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Article

Digital Integration of 5D BIM and Building Energy Modelling for Sustainable Construction Management

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Abstract: The use of BIM technology is currently limited in several segments of the Indian construction industry. However, the application of BIM technology to two residential building projects in Bengaluru, India, shows the potential for BIM to enhance construction industry performance in terms of cost control, scheduling, and environmental impact. Five-dimensional BIM was used to construct a seven-storey residential building with basement parking using Autodesk Revit, AutoCAD, and Navisworks. This model allowed for the estimation of the total quantity of concrete that would be required for the construction of the buildings at 1,428.88 m^3, as well as an estimation of the cost of constructing the concrete at approximately ₹39.57 lakh. Energy simulations were performed on the two-storey residential building in Bengaluru using Revit Green Building Studio and Autodesk Insight 360, as a way of estimating the energy that would be required to heat or cool the buildings according to the climate of Bengaluru. The energy simulations indicated that the heating and cooling energy use for the buildings was 163 kWh/m^2 per year - 7% more than the industry benchmark of 152 kWh/m^2 per year. The increased energy requirement by the residential buildings was attributed to the uninsulated walls constructed of brick masonry and the reinforced-concrete roof of the residential buildings. Additionally, a review of other construction industry projects that implemented BIM technology revealed cost savings of between ₹12.45 lakh and ₹16.60 crore, with the costs to implement BIM technology ranging between ₹1.20 lakh and ₹74.70 lakh. These results indicate that the implementation of BIM technology to residential construction projects in Bengaluru and other rapidly developing Indian cities has considerable potential to enhance the economic and environmental performance of construction projects.
Keywords: Building Information Modeling; 5D BIM; Quantity Takeoff; Clash Detection; 4D Scheduling; Building Energy Simulation

1. Introduction

The construction industry is generally characterized by fragmented information within the industry, conflicts within the documentation of construction projects, and low rates of productivity within the industry as a whole [1-3]. BIM aims to address each of these deficiencies by developing a digital model of a building and its parts (the building information model) that represents the construction project and enabling the owners of those projects to reuse those models after construction [1-3]. While many CAD software packages were published with models that represented construction projects in two-dimensional (2D) and three-dimensional (3D) representations, BIM also publishes construction models that represent projects in four-dimensional (4D) models of construction schedules, five-dimensional (5D) models of cost estimates, six-dimensional (6D) models of facility management requirements, seven-dimensional (7D) models related to sustainability of buildings, and eight-dimensional (8D) models of construction safety estimates [9].

Those models can contain information about the Level of Development (LOD) of the construction project and model, ranging from LOD 100 (models with only the essential graphical and non-graphical information for the project) to LOD 500 (models with complete graphical and non-graphical information for the project) [18]. Though each of these levels of development can be utilized to ensure that the owners of the construction projects and the construction teams have an understanding of the detail that will be required for the construction project, such levels of development are not yet universally implemented in construction projects across the world. While BIM is implemented as the standard practice for projects constructed in North America, Europe, and parts of Asia, BIM is not yet cultivated in developing countries like India [16].

The relationship between BIM models and construction energy is additionally important, as buildings account for 41% of the energy consumed by humans across the planet each year [reflecting USGBC estimates]. Moreover, energy shortages in the country of India have contributed to the inclusion of energy efficiency as an agenda item for the country. BIM software can allow for energy simulation models to be constructed for buildings in order to evaluate their energy performance, especially in the early stages of the construction process for which the costs of changing a construction plan are lessened [14,20,21]. These objectives will be pursued in the current study: the development and evaluation of a 5D BIM model for construction of a multi-storey concrete building, and the development and evaluation of a BIM-integrated energy simulation model for a residential building in India's climate. The remainder of the article proceeds as follows. Section 2 discusses the related literature for each of the objectives of the study. Section 3 describes the modeling and simulation processes used to achieve each of those objectives. Section 4 presents the results of those models and simulations. Finally, Section 5 discusses conclusions drawn from those results and recommendations regarding their application to BIM models, as well as directions for future research in these areas.

