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Research Article

From 3D to 4D BIM: A Framework for Automating Construction Planning and Resource Optimization

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Abstract

Cost overruns and schedule delays are persistent challenges in the construction phase. Developing a feasible and optimized construction plan is essential for efficient resource allocation and reliable cost estimation. Despite technological advances, many planning, inspection, and progress control processes remain manual and time-consuming. Although scheduling tools like the Critical Path Method (CPM) are common, key inputs such as task durations, sequences, and resource needs are still manually determined, with limited integration into 3D models and minimal automation. Although 4D Building Information Modelling (BIM) offers significant potential, its adoption remains limited, particularly in some developing countries, due to high initial costs and implementation challenges. This paper proposes a framework that automates the development of optimized construction schedule for reinforced concrete buildings. Using 3D BIM data, the framework generates a Work Breakdown Structure (WBS), produces detailed schedules, and links them with the BIM model to simulate progress, plan daily resource use, and minimize consumption. By integrating 4D BIM, the system enables the visualization of construction sequences, the evaluation of alternative methods, and the comparison of multiple execution scenarios based on time and resource constraints. The framework supports early decision-making, reduces planning time, and improves project delivery outcomes.

Keywords: Building Information Modelling (BIM); Construction Scheduling; Automation in Construction; BIM Integration; Resource Optimization

Highlights

- BIM-based automation framework that enhances scheduling process from 3D models.
- Seamless integration to simulate the generated schedules and the 3D model
- Resource optimization ensures realistic schedules with balanced manpower distribution.

1 Introduction

Building Information Modelling (BIM) has developed the construction industry by enabling detailed digital representations of buildings and infrastructures. Expanding to 4D, BIM began incorporating time-based simulation, allowing project teams to visualize construction sequences. Tools like Navisworks allow stakeholders to simulate activities and logistics in parallel with design updates. In recent years, BIM has also evolved to include 5D cost modelling and risk management capabilities (Abanda, 2020), supporting financial planning and proactive schedule risk mitigation using platforms such as Synchro and Vico.

Despite BIM's growth, scheduling tasks often remain manual and disconnected. Traditional tools like MS Project or Primavera require planners to extract quantities and define tasks by hand, processes prone to error and inefficiency. When BIM and scheduling are not integrated, schedule updates become burdensome, and data misalignment may occur. Beyond time-based simulation, BIM has further expanded to include cost modelling, referred to as 5D BIM. This capability allows for the integration of cost-related data – such as unit prices, labour costs, and material quantities – directly into the model. As changes are made to design or schedule, the cost impacts can be automatically estimated and updated. This enhances cost forecasting, budgeting, and financial decision-making, allowing contractors and clients to perform detailed cost analysis early in the project lifecycle through the BIM model. Tools such as Autodesk Revit with CostOX, Navisworks with 5D plugins, Vico Office, and Synchro have been developed to include 5D cost estimation, delivering real-time inputs into cost performance, like Power Bi dashboards.

Automation promises increased productivity, improved accuracy, and reduced project overhead. Research has proposed various solutions: (Hu et al., 2023) developed robust scheduling algorithms for multi-skilled resource planning under uncertain durations, using reinforcement learning. However, their approach starts from a pre-defined baseline. (Zhu et al., 2022) proposed an adaptive real-time scheduling model using neural networks, allowing for dynamic, policy-driven adjustments in uncertain environments, an approach well aligned with BIM's evolving needs.

2 Theoretical and Conceptual Foundations

This section establishes the theoretical basis of the study, reviewing the ongoing research on BIM-based automation, construction scheduling, and the digital integration frameworks between the scheduling and simulation software.

2.1 Defining Key Concepts

Building Information Modelling (BIM) is a process that integrates both the graphical and informational aspects of a construction project into a single digital environment, like REVIT environment. Unlike CAD, which provides primarily geometric or 2D representations, BIM captures 3D geometry, materials, construction logic, and other semantic data of our project (Kim et al., 2013).

