

A LEAN-BIM OPERATIONAL TRACEABLE MODEL FOR 5D COST-SCHEDULE INTEGRATION IN STRUCTURAL WORKS

Gerardo Becerra¹, Jesús Ortega², Italo Sepúlveda³, Beda Barkokebas⁴, & Luis F. Alarcón⁵

ABSTRACT

The construction industry faces persistent challenges in cost control, schedule reliability, and data consistency, particularly during the structural phase of high-rise buildings. Although Building Information Modeling (BIM) offers the potential to integrate quantities, costs, and schedules, its operational application remains limited due to the lack of standardized modeling practices and weak alignment between digital models and conventional cost–schedule structures. This study addresses this gap by developing and validating an operational, model-centered integration method that embeds a common itemized structure directly within the BIM model to support consistent cost–schedule integration. The research adopts a quantitative, applied methodology comprising four phases: (i) diagnosis of conventional ERP-based practices, (ii) design of a common itemized structure, (iii) iterative development of a parametric BIM model, and (iv) comparative evaluation against traditional workflows using data from real high-rise projects. The results demonstrate substantial improvements in traceability, automation, and data consistency, increasing cost–schedule coverage from approximately one-third of the items to over 95%. These findings show that effective 5D integration depends primarily on semantic structuring and standardized modeling logic rather than increased geometric detail, providing a practical and replicable approach for improving cost–schedule integration in structural works.

KEYWORDS

BIM 5D, cost-schedule integration, common itemized structure, structural works, lean-BIM integration.

INTRODUCTION

The construction industry is characterized by high levels of complexity and uncertainty, particularly regarding cost control, schedule reliability, and information consistency. Despite advances in digital tools and management methodologies, construction projects—especially

¹ Student Researcher, Universidad Autónoma de Chile, Santiago, Chile, gerardo.becerra@cloud.uaautonoma.cl, orcid.org/0009-0005-1332-3014

² Academic, Departamento de Obras Civiles, Universidad Técnica Federico Santa María, Avenida España 1680, Valparaíso 2390123, Chile, jesus.ortegaf@usm.cl, orcid.org/0000-0002-1148-937X

³ PhD Candidate, Department Construction Engineering and Management, Pontificia Universidad Católica de Chile, Santiago, Chile. Professor, Faculty of Architecture, Construction and Environment, Universidad Autónoma de Chile, Santiago, Chile, ilsepulveda@uc.cl, orcid.org/0000-0002-6019-9344

⁴ Assistant Professor, Department of Construction Engineering and Management, Pontificia Universidad Católica de Chile, Santiago, Chile, bbarkokebas@uc.cl, orcid.org/0000-0002-0054-1320

⁵ Professor, Department of Construction Engineering and Management, Pontificia Universidad Católica de Chile, Santiago, Chile, llalarcon@uc.cl, orcid.org/0000-0002-9277-2272

high-rise buildings—continue to experience cost overruns, schedule deviations, and fragmented information flows due to the scale of executed volumes and the interdependence of construction activities (Abdelalim et al., 2025; Aredah et al., 2019).

Within this context, BIM has been promoted as a means to improve coordination by linking three-dimensional representations (3D) with time (4D) and cost (5D). In theory, 5D BIM enables automated quantity take-off, cost estimation, and schedule integration, supporting improved decision-making and project control (Fan et al., 2015). However, empirical evidence indicates that the operational use of BIM for cost-schedule integration remains limited in practice (ElMenshawly & Marzouk, 2021).

A recurring limitation identified in the literature is the lack of standardized modeling practices aligned with the cost and scheduling structures used in Enterprise Resource Planning (ERP) systems. BIM models are often developed with a geometric or coordination-oriented focus, while budgets and schedules rely on independent breakdown structures, resulting in weak traceability and manual data reconciliation (Abdelalim et al., 2024; Fan et al., 2015). This disconnect is particularly critical during the structural phase of high-rise buildings, where large quantities and repetitive elements demand high levels of data consistency and automation. This limitation arises from a structural misalignment between BIM modeling and construction control processes, where BIM is primarily used for geometric coordination rather than 5D integration. As a result, data requires manual reinterpretation, generating variability, rework, and informational waste. This issue is not inherent to BIM, but to how models are structured, as properly configured models can support both coordination and 5D integration.

