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DIGITALIZATION IN CONSTRUCTION: EARTHWORK ESTIMATION USING BIM

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ABSTRACT

Traditional construction practices often face problems due to poor communication and coordination among project stakeholders. These issues frequently lead to inefficient use of resources, lower overall building performance throughout its lifecycle, increased material waste, and repeated delays and cost overruns (Pinto & Mantel, 1990; Shahhosseini et al., 2018). Because of these challenges, the construction industry is considered one of the major contributors to environmental impact worldwide. It is responsible for nearly 40% of global energy consumption and about 34–39% of total carbon dioxide emissions. In addition, construction and demolition activities generate roughly 25–30% of the world's total solid waste (Azhar et al., 2013; Fazeli et al., 2022).

Although sustainable construction practices and Building Sustainability Assessment (BSA) frameworks have been introduced to reduce these impacts, their use in real projects is still not widespread. One of the main reasons is the heavy dependence on manual data handling and repeated calculations at different stages of a project. This process limits real-time interaction with design models and reduces the effectiveness of sustainability evaluations, especially during the early design phase (Wong & Zhou, 2015; Kouka et al., 2024).

Building Information Modeling (BIM) has gained recognition as a powerful digital tool for advancing sustainable and low-carbon footprint. It allows the creation of a comprehensive 3D model that brings together architectural, structural, and MEP components within a unified system. This integrated platform supports sustainability efforts by enabling accurate quantity estimation and dependable energy performance evaluation (Azhar et al., 2011; Ferreira et al., 2013).

The present study investigates the potential of BIM to support optimization objectives in building projects. It proposes a structured BIM-based approach specifically designed for earthwork management and cut-and-fill optimization. The main aim is to reduce material waste and improve sustainability performance during the construction stage. By focusing on earthwork processes, the study addresses a significant yet relatively underexplored area within sustainable construction research.

KEYWORDS: Building Information Modeling (BIM); Sustainable Construction; Building Sustainability Assessment (BSA); Environmental Impact; Lifecycle Analysis; Digital Construction Tools

INTRODUCTION

By 2025, India's construction sector is expected to contribute around 9% to the country's Gross Domestic Product (GDP) and provide employment to over 70 million people, making it one of the largest sources of jobs. Due to its economic significance and employment potential, the construction industry plays a crucial role in national development. At the same time, it is among the biggest consumers of natural resources and a major contributor to waste generation. Studies indicate that construction activities consume roughly 30–40% of global natural resources, including materials like sand, aggregates, cement, steel, and timber, and generate almost 30–40% of total solid waste in the form of construction and demolition debris (Osmani, 2012; Ding et al., 2018). In countries like India, challenges in construction are further intensified by inefficient resource utilization, inaccurate quantity estimation, and poorly controlled site operations. Among various construction activities, earthwork operations are. Earthwork operations represent one of the most materialintensive and environmentally impactful stages of construction projects, which are particularly vulnerable to miscalculations, often resulting in over-excavation, excessive soil disposal, and unnecessary material transportation. Improving optimization at this early stage is therefore critical, as errors in terrain modeling and cut–fill planning directly influence both environmental impact and project cost. Despite advancements in construction research, earthwork optimization remains underexplored within BIM-based frameworks (Osmani, 2012). These high levels of resource use and waste production emphasize the urgent need for sustainable construction methods, especially those that enhance material planning accuracy and reduce waste on-site through data-driven tools like Building Information Modeling (BIM).

Although digital transformation in construction has been strongly encouraged to enhance outcomes, the use of BIM for earthwork estimation is still relatively limited. In many projects, BIM is mainly applied for visualization and coordination during the design phase. However, its potential for digital terrain modeling, stage-wise surface comparison, and automated cut-and-fill calculations is not fully utilized in construction planning. As a result, the measurable contribution of BIM to optimization during the construction phase remains constrained.