4D BIM builds on this by introducing a time-based dimension, linking construction elements to schedule data to enable visualization of construction sequences over time. Automation in BIM scheduling refers to the use of algorithms or rule-based logic to generate construction tasks, estimate durations, and apply logical sequencing with minimal human input (Kim et al., 2013; Abanda & Byers, 2017).

In this study, we employ Work Breakdown Structure (WBS), which refers to the hierarchical decomposition of a project into work packages, each associated with one or more BIM elements (Tinger, 2019). Resource-Constrained Project Scheduling Problems (RCPSPs) are defined as optimization problems where project activities must be scheduled while respecting precedence relationships and resource limitations (Herroelen & Leus, 2004).

2.2 Literature Review

Multiple frameworks underpin the development of automated BIM scheduling. The work of Kim et al. (2013) in demonstrating a framework paved the way to automatically extract quantities, materials, and spatial data from IFC-based BIM models to generate activity durations and preliminary schedules using RSMeans productivity rates.

Other approaches, such as those by Kim et al. (2013) and Aalami and Fischer (1998), incorporate rule-based logic and construction method templates to build sequencing relationships. However, these frameworks still require manual input for custom construction elements.

Recent developments in artificial intelligence have introduced reinforcement learning and genetic algorithms to address dynamic scheduling environments (Zhu et al., 2022; Elghaish et al., 2020), but these often assume a predefined baseline schedule rather than a fully automated generation.

From an optimization perspective, RCPSP has been the dominant model for formulating and solving construction scheduling problems under constraints. These models are often solved using Mixed Integer Linear Programming (MILP) or metaheuristic approaches, depending on problem scale and complexity (Hartmann & Briskorn, 2010).

Likewise, Fazeli et al. (2024) designed an automated 4D BIM development method combining optimization algorithms and resource specification models to enhance resource-leveling and workflow realism.

2.3 Knowledge Gaps and Research Opportunities

Despite significant advancements in automation and 4D BIM integration research, several notable gaps persist. Firstly, most tools still rely on manual assignment of durations and task types, limiting their reliability and accuracy. (Kim et al., 2013). Secondly, many frameworks struggle to handle project-specific variations in construction procedures or customized elements (Hu et al., 2023).

Furthermore, few approaches have successfully integrated resource optimization directly into the BIM workflow, especially for small- and medium-scale contractors. The lack of seamless interoperability between BIM platforms (e.g., Revit) and scheduling/optimization environments (e.g., Python, Gurobi) creates barriers to implementation.

Residual User Interventions in 4D BIM Linking also remain a significant challenge. Despite the advancements introduced by Fazeli et al. (2024), their proposed framework—as with the one presented in this study—still requires user intervention. Specifically, users must manually attach BIM elements to each activity to generate the 4D simulation model. Furthermore, they are expected to correctly assign the activity columns corresponding to predefined classification tables to ensure accurate linkage between tasks and BIM elements. This highlights the need for further automation in the 4D integration process to reduce human effort and minimize potential mapping inconsistencies.

This research addresses these gaps by developing a framework that:

1. Automatically defines work packages and schedules directly from BIM elements,
2. Integrates resource optimization based on RCPSP, and
3. Links outputs to 4D simulation tools (e.g., Navisworks), reducing manual workload and enhancing schedule robustness.

2.4 Proposed Conceptual Model

The proposed conceptual model outlines a data-driven workflow that links BIM elements to construction activities, applies production rates to compute durations, and generates a dependency-aware logical schedule. This schedule is then optimized under resource constraints using MILP solvers and re-integrated into the BIM environment.

The model consists of four main phases:

1. BIM Elements Processing – Filtering Elements, extracting properties and quantities.
2. Schedule Generation – Creating Work packages for each 3D element, calculate durations, and sequencing.
3. Schedule Optimization – Formulate the RCPSP problem, minimize the resource consumption by solver-based makespan.
4. 4D Simulation Integration – Auto-linking optimized activities to 3D model for visualization.