Recent studies show that 5D BIM automation depends on semantic structuring rather than geometric detail, while the lack of standardized modeling rules generates informational waste and weakens integration (Alathamneh et al., 2024; Eldeeb et al., 2022; Fan et al., 2015; Michaud et al., 2019). Although UniFormat and MasterFormat organize information, they do not ensure operational traceability (Construction Specifications Institute (CSI), 2014). This study addresses the research question of whether embedding a common itemized structure within the BIM model improves cost-schedule traceability, automation, and data consistency compared to conventional ERP-based approaches.

To test this hypothesis, the paper proposes and testing a Modeling-Anchored BIM Integration Method, referred to as the Operational-Traceable Model (OTM). The OTM embeds a common itemized structure within the BIM model as an explicit modeling rule, transforming it into the operational axis for 5D integration and enabling direct, replicable traceability between modeled elements, budget items, and scheduled activities during the structural phase of high-rise buildings.

THEORETICAL FRAMEWORK / LITERATURE REVIEW

BIM supports coordination, information integration, and decision-making by linking 3D models with schedule and cost dimensions (Fan et al., 2015). However, the operational adoption of 5D BIM remains limited, especially in cost-schedule integration and project control. A key limitation in the literature is the disconnect between BIM model information structures and ERP-based cost and scheduling breakdowns. Conventional approaches relying on Gantt charts and 2D documentation require manual linking between model elements and activities, reducing automation and control reliability (Aredah et al., 2019; Elghaish & Abrishami, 2020). Misalignment between CBS, WBS, and BIM models leads to fragmented information and inefficiencies in cost-schedule management (Fan et al., 2015). Additionally, BIM Execution Plans (BEPs) often lack guidelines to align modeling with cost and scheduling requirements.

BIM is commonly used for geometric coordination, while budgets and schedules are developed separately, resulting in weak traceability and reliance on manual processes (Safaa Eldin et al., 2024). The literature indicates that increasing geometric detail does not resolve these issues. Instead, effective 5D integration depends on semantic structuring, including consistent parameters, unit definitions, and alignment between BIM elements and cost items (Alathamneh et al., 2024; Fan et al., 2015), with practical limitations reinforced by heterogeneous modeling practices (Pishdad & Onungwa, 2024).

From a Lean Construction perspective, BIM should be understood as a mechanism to improve information flow across product, process, and organizational dimensions, rather than solely a technological enhancement. Within VDC, BIM supports planning and control, yet current use remains focused on 3D representation, neglecting alignment with execution structures (Rodriguez et al., 2021). This generates informational waste, where excessive geometric detail reduces operational usability, particularly in 5D contexts. Additionally, fragmented workflows across disconnected tools lead to redundant data handling and unreliable information flows (Suarez et al., 2020). Lean-BIM integration can therefore be defined as the alignment of BIM information with executable work units, cost, and scheduling structures, prioritizing semantic consistency and traceability over geometric detail.

The absence of standardized modeling rules reinforces informational waste, rework, and unstable data flows, highlighting the need for process standardization and continuity to improve operational reliability (Eldeep et al., 2022; Michaud et al., 2019). Although classification systems such as UniFormat and MasterFormat provide widely accepted taxonomies for organizing construction information, they do not define operational modeling rules nor guarantee traceability between BIM elements, cost items, and scheduled activities (Construction Specifications Institute (CSI), 2014). Consequently, the lack of common itemized structures and modeling protocols oriented toward cost–schedule traceability remains a critical barrier to effective 5D BIM implementation (Fan et al., 2015; Parsamehr et al., 2023; Safaa Eldin et al., 2024).

Within this context, the OTM addresses these limitations by embedding a common hierarchical itemization into the BIM model. By aligning modeling practices with measurable and schedulable construction units, the OTM turns the BIM model into the operational backbone of 5D traceability and provides the theoretical foundation for the approach tested in this study.

METHODOLOGY

This study adopted a quantitative, applied approach structured in four sequential phases: diagnosis, solution design, iterative prototyping, and comparative validation. The proposed OTM operationalizes and demonstrates BIM-based cost-schedule integration through a common itemized structure (Figure 1).