Even with its recognized advantages, BIM implementation is largely concentrated in the early design stages, with little structured application in construction monitoring and material control. This partial adoption highlights a strategic gap in fully exploiting BIM capabilities. To bridge this gap, the present study introduces a BIM-based framework specifically designed for earthwork management and cut-and-fill optimization. The proposed framework seeks to enhance the accuracy of earthwork operations and minimize material imbalance, ultimately supporting improved performance during construction.

Literature review

In rapidly developing countries such as India, these impacts are amplified by fast urbanization, inefficient use of materials, and limited adoption of lifecycle-based planning approaches. Consequently, improving sustainability performance across the construction lifecycle has become a critical focus for both research and industry practice.

In rapidly developing countries such as India, construction-related environmental impacts are amplified by accelerated urbanization and large-scale site development activities. Among various construction stages, earthwork operations represent one of the most resource-intensive and environmentally disruptive processes, involving extensive excavation, grading, backfilling, and material transportation. Inaccurate interpretation of 2D contour drawings and manual volume calculations frequently result in cut–fill imbalance, over-excavation, excessive hauling distances, and unnecessary disposal of soil, thereby increasing fuel consumption and carbon emissions.

Recent research identifies Building Information Modeling (BIM) as a strategic tool for improving sustainability performance in construction projects. Unlike conventional estimation methods, BIM enables digital terrain modeling and parametric surface generation within an integrated environment (Hammes et al., 2022). This allows planners to simulate proposed grading conditions and evaluate volumetric changes prior to execution.

Fazeli et al. (2023) reported that automated quantity extraction through BIM significantly enhances estimation accuracy by reducing manual errors and enabling systematic material mapping. Although their study focused on embodied carbon assessment, the same principle of automated data extraction is directly applicable to earthwork volume computation, where precise cut–fill quantification is critical for minimizing material imbalance.

Material efficiency improvements enabled by BIM-based workflows have also been documented. Kouka et al. (2025) observed that digital quantity take-offs and coordinated modeling can reduce material wastage by approximately 10–25% in large-scale projects. While most existing studies emphasize structural components, similar efficiency gains can be achieved in earthwork through phased surface comparison, grading simulation, and early identification of excessive excavation zones.

Furthermore, Ercal and Shafique (2023) highlighted that BIM enhances transparency in environmental impact assessment by creating traceable links between design decisions and sustainability outcomes. In the context of earthwork, such traceability enables measurable comparison between existing and proposed terrain conditions, facilitating data-driven decisions that reduce unnecessary excavation and transportation.

Despite these advantages, current literature indicates that BIM adoption for sustainability remains largely concentrated in lifecycle assessment and design coordination (Fazeli et al., 2023; Hammes et al., 2022). Systematic application of BIM for earthwork optimization, cut–fill balancing, and construction-stage terrain analysis remains insufficiently explored, revealing a significant gap between BIM's theoretical sustainability potential and its practical deployment in early-stage site development.

Sustainability challenges are particularly critical in industrial and warehouse buildings due to their high material consumption, long-span structural systems, and substantial operational energy requirements. Kouka et al. (2022) reported that the use of BIM for structural refinement and strategic material selection can play a significant role in reducing embodied carbon, especially in steel-dominant construction systems. However, achieving such outcomes requires a well-coordinated modeling approach that combines structural, architectural, and MEP systems within an integrated sustainability framework.

The literature consistently suggests that BIM should not be viewed solely as a drafting or visualization technology. Rather, it serves as a comprehensive digital platform capable of supporting sustainability objectives across all phases of a project lifecycle. Nevertheless, a disconnect persists between BIM's theoretical sustainability capabilities and its practical implementation, particularly during early site development activities. To address this limitation, the present study proposes and applies a structured BIM workflow centered on earthwork optimization and Bill of Quantities (BOQ) validation during the construction stage.