This model serves as both the architectural backbone and operational logic of the research, enabling end-to-end automation of construction scheduling within a BIM framework.

3 Methodology

This study adopts a mixed-methods research design, combining rule-based algorithmic development, computational modelling, and optimization techniques with case study validation to demonstrate the feasibility of automated schedule generation in BIM environments. The mixed-methods approach is appropriate for addressing the current study's objective to develop a fully automated framework for generating construction schedules, optimizing resource allocation, and producing 4D simulations with minimal human intervention.

The methodology is designed to bridge the gap between traditional scheduling practices and BIM-integrated automation. It does so by employing quantitative procedures, such as algorithmic logic to create the schedule, mathematical optimization (RCPSP) to optimize the resources consumption within the available limits, and productivity-based duration estimation.

3.1 Research Design and Tool Environment

The framework integrates several computational tools and environments to enable seamless automation:

- Autodesk Revit for 3D model development and element classification.
- Dynamo and Python for parametric data extraction, logic-based activity generation and sequencing.
- Microsoft Excel + VBA for defining work packages, productivity rates, and enabling flexible user inputs.
- Pyomo and Gurobi for mathematical modelling and solving resource-constrained scheduling problems (RCPSP).
- Navisworks Manage for 4D simulation and visualization of schedule execution over time.

The tools were selected for their compatibility with BIM workflows, extensibility, and ability to automate previously manual planning tasks.

3.2 Methodological Framework

The proposed methodology is structured into sequential stages that reflect the process from data collection to simulation. These steps are:

1. Definition of Work Packages and construction methods: Users define tasks using flexible templates that represent real-world construction processes, such as the typical work packages for each element type (e.g., PC Formwork → PC Pouring → RC Formwork, see Step 1 in Figure 1).
2. Activity List Generation from BIM Elements: BIM elements are classified by category (e.g., structural slabs, columns), grouped by levels and zones, and assigned tasks using Dynamo and Python. Construction logic (e.g., Structural Foundations → Columns→ Walls → Floors, see Step 2 in Figure 1) is encoded as user-defined rules or derived from historical data and logical sequence.

3. Zone Extraction and Sequencing: Elements are grouped into zones based on spatial definitions (levels, grids, joints). Zone-level dependencies are defined by users to reflect actual execution plans (Li, X,2010) & (Bilec, 2006).
4. Duration Estimation: Durations are calculated using BIM-derived quantities divided by productivity rates. These rates are sourced either from historical data or industry standards.
5. BIM-Based Schedule Generation: The defined task sequences and estimated durations are integrated to generate a schedule like the baseline schedule. Productivity rates are allocated to each task type and start/finish times are computed accordingly. (See Section 3.2.1)
6. Schedule Optimization: The RCPSP is formulated and solved using Pyomo and Gurobi to minimize makespan while satisfying resource and precedence constraints. (See Section 3.2.2)
7. Linking to BIM for 4D Simulation: Activity IDs are embedded into Revit model elements via shared parameters (to be linked later with the 4D simulation model). The enriched model and schedule are integrated into Navisworks TimeLiner. (See Section 3.2.3)
8. Schedule Evaluation. (See Section 3.2.4)