2. Related Work

The related literature on BIM includes three main categories of research: research that documents the return on investment in BIM for various construction projects, research on the use of BIM in construction processes, and research on the use of BIM as a means of simulating the energy performance of constructed buildings.

2.1. Documented BIM Return on Investment

Azhar and Richter documented the construction of a number of construction projects that implemented BIM software, and provided outcomes to each of those projects. Table 1 describes four of those projects.

Table 1. Consolidated BIM return-on-investment evidence from documented case studies [4].

Project	BIM Scope	BIM Investment	Documented Benefit	Return Driver
Aquarium Hilton Garden Inn, Atlanta (USD 46M hotel + parking) [4]	Design coordination, clash detection, sequencing	USD 90,000 (0.20% of budget)	USD 200,392 net savings (590 clashes resolved)	Pre-construction clash avoidance
Savannah State University academic building (USD 12M) [4]	Predesign planning, option/value analysis	USD 5,000 (0.04% of budget)	USD 1,995,000 savings; 2-week decision cycle	Rapid multi-option scope/cost comparison
The Mansion on Peachtree, Atlanta (USD 111M, 29-month build) [4]	Planning and construction documentation	USD 1,440 (0.001% of budget)	USD 15,000 savings; on-time, on-budget delivery	RFI reduction via 3D coordination

Emory Psychology Building, Atlanta (USD 35M, LEED) [4]	Sustainability, daylighting and orientation analysis	Not separately reported	Reduced envelope area and avoided late-stage redesign	Early-stage passive-design iteration

The examples of BIM applications presented in the relevant literature demonstrate that despite the relatively small fraction of the total construction cost that is invested in BIM technology, the costs that are avoided through its application are significantly higher. Furthermore, the phases of construction during which BIM software is most effectively applied appear to differ between case studies; the case studies of Savannah State University applied BIM software during the predesign stage of construction, while the Aquarium Hilton Garden Inn case study applied BIM software during the design and construction stages of construction. The stages of BIM application during construction by the authors of the present study, therefore, are developed as an integrated process applied during each stage of construction.

2.2. BIM Applications in the Construction Process

The stages of construction include conception, design, pre-construction, procurement, construction and post-construction [5]. BIM software applications within these stages include applications related to the design of construction elements, the detection of clashes between different elements, quantity takeoffs and cost estimations for construction elements, scheduling of construction elements, management of the spaces and elements within the building and the transfer of information between the construction and operations phases of a building [10,11]. Software packages that include these functions include AutoCAD, Revit, ArchiCAD, Tekla and SketchUp [12,13]. The integration of these software packages and construction elements into a unified system is an area of active research [15].

2.3. BIM-Integrated Building Energy Simulation

Some of the functions of BIM software also relate to the energy performance of buildings. Farzaneh et al. [20] presented a review of the incorporation of BIM software in conjunction with energy modeling software during the design stage of construction projects. Park et al. [21] applied BIM software to evaluate energy performance within construction projects within the Korean architectural context. Wang et al. [14] presented methods for the performance of energy analysis for constructed buildings. Additionally, Laine and Karola [6] presented findings of the energy performance of buildings constructed using BIM models. Each of these studies will be applied to the construction of a residential building in the hot semi-arid climate of Bangalore, India [7], the energy performance of which has not been well-studied within the context of BIM construction technology.

3. Methodology

Two methodologies will be employed within the construction of the buildings described in this research study. Both methodologies will employ the same software applications: AutoCAD, Revit and Navisworks (as well as Microsoft Excel to link the construction elements to cost and time schedules). The first methodology will construct a seven-storey residential building that incorporates basement parking, from construction to the five-dimensional evaluation of the construction (structural, geometrical, cost, construction scheduling and coordination). The second construction methodology will construct a two-storey residential building that incorporates energy performance analysis with BIM software through Revit's building elements, Green Building Studio and Insight 360 [16,17]. Figure 1 presents an overview of the technologies to be employed within the study.