METHODOLOGY

This research adopts a quantitative approach using Building Information Modeling (BIM) to assess earthwork precision, material efficiency, and construction-stage sustainability within a project. The methodology ensures that the BIM model functions not only as a visualization tool but also as a data-rich analytical platform capable of supporting earthwork calculations, quantity take-offs, and progress-based waste assessment.

The proposed workflow follows a structured sequence of steps, starting with data collection and the establishment of the BIM environment. This is followed by model creation, quantity extraction, and verification of the obtained results. An active industrial warehouse project has been selected as the case study to demonstrate the application of this approach. The study highlights the development and utilization of a three-dimensional BIM model using Autodesk Revit, which serves as the central platform for quantity take-offs, detailed visual progress monitoring, and analysis of construction waste.

This research places special emphasis on earthwork estimation, quantity extraction, and BOQ reconciliation, aiming to address an existing gap in BIM-based sustainability studies where material losses from earthwork activities have received limited attention. The overall methodology is structured into the following stages:

1. Data Collection and Pre-Modelling Preparation

The first step involves gathering and verifying all necessary project data required for the precise development of the BIM model. This includes topographic and contour survey drawings, spot levels, benchmarks, and architectural plans that define the spatial layout of the building. Structural drawings that detail grids, foundations, columns, and roof framing elements are also collected, along with the Bill of Quantities (BOQ), which will later be used for quantity reconciliation. The accuracy of these inputs is essential, as any mistakes at this stage directly impact the reliability of earthwork calculations and material quantity estimations.

Modelling phase-

1. Site model (topographic model)
2. Structural model
3. Architectural model

4. MEP model

i. Site Model (Topographic Model)

Topographic modeling forms the foundation of the proposed BIM-based earthwork analysis. Existing site conditions are developed by importing surveyed contour lines and spot elevation data into Autodesk Revit to generate a digital topographic surface representing preconstruction ground levels. Two-dimensional AutoCAD survey drawings are converted into a three-dimensional terrain model to ensure accurate spatial representation of site conditions.

The generated surface is assigned to the “Existing” phase to clearly distinguish original ground levels within the BIM environment. To enhance volumetric precision, a higher density of elevation points is incorporated in critical areas such as steep slopes, cut–fill transition zones, and foundation-intensive regions, while fewer points are used in relatively uniform flat areas.

A “Proposed” topographic surface is then created using the graded region functionality by modifying the existing terrain to reflect finished formation levels, building platforms, access roads, and drainage gradients. Building pads are inserted beneath the warehouse footprint at specified formation levels to define excavation boundaries and simulate soil removal associated with foundation works.

The phased distinction between existing and proposed terrain enables automated volumetric computation within the BIM environment. The graded region tool calculates total cut volume, total fill volume, and net earthwork balance, providing a quantitative basis for assessing excavation precision, material efficiency, and construction-stage sustainability performance.

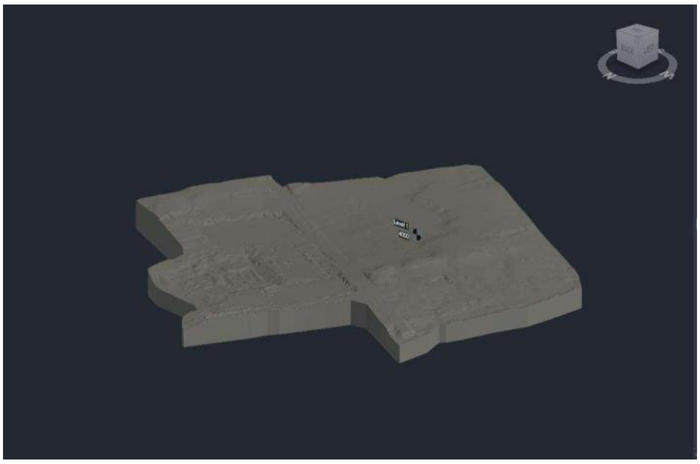

Fig. 1: 3-dimensional topographic model of the industrial warehouse, developed from a 2-dimensional AutoCAD drawing.