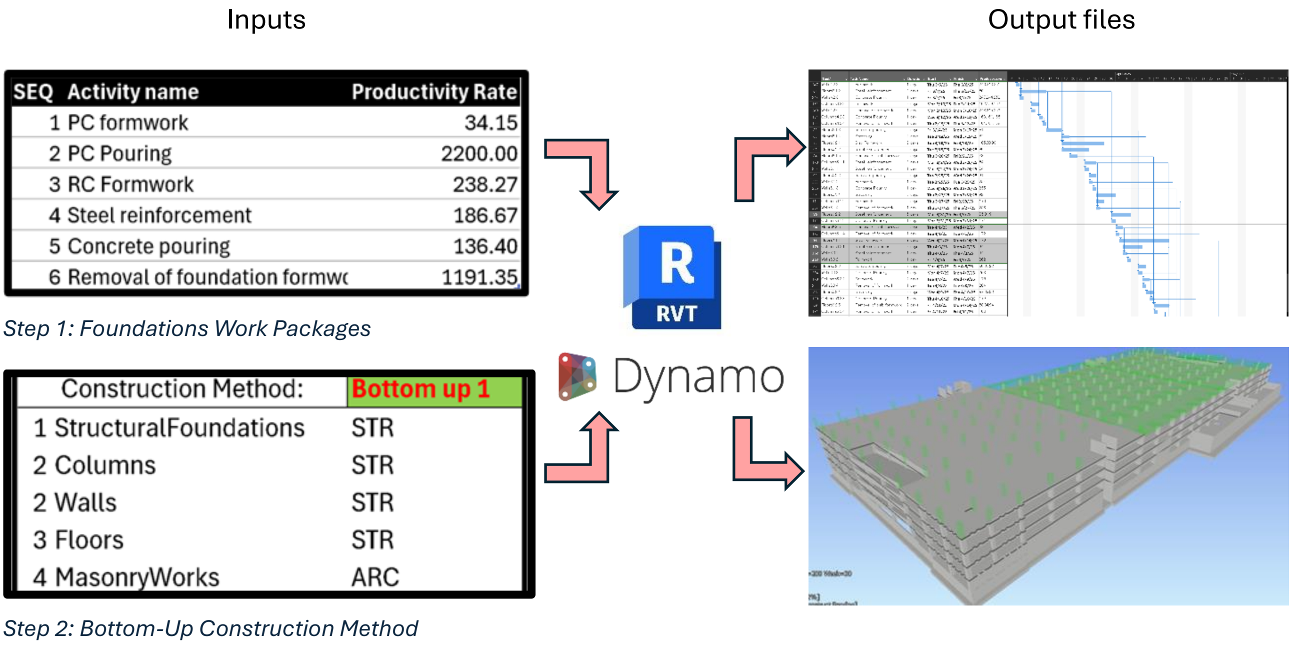

Fig. 1 Outline of the Proposed Methodology

3.2.1 Data Collection and Processing (Steps 1 – 5)

To automate the generation of construction schedules from BIM models, this framework employs a combination of Autodesk Dynamo visual scripting and Python-based scripts. Dynamo allows users to filter, extract, and structure Revit model data without requiring advanced programming skills, while Python handles logic processing, activity sequencing, and data transformation.

The process begins with automatically filtering elements by category (e.g., structural columns, floors) and assigning parameters such as Zone ID and Task Type. Quantities like volume and area are calculated, and the extracted data is exported to Excel or CSV formats for use in downstream schedule generation.

The core scheduling logic includes assigning unique Activity IDs to each task based on the element type, level, and zone. This structure helps distinguish tasks and supports traceability across the schedule.

Python scripts then use this structured data to generate:

- Activity IDs

- Quantities
- Predecessor logic (based on zone-level dependencies and user-defined sequencing rules)

Tasks are grouped by zone and discipline (e.g., structural, architectural), and the logic accounts for spatial execution order, such as completing columns before walls. Dependencies are created dynamically by analyzing the relationship between tasks across zones, simulating realistic construction flows. Finally, user-defined productivity rates are applied to the extracted quantities to calculate task durations and generate BIM-based schedule.

3.2.2 Schedule Optimization (Step 6)

An optimization step was added to improve the initial schedule by resolving resource imbalances. The model was formulated as a Resource-Constrained Project Scheduling Problem (RCPSP), aiming to maintain the total project duration while ensuring that resource consumption remains within the available limits and that activity sequencing is respected.