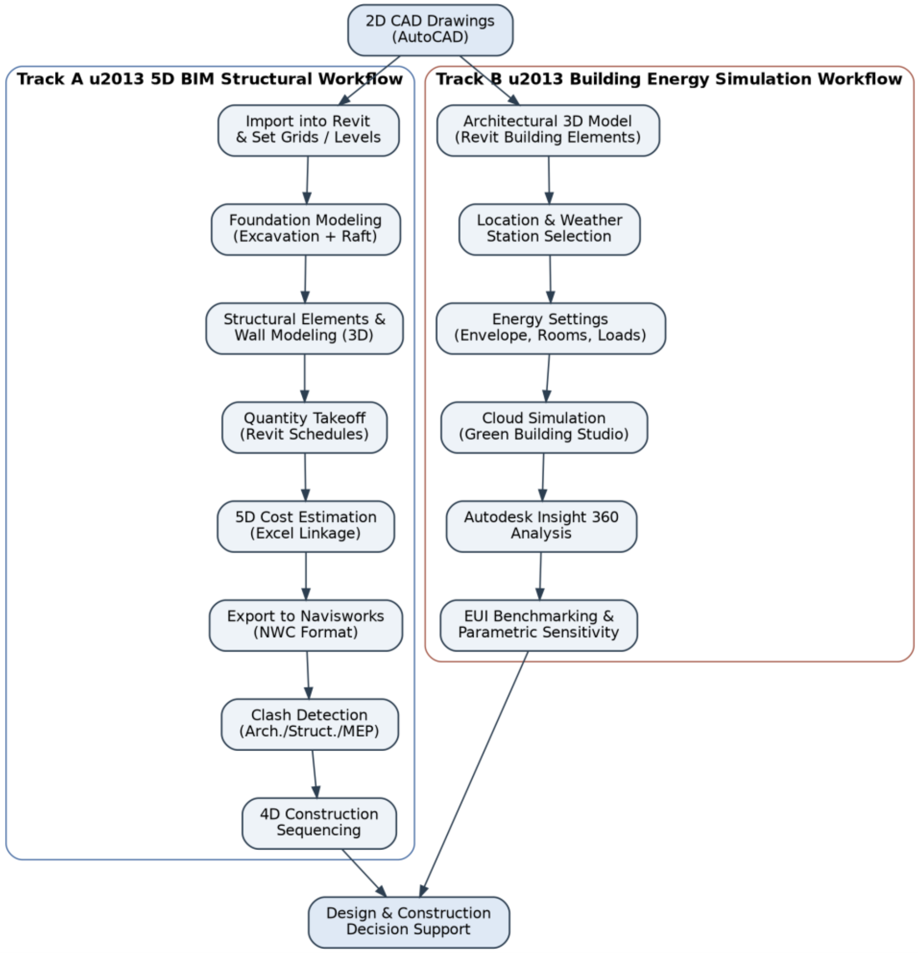

Fig. 1. Integrated research framework combining the 5D structural BIM workflow (Track A) and the BIM-integrated building energy simulation workflow (Track B).

3.1. Track A — 5D Structural BIM Workflow

The existing 2D architectural drawings from AutoCAD were imported into Revit to create the 3D model. The foundation was laid out first, including the excavation and the raft foundation with backfill. The structural elements for each of the seven storeys and the basement were laid out in the same manner. Finally, the model was detailed with features like doors, windows and finishes. The model was scheduled in Revit to create a quantity takeoff report that included six schedules for different categories of construction materials (Section 4.1, Table 2). The quantities from these schedules were exported to Excel and each material category was multiplied by the unit cost of that material to create the 5D cost estimate of the construction project.

