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BUILDING INFORMATION MODELING (BIM) AND SMART TECHNOLOGY INTEGRATION FOR OPTIMIZATION BUILDING LIFE CYCLE MANAGEMENT

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ABSTRACT

Abstract: Collectively, these five journals highlight the central role of Building Information Modeling (BIM) as an integrated data foundation, combined with smart technology and optimization to address complex challenges throughout the building asset lifecycle. The first journal proposes a dynamic framework that integrates BIM and Artificial Intelligence (AI), using a three-layer architecture and advanced engines (such as the 4-in-1 Network Diagram Engine and Blueprint Engine), to improve construction schedule management and overcome the limitations of static tools such as Gantt charts. This connection is reinforced by the second paper, which presents a dynamic BIM scheduling framework that combines Discrete Event Simulation (DES), System Dynamics (SD), and ACOR optimization algorithms to adaptively adjust schedules and costs based on real-time productivity and budget constraints, resulting in up to a 34.4% improvement in project duration accuracy. Meanwhile, the third paper applies Integer Linear Programming (ILP) in a microservice-based BIM architecture to optimize scheduled maintenance (Operation & Maintenance/O&M) by grouping tasks to minimize operational disruption, which was shown to reduce total active workdays by up to 58.9%. The integration of optimization algorithms is also evident in the fifth journal, which uses the Sine Cosine Algorithm (SCA) for constructability assessment and scheduling, supporting the theme of multi-dimensional optimization. The fourth journal brings a sustainable design perspective by utilizing BIM (Revit and Insight 360) to analyze and optimize building energy performance against ARCH2030 and ASHRAE 90.1 standards in various climates, highlighting that optimized designs can reduce energy consumption by 46% to 50%. Overall, the five studies demonstrate that the integration of BIM with various advanced computational techniques (AI, simulation, and metaheuristic algorithms) is crucial for the transition from static planning to dynamic, accurate, and adaptive project management throughout the building lifecycle.

Keywords: *BIM; AI; Scheduling Optimization; Energy Management; Scheduled Maintenance*

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A. BACKGROUND

The construction industry faces increasing demands for smarter and more systematic project management, but traditional project scheduling tools, such as Gantt charts, often struggle with dynamic adjustments and real-time optimization, resulting in inefficiencies and delays. In general, about 85% of large-scale construction projects experience schedule overruns, largely due to inflexible progress planning and slow response mechanisms. In addition, conventional methods tend to rely on manual trial-and-error processes, which result in rigid estimates and require costly revisions mid-project. In the Operations and Maintenance (O&M) phase, the challenges are even greater because this phase is usually the longest in a building's life cycle, and planning inefficiencies can lead to operational disruptions and increased costs.

This inherent limitation lies in the static nature of conventional scheduling methodologies, which hinders responsiveness to dynamic execution variables (e.g., sudden weather changes, supply chain disruptions, or emerging location risks). Research shows that existing models, despite integrating BIM and AI, often still rely on static models that fail to adequately account for project uncertainty. In the context of O&M, maintenance activities tend to be interpreted as a series of independent projects, resulting in fragmented schedules and inefficiencies. Furthermore, the simplification of the non-linear relationship between time and cost in traditional planning contributes to significant inaccuracies. Therefore, there is a clear need for a framework capable of integrating real-time data and advanced computational techniques to address the multi-variable complexity in project management.

A prominent solution is the deep integration of Building Information Modeling (BIM) and smart technologies, which promises overall improvement in asset management. BIM is broadly defined as a digital methodology for generating and managing asset data throughout its lifecycle, facilitating collaborative decision-making. Studies show that BIM improves efficiency and precision, providing advantages in cost evaluation and real- time visualization that enhance transparency and collaboration. On the other hand, Artificial Intelligence (AI) technologies including Machine Learning (ML), Genetic Algorithms (GA), and Reinforcement Learning (RL) have been applied to analyze historical data, predict delays, and intelligently optimize scheduling and resource allocation strategies.

The solution framework supporting this dynamic project management includes several approaches: (1) For construction scheduling, a dynamic framework is proposed that integrates 3D BIM data, Discrete Event Simulation

(DES), System Dynamics (SD), and optimization algorithms Ant Colony Optimization for Continuous Domains (ACOR).