The optimization process was implemented using Pyomo as the algebraic modeling framework and Gurobi as the MILP solver, selected for its high efficiency with large-scale scheduling problems. This optimization was integrated into the BIM workflow in four key steps: data extraction from the generated schedule, model formulation, solution using the solver, and reintegration of optimized timings into the 4D BIM model for visualization.

The problem is structured as a Resource-Constrained Project Scheduling Problem (RCPSP), which is a well-established NP-hard problem in operations research. The RCPSP involves determining start times for each activity in a project, given precedence, and resource constraints, such that the makespan (total project duration) is minimized.

Inputs

A: Set of all project activities	u_{ir}: Resource usage of activity i on resource r per unit time
p_i: Duration of activity $i \in A$	c_r: Total capacity of resource $r \in R$ per unit time
R: Set of resource types	T: Project time horizon

Decision Variables

$x_i \in Z_{\geq 0}$: Start time of activity i

$a_{i,t} \in \{0,1\}, 1\ if\ acitivity\ i\ is\ active\ at\ time\ t, 0\ otherwise$

$project\_end \in Z_{\geq 0}$: the latest finish time across all activities

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Define Objective

Minimize the project duration, defined by the latest finish time of all project activities:

$$Minimize\ project\_end$$

This means the model seeks the shortest total project duration by identifying the latest activity finish time.

Constraints

Start Time Feasibility: $0 \leq x_i \leq T - p_i \ \ \forall i \in A$

Precedence Constraints: $x_j \geq x_i + p_i \ \ \forall (i \rightarrow j)$

Activity Time Window Indicators:
Enforce $a_{i,t} = 1$ if and only if activity i is active at time t: $x_i \leq t + M(1 - a_{i,t})$

$$t + 1 \leq x_i + p_i + M\left(1 - a_{i,t}\right) \ \forall i \in A, \forall t \in T$$

Where M is a large constant (e.g., $M = T$)

Resource Constraints: $\sum_{i \in A} u_{ir} \, a_{i,t} \leq c_r \ \forall r \in R, \forall t \in T$

Early Start Enforcement: $project\_end \geq x_i + p_i \ \forall i \in A$

Solver & Output:

- The model is implemented using Gurobi with integer start-time variables and binary time-activity indicators.
- After optimization, the output schedule is exported to Excel, listing each activity's start and end time.

3.2.3 BIM Integration (Step 7)

Activity IDs are embedded in the Revit model and linked with the optimized project schedule in Navisworks to enable 4D simulation.

3.2.4 Empirical Case Study Validation (Step 8)

The framework was applied to a real-world commercial building project. The generated schedule and the optimized schedule were compared in terms of:

- Project duration (makespan)
- Resource utilization consistency
- Feasibility of task sequencing
- Visual 4D simulation accuracy in Navisworks between both models
- Robustness Analysis: Assess schedule stability against potential delays during execution.

The outputs were validated against expert planning logic typically used by experienced project planners.

4 Results - Key Findings

This section presents the results of case studies in which the proposed automated BIM-based scheduling and optimization framework was applied to a real construction project — a commercial building in Riyadh. The findings are structured to align with the study's objectives, including automated activity list generation, schedule creation, resource optimization, and 4D simulation integration all within the same framework.

4.1 Automated Schedule Generation (Pre-Optimization)

- The proposed framework successfully generated construction activity lists directly from the 3D BIM models.
- Each activity was assigned a unique ID, estimated duration (based on extracted quantities and productivity rates), and logical dependencies.

- The generated schedule included start and finish times prior to optimization, forming the baseline for further evaluation.
- Resource histograms demonstrated excessive and uneven use of construction resources in the unoptimized schedule (see **Error! Reference source not found.**2).

4.2 Schedule Optimization Output

- After applying the RCPSP optimization model, the schedule was restructured to reduce resource overload while preserving the original project makespan (See Table I).
- Non-critical tasks were shifted to balance daily workloads and minimize idle time.
- A comparative histogram analysis (Figures 2 & 3) illustrates these improvements clearly.