The 3D model was exported from Revit to Navisworks. Navisworks is used to import the architectural, structural and MEP (mechanical, electrical, plumbing) models, including the drainage and water-supply systems. These models can be screened for potential clashes in construction using Navisworks' clash detection software. Finally, the construction schedule that was created in Excel can be linked to the construction model to create a 4D construction schedule. Fig. 2 depicts the 3D structural model together with the residential energy model.

Fig. 2. Rendered 3D BIM models used in this study: (a) seven-storey reinforced-concrete structure with basement parking (Track A); (b) two-storey residential building used for energy simulation (Track B).

3.2. Track B — Building Energy Simulation Workflow

The energy model of the two-storey residential building is situated on a plot of approximately 505 m² in Bengaluru, India. The town experiences a tropical savanna climate (Köppen-Geiger classification: Aw). The architectural model was developed using Autodesk Revit by adding the rooms of the building to represent the building's geometry as detailed in the architectural drawings of the building. The geographic location of the building and the nearest weather station were defined in the software prior to the energy simulation of the building. Additional parameters for the energy model of the building were also assigned to the energy model, including information about the type of building, its occupants, the ground plane of the building, the infiltration of the building, its equipment, lighting, and HVAC systems. The external walls of the building were comprised of approximately 230 mm of fired-clay brick with a 10 mm layer of cement plaster on both of its facing walls. The roof of the building was comprised of a 150 mm thick reinforced-concrete slab, 50 mm of cementitious screed and plaster, 50 mm of terrace-tile on the slab, and 10 mm of internal ceiling plaster. The energy simulations of the building were performed using Autodesk Green Building Studio software, and the simulation results were evaluated using the Autodesk Insight 360 interface. The software also enabled the performance of sensitivity analyses of the building without having to reconstruct the energy model.

4. Results and Discussion

4.1. 5D Structural Modeling Outcomes

Following the modeling of the structure, the structural sheets and estimates for each structural component were automatically generated by the software; the total estimate for the quantity of concrete that would be required to construct the structural components of the building was 1,428.88 m³, which would cost approximately Rs 3957344.62 at an estimated cost of Rs 8,000/m³ for the concrete. This estimation step eliminated the need for the typical and labor-intensive step of manually creating a take-off and cost estimate for the structural components, indicating the efficiency of the process in comparison to traditional construction estimating methods.

Table 2. Automated material quantity takeoff and concrete cost estimate for the seven-storey structural model (Revit schedules).

Building Element (Revit Material Takeoff)	Quantity	Unit
Structural columns	45.60	m³
Floor slabs	977.43	m³
Structural framing	59.71	m³
Walls	341.25	m³
Stairs	4.89	m³

Grand total concrete volume	**1,428.88**	**m³**
Unit rate	8,000	Rs/m³
Total estimated concrete cost	**3957344.62**	**Rs**

The clash detection software installed within Navisworks identified several clashes between the architectural, structural, and MEP models. The most notable of these clashes was between the floor slabs and the drainage piping within the structure (Fig. 3c). These types of clashes were encountered within the original construction of the structure and necessitated demolishing some of the structure to account for the drainage system. Avoiding these clashes as with the Aquarium Hilton Garden Inn project reported in Table 1 (where 590 construction clashes were avoided through BIM, saving the construction contractors USD 200,392) indicates potential cost savings for the construction of this structure. Additionally, coordinating the model with the schedule derived from the Excel sheet allowed for the creation of a 4D model of the construction sequence (Fig. 3d), an improvement over the construction schedule that existed independent of the 3D models of the construction elements.