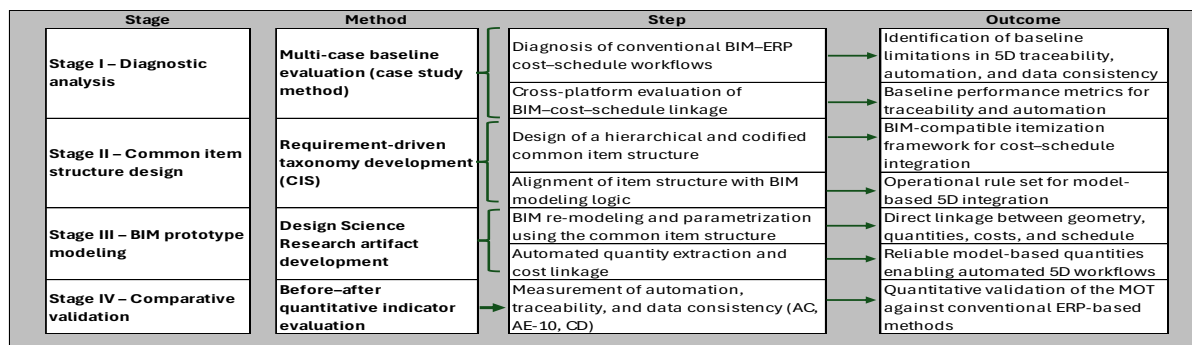


Figure 1: Research design

Stage I, involved a comparative diagnostic analysis of historical cost control and scheduling data from two completed high-rise building projects managed with conventional ERP-based workflows. It established a baseline for traceability, automation, and cost-schedule data consistency, identifying structural limitations in traditional practices without altering the original data. On this basis, performance indicators were defined to evaluate these dimensions and to assess the impact of the OTM on the linkage between modeling or planning and control, as well as on workflow coherence.

Two indicators were defined. The Automation Coverage Index (AC-Index) measures the percentage of budget items and scheduled activities with complete budget and actual data, reflecting traceability between modeling or planning and control; in the OTM, it corresponds to the percentage of common itemization entries with quantities exported from Revit to Presto/Cost-It. Data Consistency (DC) evaluates the coherence between the BIM model, extracted quantities, budget items, and scheduling logic using a normalized ordinal scale from 1 to 5 based on relative deviation thresholds. Lower deviations indicate greater coherence and operational reliability: deviations below 5% receive a score of 5, deviations between 5% and 10% score 4, deviations between 10% and 20% score 3, deviations between 20% and 30% score 2, and deviations of 30% or more score 1, following criteria adapted from De Solminihac & Thenoux (2020).

The DC scoring thresholds are adapted from the technical consistency limits proposed by De Solminihac and Thenoux (2020) and operationalized into a normalized ordinal scale to support comparative 5D analysis (De Solminihac & Thenoux, 2020). The Data Consistency (DC) indicator is based on an ordinal scale derived from deviation thresholds used in construction cost control. While this enables a synthetic assessment of data coherence, transforming continuous variables into discrete categories may introduce subjectivity. However, the thresholds align with accepted tolerance ranges, supporting its use as a comparative proxy rather than an absolute measure. Future improvements may include sensitivity analysis and inter-rater reliability assessments.

In addition, the Effective Automation Index $\leq 10\%$ (EA-10) measures the percentage of traceable items whose deviation between budget and actual is less than or equal to 10%, representing the proportion of items with acceptable consistency. Similarly, in the OTM, EA-10 is defined as the percentage of items whose deviation between exported quantities and control quantities in Revit was $\leq 10\%$. This threshold is adapted from the cost control criteria proposed by De Solminihac and Thenoux (2020), who indicate that deviations within $\pm 10\%$ are generally considered acceptable in building construction projects.

Stage II, applied a methodological design approach based on the analysis of existing construction classification standards and their reorganization into a hierarchical structure centered on the building level as the primary operational unit. Through the adaptation of recognized classification systems (MasterFormat, UniFormat, Omniclass, and local standards), a hierarchical and codified common itemized structure was developed, in which each building level acts as the central aggregation unit for measurable and schedulable construction items, aligned with BIM modeling logic and the operational requirements of 5D cost-schedule integration.

Stage III, an experimental BIM prototyping approach was implemented. As illustrated in Figure 2, the BIM model was progressively developed and parameterized according to the common itemized structure through successive iterations, adjusting model granularity and parameters until automated quantity generation and reliable cost-schedule linkage were achieved.