This approach utilizes SD to model the non-linear variation in labor productivity over time. (2) For scheduled maintenance (O&M), mathematical optimization models, such as Integer Linear Programming (ILP), are used to group frequently recurring maintenance tasks into optimized work clusters, reducing total active workdays and minimizing operational disruptions. (3) For sustainable energy optimization, BIM-based simulations (using tools such as Autodesk Revit and Insight 360) are combined with location specific climate data to analyze and optimize building energy performance against international standards such as ARCH2030 and ASHRAE 90.1. This analysis identifies key design factors such as HVAC type, lighting efficiency, and building envelope construction. These approaches are supported by the use of advanced metaheuristic algorithms, such as ACOR and the proposed Sine Cosine Algorithm (SCA) for constructability assessment and scheduling.

Operationally, the dynamic BIM-AI framework is built on a three-layer architecture (data, analysis, and application layers). Key innovations include a 4-in-1 Network Diagram Engine and Blueprint Engine for intuitive visualization and automated task management, which aim to significantly improve efficiency and accuracy. Meanwhile, BIM integration for O&M is facilitated through a microservice architecture and orchestrator (e.g., Dynamo for Revit) that enables flexible and scalable links between BIM models, spreadsheet databases, and Python/Gurobi-based Optimization Engines. The use of optimized BIM simulation in energy case studies has been proven to reduce energy consumption by 46% to 50% after implementing the ARCH2030 target.

The main objective of these studies is to advance project management theory and practice by integrating BIM with optimization techniques, AI, and advanced simulation (including ACOR, ILP, and Deep Learning) to facilitate dynamic, adaptive, and efficient management throughout the building lifecycle, including scheduling, O&M, and sustainable energy performance.

B. IMPLEMENTATION METHOD

The methodology presented in this study reflects an integrated and multidimensional approach, combining the strengths of Building Information Modeling (BIM), advanced simulation, and optimization algorithms to address challenges management project at various phases of the life cycle. buildings. Overall, implementation involves developing a digital architecture framework (such as a three-layer or microservice-based architecture) and testing it in real-world project case studies. These frameworks collectively operate as an intelligent project management platform that aims to transition from static planning to adaptive and dynamic management.

Implementation Activities: Implementation is dominated by research and development (R&D) activities, including: (1) Development of a Theoretical Framework that integrates BIM with AI, Simulation, and Optimization; (2) Modeling and Data Acquisition from BIM models (using Autodesk Revit) and real-time site data (via sensors/IoT); (3) Development of Algorithms and Analysis Engines (such as ILP or ACOR optimization engines) using programming languages such as Python, Gurobi, and VB.NET; and (4) Empirical validation through case studies in large-scale construction projects (water reservoir tunnels in China), operating university buildings, and energy performance analysis in office buildings in various climates (Egypt and Indiana, USA). In the context of these findings, "partners" or implementation environments include civil construction environments, operational facilities, and energy design simulations.

Implementation Steps: The implementation phase begins with the Pre-Activity Phase (Data Foundation), where a 3D BIM model is developed to extract work quantities, material specifications, and operational information. This data layer collects real-time data from the site (e.g., personnel location, equipment usage, weather conditions) and historical data for AI training. In addition, this framework integrates spatial information through BIM + GIS for geographical context. In scheduling projects, this data is processed to calculate non-linear variations in worker productivity using System Dynamics (SD), which is based on expert surveys of influencing factors (e.g., motivation, fatigue, and material availability). Specifically for O&M optimization, spreadsheet databases are used as input, coordinated by Dynamo Orchestrator for Revit.

Main Activities (Analysis and Optimization): Once the data has been prepared, the Analysis Layer is applied. In dynamic schedule management, AI algorithms (including LSTM, XGBoost, and Transformer) are used for predictive analysis and multi-objective optimization. The Dynamic BIM-SD-DES Framework combines Discrete Event Simulation (Simphony.NET v4.0) to assess changes in productivity and constraints budget time real, with The ACOR (Ant Colony Optimization for Continuous Domains) algorithm to optimize costs and time, while considering non-linear time-cost relationships. For Scheduled Maintenance (O&M) optimization, Integer Linear Programming

(ILP) and the Gurobi solver are used to group tasks to minimize active workdays, implemented in a Python-based microservice architecture. Meanwhile, energy performance optimization (Source 4) uses BIM simulation tools such as Autodesk Insight 360 (with the EnergyPlus engine) to compare 24 different design parameters (such as HVAC type, wall insulation, and infiltration) against the ARCH2030 and ASHRAE 90.1 standards. Another source also proposes the use of the Sine Cosine Algorithm (SCA) for constructability assessment.