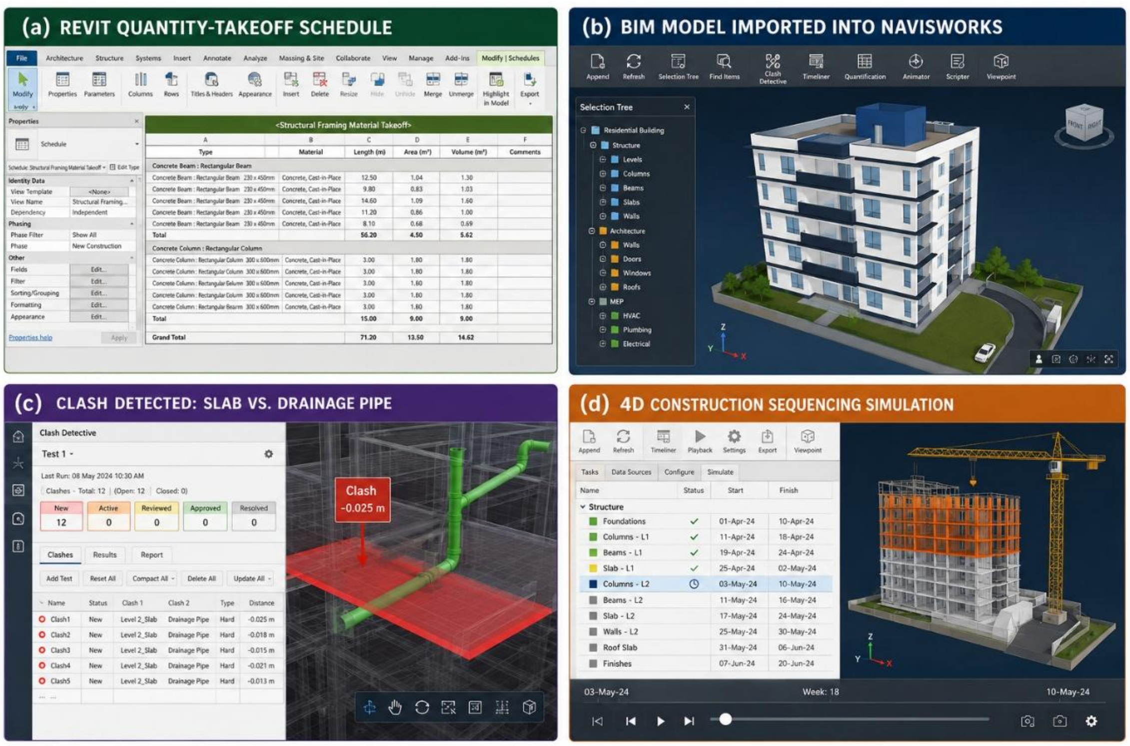

Fig. 3. 5D BIM process outputs: (a) automated Revit quantity-takeoff schedule; (b) coordinated model imported into Navisworks; (c) clash detected between a floor slab and a drainage pipe; (d) 4D construction-sequencing simulation.

4.2. Building Energy Simulation Outcomes

The climatic inputs for the Bengaluru site (Fig. 4) indicate a tropical savanna climate that is somewhat moderated by the city's elevation. The hottest period of the year occurs between March and May, with average temperatures of 33-35 °C. December and January are the coolest months of the year with average minimum temperatures of 15-17 °C. The predominant wind directions within Bengaluru include easterly and north-easterly winds during the dry and winter months, while westerly and south-westerly winds dominate during the south-west monsoon season (June-September). The solar radiation that reaches the region is abundant throughout the year, with average solar irradiation values of 5.5-6.0 kWh/m²/day. The maximum levels of solar radiation are experienced between March and May, while the minimum levels of solar radiation reach the south-west monsoon season (June-September). These factors indicate that Bengaluru is a suitable location for the installation of PV systems.