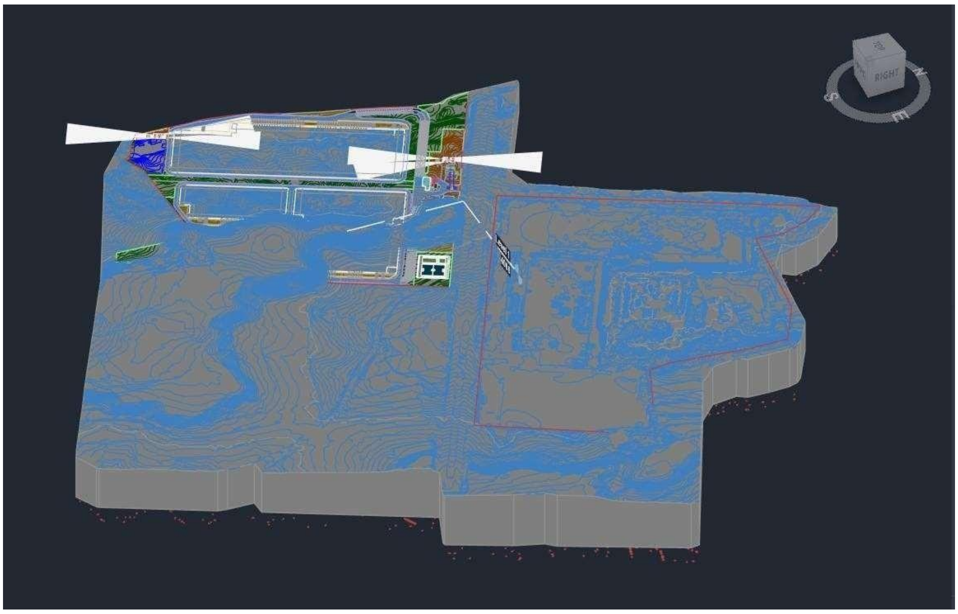

Fig. 2: Topographic Model Defining the Contour Details.

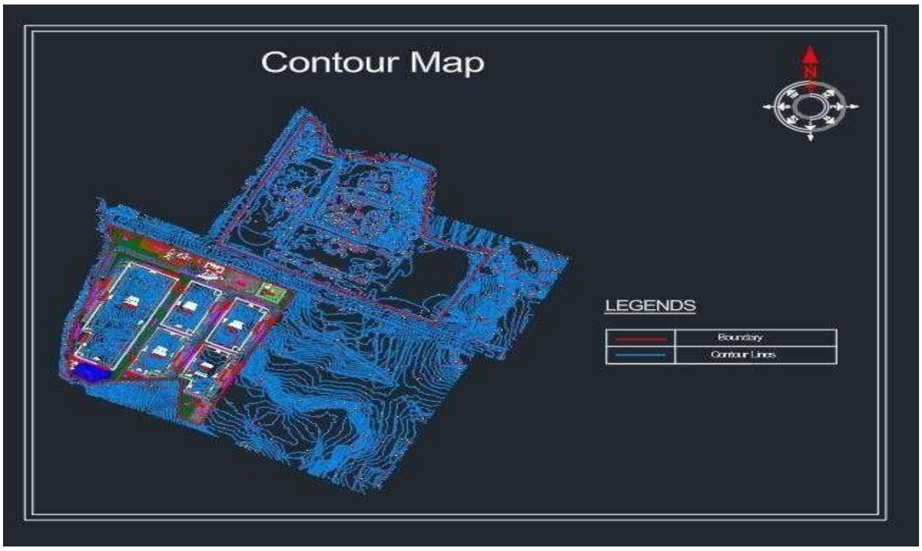

Fig. 3: AutoCAD Contour Survey Drawing.

The BIM model's geometric layout, spatial characteristics, and material specifications are created following an information-rich modeling standard to enable automated quantity extraction, as described by Demian et al. (2014) and Hollberg et al. (2020).