Monitoring and Evaluation: Optimization results are presented through Application Layers and visualized, often directly in the BIM model (such as mapping schedules to Revit elements). The first journal implements a 4-in-1 Network Diagram Engine and Blueprint Engine for intuitive progress monitoring and automated workflow management. Model accuracy validation was performed by comparing the optimized model results (e.g., project duration of 142 days) with the actual project performance (152 days), showing a significant reduction in schedule errors compared to the contractor's baseline. Additional validation was conducted through semi- structured interviews with 15 industry experts (technical, practitioners, and end-users) to assess the feasibility and implementation challenges.

C. RESULT AND DISCUSSION

This Results and Discussion section presents the main findings from the implementation of the integrated framework, which focuses on three main domains: dynamic construction scheduling, scheduled maintenance optimization, and energy performance optimization, followed by a cross-journal performance evaluation.

1. Implementation and Result of Dynamic Scheduling

The application of the BIM-AI framework for dynamic schedule management in a large-scale water reservoir tunnel project in China showed a significant increase in efficiency. This framework integrates data layers, analysis (using AI algorithms for prediction), and applications (for visualization and decision support). The main features implemented at the application layer are the 4-in-1 Network Diagram Engine and Blueprint Engine. Engine Diagram Network 4-in-1 combines Gantt Chart, Timeline Network Diagram, Double-Coding Network Diagram, and PERT Chart.

The validation results in the tunnel case study show that the AI prediction model achieved a task progress forecast accuracy of up to 96.3% (using the Transformer model). This framework reduced the Mean Absolute

Error (MAE) of task progress forecasts by 65.4% (from 5.2 days to 1.8 days) compared to traditional methods. In addition, the system successfully reduced the delay time from sensor anomalies to early warnings to less than 3 minutes, which is an improvement of more than 99% compared to manual inspections (which take hours). This improvement is also reflected in a 67% increase in decision-making response time efficiency (averaging a reduction from 45 minutes to 15 minutes).

Meanwhile, the dynamic BIM-SD-DES framework optimized with the ACOR (Ant Colony Optimization for Continuous Domains) algorithm successfully addressed project uncertainty. In a construction case study, this model predicted a project duration of 142 days, which was much closer to the actual completion time (152 days) than the contractor's baseline (90 days). As a result, this model reduced scheduling errors from 41% to 6.6%. Overall, this framework achieved a 34.4% improvement in scheduling accuracy based on actual project duration. Optimization also reduced total project costs by 15% (347,686) compared to without optimization (407,175).

2. Implementation and Result of Scheduled Maintenance Optimization

The methodology focuses on the Operations and Maintenance (O&M) phase using Integer Linear Programming (ILP) in a microservice architecture to optimize preventive maintenance scheduling. This model aims to minimize the total number of active workdays in operational buildings, thereby limiting operational disruptions. The Gurobi solver is used to find the optimal ILP solution.

In a case study involving 56 different maintenance activities spread throughout the year, the optimization model successfully grouped these activities into 12 clusters. This optimized configuration reduced the total workdays required to 62 days, compared to 151 days in the non-optimized scenario (where each activity started at its standard interval). This represents a reduction in total active maintenance days of 58.9%. The optimization results were communicated back to the BIM model (Autodesk Revit) via the Dynamo orchestrator, which updated four BIM-specific parameters (NextActivityId, NextActivityName, NextActivityStartDate, and NextActivityEndDate) for spatial visualization of the schedule.

3. Implementation and Result of Sustainable Energy Performance Optimization

Energy performance optimization using BIM (Autodesk Revit) combined with EnergyPlus-based simulation through Autodesk Insight 360. The objective is to analyze 24 different design parameters to achieve the Architecture 2030 (ARCH2030) and ASHRAE 90.1 standards.