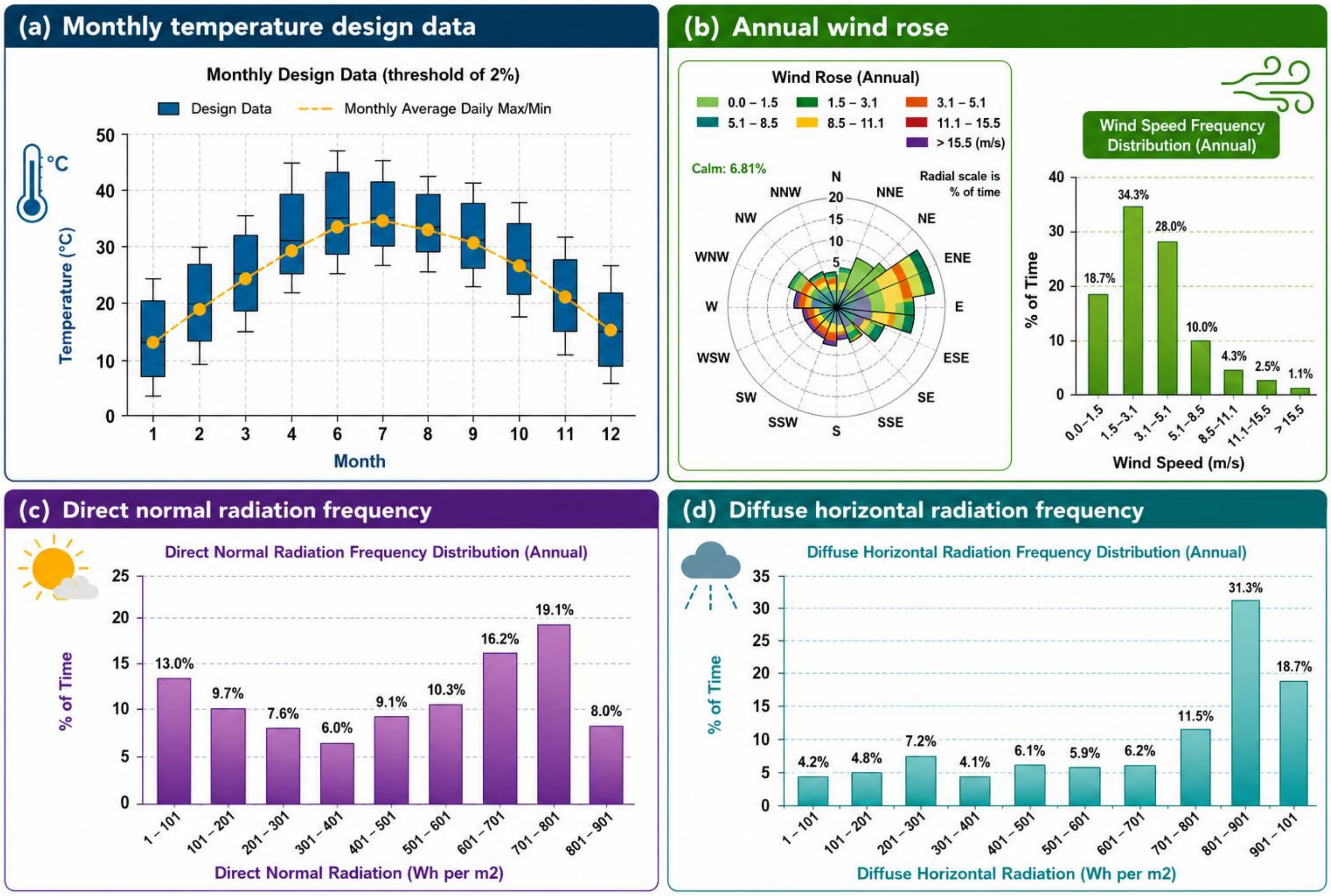

Fig. 4. Site climatic and solar-radiation inputs used for the energy simulation, Bangalore, India: (a) monthly design temperature data; (b) annual wind rose; (c) direct normal radiation frequency; (d) diffuse horizontal radiation frequency.

These climate patterns have direct implications for the design of buildings in Bengaluru. During the south-west monsoon season (June to September), westerly and south-westerly winds dominate the area. East and north-easterly winds are experienced during the dry season. Window openings should be made on the west, south-west and east and north-east façades to allow for ventilation in the building. However, the windows on the east and west façades should be shaded to avoid solar heat gain. The mild winter climate means that the need to minimize heat loss from the buildings is less critical. The energy analysis of the buildings in BIM software helps to determine how to best design the buildings to minimize energy usage.