1. Structural Modelling of Substructure Components

After establishing formation levels and performing cut-and-fill analysis, the next step focuses on modeling the substructure elements according to actual construction sequencing and excavation requirements. Structural grids, labeled A–U and 1–27, are set up, and corresponding levels are assigned based on the design drawings to improve estimation accuracy. In the industrial warehouse, the foundation comprises reinforced concrete columns up to a designated height, above which steel H-section columns are installed; this arrangement is known as a pedestal system. Anchor bolts connect the concrete pedestals with the steel columns. Footing dimensions and depths are determined based on soil strata and load distribution considerations. Plinth beams with specified dimensions are also modeled at this stage. Following the completion of footings and columns according to structural drawings, reinforcement detailing for the pedestals is added. Superstructure elements, including jack beams, rafters, and purlins, are then modeled with specified dimensions and slopes. Finally, sidewall bracing and structural connections are incorporated to complete the structural model.

2. Architectural Model

The architectural modeling phase focuses on defining the warehouse's external form, internal layout, and building envelope systems. External wall systems, such as waffle walls with varying dimensions specified in the drawings, are modeled to accurately represent the building envelope, while internal elements like mezzanine floors are treated as functional operational zones. Mezzanine floor slabs and roof coverings are created following structural and functional requirements. Openings, including industrial doors, rolling shutters, skylights, and ventilation louvers, are added to realistically reflect access, daylight, and ventilation conditions. Throughout this stage, architectural elements are continuously coordinated with the structural model to avoid clashes, ensure constructability, and maintain necessary clearances. Material properties are assigned to architectural components to enable precise quantity takeoffs and sustainability assessments, especially for envelope materials that significantly impact overall material usage.

3. Mechanical, Electrical, and Plumbing (MEP) Modelling

The final phase of BIM modeling addresses the mechanical, electrical, and plumbing (MEP) systems, representing the essential services needed for warehouse operations. Mechanical systems, including ventilation ducts, exhaust systems, and HVAC units where applicable, are modeled to ensure proper indoor environmental control. Electrical systems cover lighting fixtures, cable trays, distribution boards, and power routing, designed to meet operational and safety requirements. Plumbing systems consist of water supply lines, sanitary drainage, and rainwater disposal networks integrated with roof and site drainage.

MEP elements are developed at a suitable level of detail to facilitate accurate spatial coordination with structural and architectural components. While the primary focus of quantity take-offs is not on MEP items, including them ensures a fully coordinated, clashfree model and supports energy analysis, thereby contributing to sustainable construction performance throughout the building lifecycle.

3. Model Integration, Quantity Extraction, and Analytical Evaluation-

1. Model Integration and Coordination

Stage 3 involves combining all discipline-specific BIM models into a single, coordinated environment to enable effective analysis and decision-making. The topographic, structural, architectural, and MEP models developed in earlier stages are merged in Autodesk Revit to form a unified project model. Shared coordinates, grids, and levels are checked to ensure consistency across all components. Interdisciplinary coordination is then conducted to detect and resolve clashes between structural, architectural, and MEP elements, improving constructability and reducing potential rework and material waste.

This integrated model serves as a complete digital representation of the industrial warehouse and provides the basis for quantity extraction and energy analysis to support sustainability throughout the building lifecycle.

2. Assignment of Phases, Materials, and Parameters-

After integrating the models, project phases, and material properties are systematically assigned to all relevant elements. Components are categorized by phase, such as Existing and New Construction, especially for topographic and substructure elements, to ensure accurate earthwork calculations. Material attributes, including concrete grades, steel sections, and cladding systems, are applied to structural and architectural components. Additionally, shared parameters like BOQ item numbers, work package identifiers, and construction sequence codes are included in the model. This organized parameterization allows BIM-derived quantities to be directly linked with conventional measurement and cost practices, enabling effective comparison with the site BOQ.