Table I. A comparison of total number of crews for each type of resources before and after the optimization model

Resource Name	Generated Schedule	Optimized Schedule
Formwork & Scaffolding	24 Crews	16 Crews
Steel Fixers	32 Crews	16 Crews
Concrete Pouring	24 Crews	8 Crews

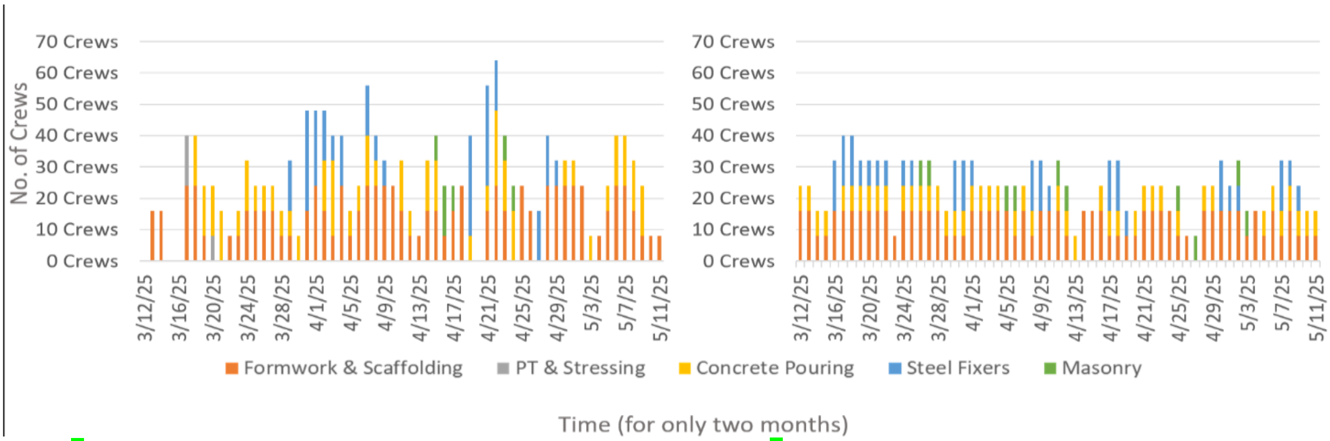


Figure 2 Resource Histogram (for only two months) - Generated Schedule

Figure 3 Resource Histogram (for only two months) - After Schedule Optimization Schedule

4.3 4D Simulation Output

- The final schedule was successfully linked to the 3D BIM model using shared parameters and exported to Navisworks for time-based simulation.
- Each activity's timing was reflected in the simulation output, enabling stakeholders to observe logical sequence in a time-aware format.
- Figure shows snapshots of the resulting 4D simulation (25%, 50%, 75% and 99% progress).