Autodesk Insight 360 software helps to calculate the energy use of the building. The energy use of the building was determined to be 163 kWh/m²/year, which is 7% more energy than a comparable building. This difference in energy use is due to the high transmittance of the building's envelope. The envelope of the building uses 230 mm of brick walls without insulation and a 150 mm thick roof of reinforced concrete without insulation. Such an envelope allows a significant amount of heat to be lost into the building. Using insulation on the roof or using roofing materials that reflect solar radiation would reduce the energy consumption of the building.

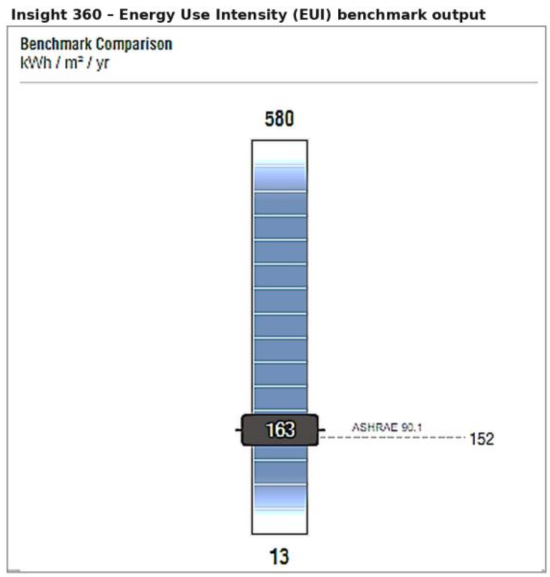

Fig. 5. Insight 360 Energy Use Intensity (EUI) benchmark output: simulated building EUI of 163 kWh/m²/year versus an ASHRAE 90.1 reference of 152 kWh/m²/year.

4.3. Parametric Sensitivity of Design Variables

The parametric sensitivity analyses of Insight 360 (Fig. 6) determine the relative impact of various building parameters on the energy performance of the building without performing the simulation again for each set of parameters. Of the HVAC systems considered, the high-efficiency VAV system had the lowest energy consumption. The impact of each of the other parameters is reflected in the sensitivity analyses; for instance, the energy savings that could be achieved by using either higher insulation levels for the building walls or utilizing higher-efficiency lighting fixtures are reflected in those analyses. Finally, the parameters that are represented in the sensitivity analysis of the operating schedule is the assumed level of occupancy of the building, which could be better determined by performing an occupancy study of the building in future projects.