3. Earthwork Quantity Extraction and Validation -

Earthwork evaluation is a key part of this phase, performed using graded regions and earthwork calculation tools in Autodesk Revit. Cut and fill volumes are determined by comparing existing and proposed topographic surfaces, with building pads designated as excavation areas beneath the planned warehouse. The outputs include total cut volume, total fill volume, and net earthwork volume, which are crucial for assessing material transport and disposal needs.

To ensure accuracy, cross-sectional views are created at selected points to compare existing ground levels with formation levels and foundation depths. Additional spot checks are conducted by contrasting BIM-derived quantities with simplified manual calculations to verify the reliability of the results.

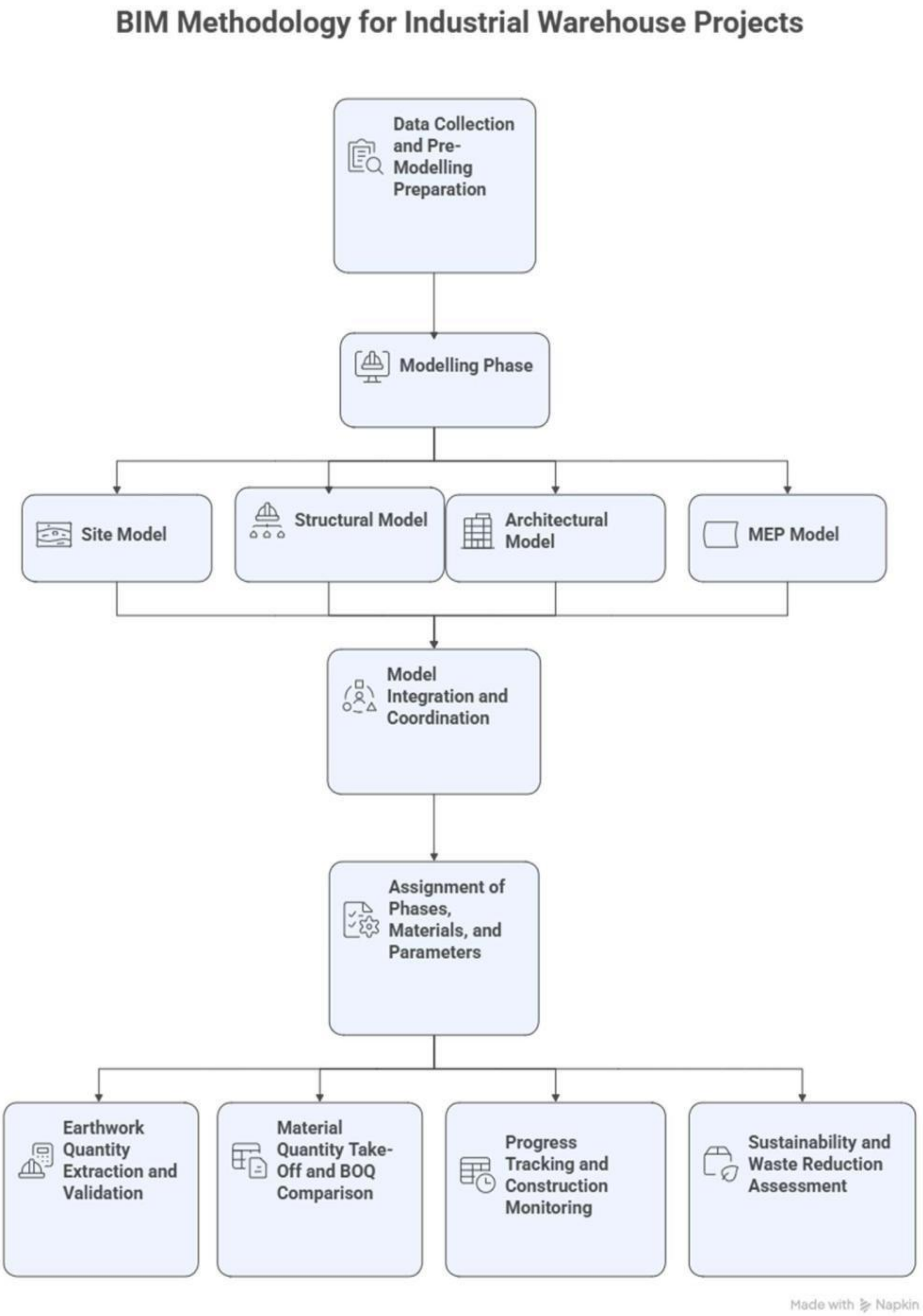

Fig. 4: Flow chart representing stages involved in BIM model development.

Overall, the proposed methodology demonstrates a structured BIM-driven approach that enables precise earthwork estimation, reliable material quantity take-offs, and systematic sustainability assessment through integrated modeling and data-focused analysis.

RESULTS AND DISCUSSION

In this study, sustainability is primarily achieved through energy analysis, material optimization, clash detection, waste reduction, improved decision-making, and the reduction of communication gaps among stakeholders during the early stages of construction. These outcomes are largely facilitated by the BIM-based quantitative workflow employed in the research. The results indicate that integrating earthwork calculations, automated quantity take-offs, BOQ reconciliation, progress tracking, solar analysis, and a unified BIM environment collectively enhances sustainability performance in construction projects.

Firstly, sustainability in earthwork operations is realized by separating existing and proposed ground surfaces and calculating cut-and-fill volumes within the BIM environment. This process promotes optimal earthwork balancing by identifying opportunities to reuse excavated materials, thereby reducing the need for material disposal or import. These findings align with Osmani et al. (2012, 2015) and Tam et al. (2018), who emphasized that excessive excavation and inadequate early planning contribute significantly to material waste.