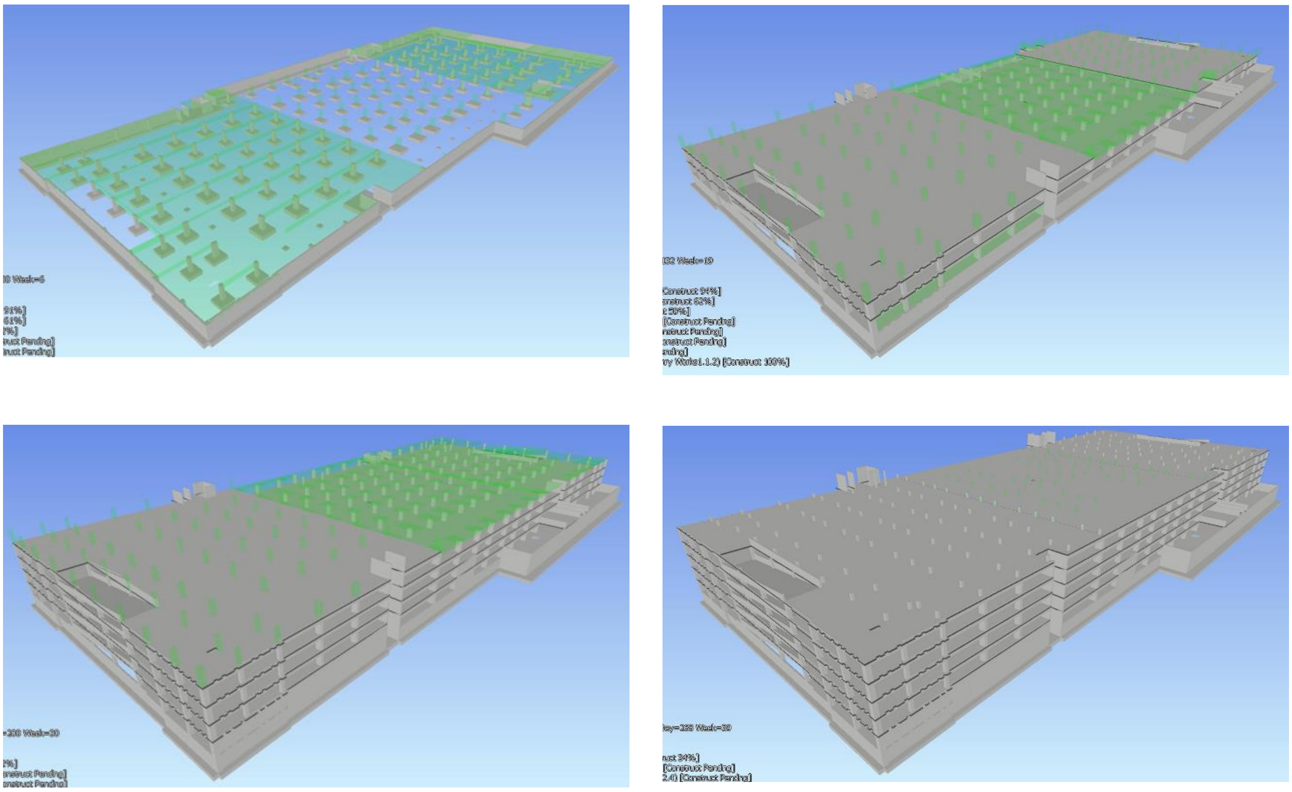
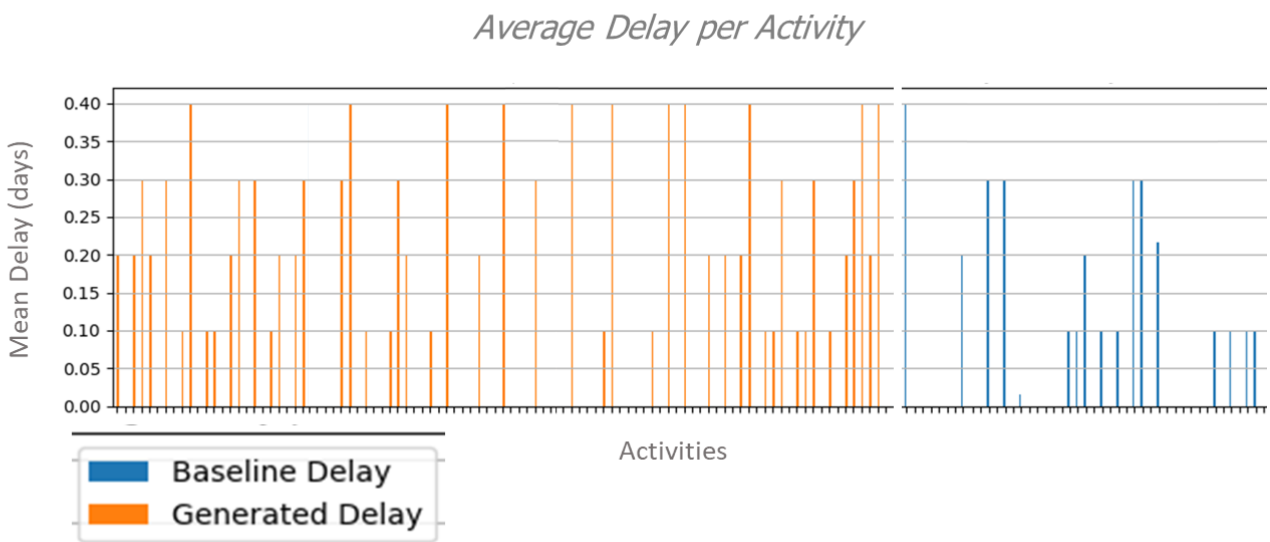