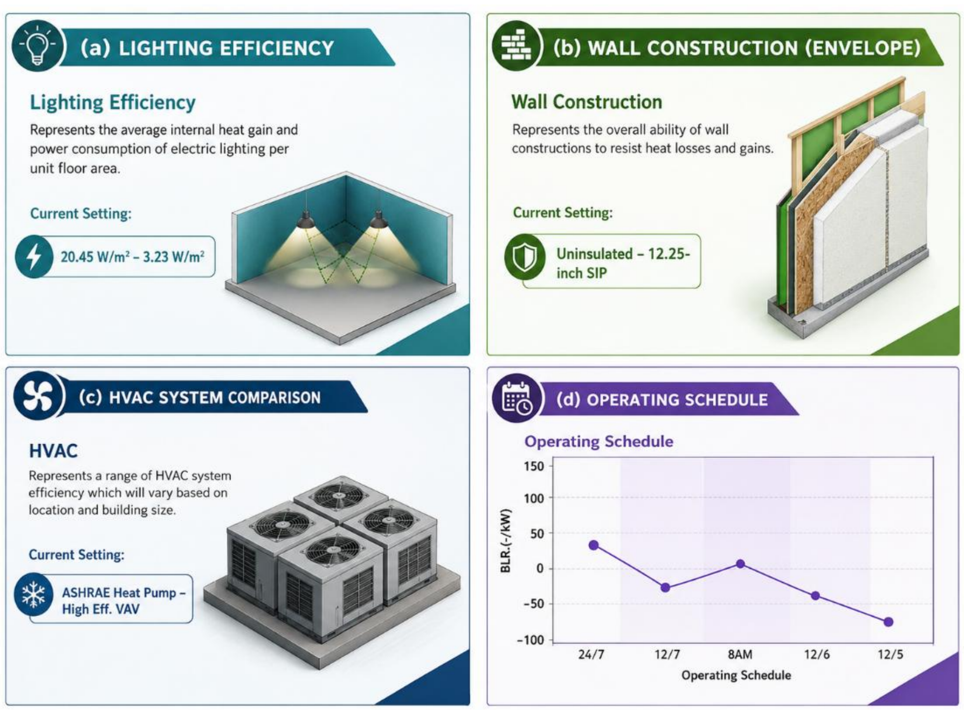

Fig. 6. Insight 360 parametric sensitivity of key design variables on simulated building energy performance: (a) lighting efficiency; (b) wall construction (envelope); (c) HVAC system comparison; (d) operating schedule.

4.4. Cross-Comparison, Limitations and Future Work

Overall, these results indicate that the Building Information Model can simultaneously support construction efficiency and sustainability objectives. However, there are also some limitations to the study. For instance, each workflow was performed on a single building each. The cost savings figures (Table 1) are from published articles on each of the individual buildings, and the construction costs are estimated (Table 2) from available literature; actual as-built costs were not available for those buildings. Furthermore, the energy model has used default assumptions for occupancy, lighting, and equipment within the Rooms category of the building, rather than using cost and energy meters data collected after occupancy of the buildings.

Another consequence of the limited data from each of the buildings is that the information available from these buildings can be insufficient to train data-driven models. For instance, artificial neural networks or tree-based ensemble models can be trained to learn relationships between building characteristics and energy use intensity (EUI). However, the small data set from these two buildings is unlikely to contain enough data to effectively train such a model without overfitting the data. Therefore, collecting a dataset of buildings with similar characteristics (like those built through Insight 360) is a focus of future work to enable training of such models with a genuine data sample.

5. Conclusion

This study implemented and evaluated two BIM workflows within the integrated Autodesk software suite for construction projects in Bengaluru, India. The first workflow implemented 5D BIM methods to a 7-storey concrete building project. The 2D project drawings were converted to a 3D BIM model, and quantity take-off and cost estimation, scheduling and clash detection were performed with the model to determine that the construction would require 1,428.88 m^3 of concrete at a cost of ₹39.68 lakh. The second workflow integrated BIM with a whole-building energy simulation software package to a 2-storey residential building using climatic data representative of Bengaluru. The energy intensity of the buildings was calculated as 163 $kWh/m^2/year$, which is 7% higher than the industry benchmark of 152 $kWh/m^2/year$. The difference in energy intensity between the calculated and benchmark values was mainly due to the thermal performance of the uninsulated walls and roof of the residential buildings.

The results of this project are generally in line with other BIM case studies in that while investments in the order of ₹1.20 lakh to ₹74.70 lakh were required to implement BIM software and hardware to the construction projects, estimated benefits were in the range of ₹12.45 lakh to ₹16.60 crore. The use of BIM software improves various aspects of construction management for building projects in India. The widespread adoption of BIM software throughout the life cycle of construction projects in India can bring further economic and environmental benefits to the country, especially to its rapidly urbanising cities.

Future research in this area can use BIM software to analyse various building projects located in different climatic zones of India. Additionally, future research can calibrate energy models based on actual energy consumption by buildings to create databases of energy use and costs of buildings in India. These databases could lead to the development of models for prediction of the energy performance of buildings in India under various conditions.

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