Secondly, material efficiency is improved through automated quantity take-offs from datarich parametric BIM models. Quantities for concrete, reinforcement, and structural steel rely less on conservative estimates typical of conventional BOQs. This aligns with Demian et al. (2014) and Hollberg et al. (2020), who show that data-driven BIM environments enable more accurate material estimation and better sustainability outcomes. Variations in quantity estimates directly affect procurement efficiency and help reduce material wastage.

Third, aligning the quantities generated from the BIM model with the values stated in the BOQ is essential from a sustainability perspective. Any discrepancy or overestimation can lead to unnecessary material procurement, increasing waste and resource consumption. The variations identified in this study are consistent with the observations of Regui et al. (2020) and Mateus et al. (2019), who reported that traditional BOQs often lack geometric accuracy and may not precisely represent actual construction needs.

In general, the findings demonstrate that sustainability can be translated into measurable and practical outcomes, including reduced excess excavation, minimized material overestimation, and lower waste caused by rework. The proposed methodology aligns with the conclusions of previous researchers such as Osmani et al., Tam et al., Chan et al., Demian et al., Regui et al., Mateus et al., and Hollberg et al., highlighting that BIM-based quantitative workflows effectively enhance construction sustainability. By integrating earthwork optimization, accurate quantity extraction, BOQ validation, and progressoriented monitoring, the approach supports improved material efficiency and significant waste reduction during construction.

CONCLUSIONS

This study develops a structured BIM-based workflow aimed at enhancing earthwork operations and promoting sustainability during the construction phase of industrial warehouse projects. Instead of concentrating on empirical performance measurement, the research presents a systematic modeling approach that combines terrain evaluation, stage-wise surface comparison, quantity extraction, and BOQ verification within a single integrated digital platform.

The proposed workflow illustrates how BIM can be effectively used as a decision-support tool for earthwork planning. It improves clarity in volume calculations, strengthens coordination among disciplines, and supports the early integration of sustainability considerations. Furthermore, the framework establishes a basis for future empirical investigations that can measure material savings, carbon emission reductions, and cost efficiency through practical project applications.

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