The case study was conducted on office buildings in two different climates: Egypt (hot climate) and Indiana, USA (cold climate). The results show that optimization driven by ARCH2030 standards dramatically reduces energy consumption:

- In hot climates, average annual energy costs fell by 46% (from $18.0/m²/year to $9.73/m²/year).
- In cold climates, average annual energy costs fell by 50% (from $20.4/m²/year to $9.91/m²/year).

Sensitivity analysis identified high-potential design parameters:

- In hot climates, the most important parameters are Operating Schedule, Plug Load Efficiency, HVAC Type, and Solar Panel Surface Area.
- In cold climates, the most important parameters are HVAC Type, Wall Construction, Lighting Efficiency, and Infiltration (ACH).

4. Monitoring and Evaluation

In general, the acceptance of this new framework is viewed positively. Semi-structured interviews with 15 industry experts revealed that 12 out of 15 respondents acknowledged the innovative value of BIM-AI integration. Table 1 (from Source 1) compares the performance metrics of the BIM- AI Framework with Traditional Methods, showing substantial improvements:

Table 1. Comparation the Performance Metrics of the BIM- AI Framework with Traditional Methods

Index	Method Traditional	BIM Framework – AI	Level Improvement
Deviation Level Progress	18.3	10.6	42
Unemployment Period Resources	23 hours/week	16.8 hours/week	27

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Response Time Delayed	45 minutes	15 minutes	67
Error Rate Task Coordination	12.1	1.4	88

5. Challenges Encountered

Although proven effective, various limitations were identified in the implementation of this framework:

a) Interface and Usability Issues: The complexity of the interface and the large amount of content presented can be burdensome for users without technical expertise.
b) Mobile System Performance: The limitations of mobile system performance, especially under poor signal conditions, remain an issue.
c) Human Resource Management: The current framework does not address the variation in professional skills among team members, which can lead to suboptimal resource allocation. Interview results indicate a "personnel skills mismatch."
d) Execution Gap: Delays in personnel scheduling often cause gaps in the implementation of AI-generated optimization plans, resulting in a 22% execution gap in AI recommendations.
e) Data and Computation Demands: Dynamic models such as BIM-SD-DES-ACOR require accurate, high-resolution productivity data and have relatively high computation demands, which can limit real-time application on very large projects.
f) BIM Interoperability in O&M: Reliance on Autodesk Dynamo limits interoperability with alternative BIM platforms. Additionally, the initial ILP model deliberately ignores spatial conflicts or shared resources, limiting BIM's role primarily as a post-optimization visualization tool rather than an active scheduling driver.

To address these challenges, it is recommended that future systems focus on improving AI-driven HR management modules for personnel profiling and competency-based task allocation. Further improvements should aim to simplify the user interface and enhance the stability of mobile systems.

D. CONCLUSION AND RECOMMENDATIONS

Deep integration between Building Information Modeling (BIM) and smart technology, simulation, and optimization has been proven to significantly improve efficiency, accuracy, and adaptive capabilities in building lifecycle management, which is a response to the limitations of conventional static planning tools. Dynamic frameworks, such as those proposed for schedule management, show substantial improvements by reducing task coordination error rates by up to 88% (from 12.1% to 1.4%). Additionally, overall scheduling accuracy, driven by the integration of Dynamic Systems (DS), Discrete Event Simulation (DES), and ACOR optimization, increased by 34.4% (reducing errors from 41% to 6.6% compared to the contractor baseline). In the Operations and Maintenance (O&M) phase, the application of Integer Linear Programming (ILP) successfully grouped preventive maintenance activities, resulting in a total reduction of 58.9% in active workdays. Meanwhile, in the context of energy performance and sustainability, BIM-based design optimization (using Revit and Insight 360) against the ARCH2030 standard resulted in consistent reductions in average energy consumption: 46% in hot climates (Egypt) and 50% in cold climates (Indiana, USA), effectively achieving the specified energy targets. This success was consolidated by tangible operational improvements, including a 67% reduction in decision-making response time (from 45 minutes to 15 minutes) and a 27% reduction in resource idle time.

Although this validated framework demonstrates superior performance, several technical and operational limitations require attention for wider industrial adoption. Technically, the system must address the need for accurate, high-resolution productivity data, improve the stability of mobile systems in poor signal areas (where delays reach 8 seconds), and develop models to integrate spatial constraints or shared resource conflicts.

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