Figure 4 The proposed case study - The 4D simulation file created by the framework

4.4 Robustness score

This section introduces a quantitative method to evaluate schedule robustness by simulating uncertainty in activity durations and measuring how well the schedule absorbs delays; how much will the actual execution times deviate from planned start times when durations are uncertain. To this goal, we adopt the robustness evaluation model inspired by the work of (Ke, H., 2015) where multiple linear uncertain variables are used to model duration variability. This approach uses a belief-based system that is both fast to compute and easy to understand. Each activity's duration is assumed to be within a bounded interval and varies based on increasing belief degrees. The expected deviation across multiple scenarios becomes the basis for calculating a robustness score for the schedule. By using this method, the generated schedule will be evaluated in terms of the robustness, along with the baseline schedule.



The calculated robustness scores, lower value means the schedule deviates less from plan under uncertainty.

5 Discussion

The methodology applied a quantitative design using real project data extracted directly from Autodesk Revit models. Dynamo visual scripting and Python automation were employed to classify elements, assign construction zones, and generate structured activity lists. Task durations were then estimated using BIM-derived quantities and standard productivity benchmarks, forming the foundation for Critical Path Method (CPM) scheduling. A further optimization step was introduced to resolve resource overloads by framing the problem as a Resource-Constrained Project Scheduling Problem (RCPSP), solved using Pyomo and Gurobi.

The key findings highlight how the initial logic-based schedule, despite the logical task sequencing, often exceeded resource availability and failed to ensure smooth resource distribution. Resource histograms before and after optimization confirmed reduced peak demands, improved continuity of crew utilization, and minimal changes to the total project duration. These outcomes demonstrate the value of combining logic-based sequencing with mathematical resource optimization, particularly in resource-limited environments common in real construction projects.

6 Conclusions

6.1 Summary of Findings

The automated and optimized BIM-based scheduling system showed clear benefits, including:

- Implementation with widely available tools: The framework is built using commonly accessible software (Revit, Excel, and Navisworks), even feasible for small- and medium-scale contractors.
- It goes beyond traditional CPM methods by reducing project duration while achieving balanced resource allocation.
- It enables 4D BIM integration, enhancing construction visualization and stakeholder coordination.
- The entire workflow remains within the BIM environment, ensuring data consistency and seamless platform interoperability

6.2 Limitations and Suggestions for Future Work

Future research may focus on:

- Enhanced Data Collection and Machine Learning Integration: Developing methods to gather comprehensive, project-specific historical data to improve predictive analytics.
- Integration of 5D BIM: Including comprehensive cost integration (5D BIM) within the scheduling framework to enhance budgeting accuracy and financial planning.
- Improving Computational Efficiency: Due to increased computational complexity for larger projects that may affect optimization run times, improving computational efficiency is necessary.
- Refinement of Automation: Due to the manual definition of zones, construction joints, and the restriction to finish-to-start (FS) activity relationships, there is a need for continued refinement of automation to accommodate complex relationships and dynamic project conditions in future.

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Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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