weighing between 40 to 150 tons. Industrial module construction is a fundamental aspect of construction in Alberta, and PCL's infrastructure is optimized for handling the transportation of these large and heavy modules.

Fig. 3.8. Industrial module construction prefabrication and preassembly facility (photo courtesy of U. Hermann, PCL)

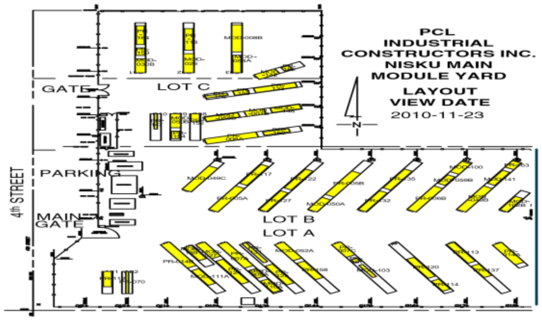

Fig.3.9. 2D yard layout drawing generated from simulation output data

Expansion to Heavy Lift Crane Scheduling

Building on the success of simulation in the module yard facility, PCL extended its use of simulation technology to the selection and scheduling of heavy lift cranes. These cranes are responsible for placing fabricated modules and other heavy equipment at industrial project sites. The scheduling process involves complex constraints, including the order in which modules must be lifted and physical limitations.

Case Study Results

The successful integration of simulation technology into PCL's construction processes highlights the collaborative efforts between PCL, the University of Alberta, and the support from NSERC. Simulation has revolutionized construction planning, scheduling, and visualization, offering enhanced accuracy and efficiency in the industry.

Case Study 3

The proposed framework is applied to a case study to demonstrate the usefulness of evaluating muscle fatigue and its impact on construction operations. In this case study, we focus on masonry work for building a three-story research complex, located at the north campus of the University of Michigan.

Site Conditions and Project Overview

Site conditions obtained from this project served as the basic conditions for developing a Discrete Event Simulation (DES) model for masonry work. As shown in Figure 3.10, the masonry work aimed to construct a concrete block wall with 7 courses and 24 concrete blocks (15.2 × 20.3 × 40.6 cm) per course. A crew for this operation consisted of three masons and one laborer. The masons took a major role in masonry work, such as cutting and laying blocks, or installing rebar if needed, while the laborer performed supportive tasks, mainly material-handling tasks, including preparation and distribution of materials (e.g., blocks and mortar).

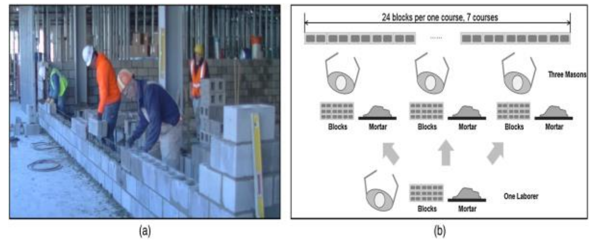

Fig. 3.10. Site conditions (image by authors): (a) site photo; (b) site layout

Evaluating Muscle Fatigue

The case study examines how different operational plans affect workers' muscle fatigue, and in turn, time and cost performance of the masonry work. Figure 3.11 shows physical demands and corresponding muscle fatigue for a mason and a laborer according to different crew compositions when voluntary rests to recover from fatigue are not considered. Muscle fatigue can significantly affect work performance, especially for the laborer due to excessive physical demands.

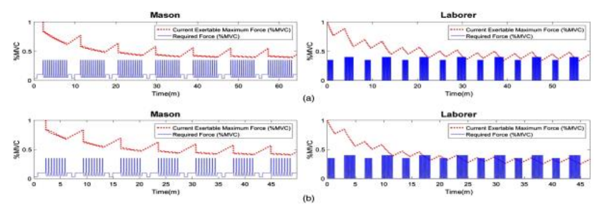

Fig. 3.11. Fatigue evaluation for masonry work with different crew compositions: (a) two masons and one laborer; (b) three masons and one laborer.

Case Study Results

This case study on masonry work demonstrates how the proposed framework can be applied to actual construction operations. It highlights the importance of considering muscle fatigue in construction planning and decision-making. The framework enables the identification of potential ergonomic issues and supports the development of effective ergonomic interventions prior to work.

Case Study Common Result:

The common result, when aligning with the use of BIM and game engine-based visualization, is that these technologies enable construction companies to not only optimize crew compositions for construction tasks but also visualize and simulate these optimizations effectively. BIM provides detailed 3D models and data-rich insights into the construction site, while game engine-based visualization offers immersive experiences that aid in assessing crew compositions and their impact on project efficiency and worker well-being.

Solution:

To harness the potential of BIM and game engine-based visualization for crew composition optimization, construction companies can implement the following solution: Integrate BIM and Game Engine-Based Visualization for Crew Optimization.By aligning BIM and game engine-based visualization with crew composition optimization, construction companies gain a powerful toolset that not only enhances project planning but also allows for dynamic adjustments based on real-time insights. This integrated approach promotes efficiency, reduces costs, and prioritizes worker well-being throughout the construction process.

IV. CONCLUSION

In summary, this article delivers a multifaceted contribution that marks a substantial advancement in the field of construction simulation modeling. Its three core contributions include an innovative simulation modeling approach, the development of a robust framework, and the practical utility of the implemented framework as a planning tool. The novel simulation modeling approach, utilizing distributed simulation, hierarchical control structures, and parametric modeling, facilitates seamless integration between BIM and construction simulation models. This approach empowers users to create highly detailed models that account for project-specific constraints and offers simulation-based animations for visualization and validation.

While these contributions represent significant strides, there are promising avenues for future research and development in this domain. Firstly, augmenting libraries housing Constructable Elements and generic simulation models for construction activities is essential. As these libraries expand and diversify, they will enable the creation of even more intricate and accurate simulation models. Secondly, enhancing simulation-based animations is crucial for providing a more dynamic representation of resource motion. This evolution will contribute to a more immersive visualization experience.

As we look to the future, this research serves as a testament to the potential for innovation and advancement within the field of construction simulation modeling. By addressing identified limitations and pushing the boundaries of simulation-based construction modeling, researchers can continue to shape the future of construction planning and execution. The integration of cutting-edge technologies and methodologies promises to revolutionize the construction industry, making it more efficient, cost-effective, and environmentally sustainable.

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