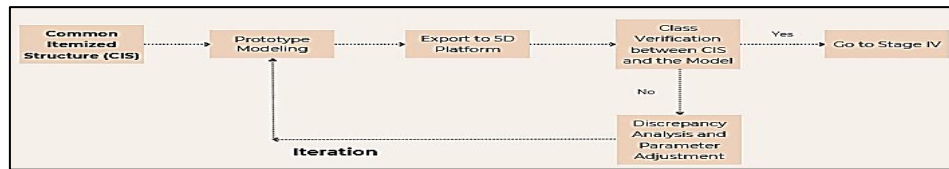


Figure 2: Iterative BIM Prototyping Workflow Based on the Common Itemized Structure

Stage IV, consisted of a quantitative comparative evaluation of the BIM prototype against the ERP-based baseline using AC-Index, EA-10, and DC indicators. The baseline, derived from two high-rise projects with BIM limited to geometric modeling, represents typical industry performance. The comparison assessed the model's capacity to achieve traceable and automated cost-schedule integration, following 5D best practices (Fan et al., 2015) and addressing interoperability challenges identified in BEP and QTO studies (Alathamneh et al., 2024; Safaa Eldin et al., 2024).

The workflow included Revit 2025 for modeling, Presto with Cost-It (and Ondac Evolution) for quantity extraction, and Excel for data consolidation. A JavaScript script was used to normalize units. Target thresholds were set at AC-Index $\geq 95\%$, DC $\geq 4.5/5$, and EA-10 $> 90\%$, aligned with QTO-5D standards (Alathamneh et al., 2024). The analysis combined ERP baseline data with iterative KPI application to the BIM prototype, refining modeling and itemization until targets were met. Validation focused on structural elements due to their cost-time relevance. Baseline cases used 2D and ERP workflows, with BIM limited to coordination. Despite being limited to two cases, shared characteristics ensured comparability, and results reflect typical industry conditions with potential transferability.

Baseline cases correspond to conventional practices where BIM is primarily used for geometric coordination (clash detection), without parametric structuring for measurement or 5D integration. As a result, modeled elements do not support quantity take-off or direct linkage with cost and scheduling, conditioning the scope of comparison. In contrast, the OTM-based model preserves coordination capabilities while incorporating semantic structuring that enables its use for quantity take-off, cost estimation, and scheduling. This functional duality supports the comparison, showing that BIM can be extended toward 5D management without compromising coordination performance.

RESULTS

STAGE I - MULTI-CASE BASELINE EVALUATION (CASE STUDY METHOD)

This stage establishes the baseline performance of conventional BIM-ERP workflows. The results show low traceability between the model, budget, and schedule, with reduced levels of automation and poor data consistency. The metrics presented in **Table 1** quantitatively confirm the structural limitations of the traditional approach and define the reference point for evaluating the proposed method.

Table 1: Baseline performance metrics – conventional ERP workflows

Indicator	Building A (ERP)	Building B (ERP)
AC-Index	33%	25%
EA-10	0.03%	0.02%
Data Consistency – DC (1–5)	1.01	1.01

STAGE II – REQUIREMENT-DRIVEN TAXONOMY DEVELOPMENT COMMON ITEMIZED STRUCTURE (CIS)

The result of this stage corresponds to the definition of a hierarchical and codified Common Itemized Structure (CIS), compatible with BIM modelling logic. This CIS constitutes the methodological framework of the proposed approach, establishing the semantic basis necessary to coherently articulate geometry, quantities, costs, and scheduling, thereby enabling 5D integration directly from the BIM model (Table 2).

Table 2: Outcome of stage II – common item structure.

Aspect	Conventional approach	OMT common item structure
Cost structure	ERP-based, external to BIM	Embedded in BIM model
Coding logic	Budget-oriented	Model-oriented (parametric)
BIM compatibility	Partial	Full
Cost–schedule linkage	Manual	Rule-based

Figure 3 illustrates an example of the Common Itemized Structure (CIS) applied to structural works at the floor level, showing the hierarchical breakdown of a single floor into concrete and formwork items. Each terminal item represents a measurable construction unit defined through hierarchical coding, enabling direct mapping between BIM elements, cost items, scheduling activities, and measurement units. BIM elements of the same type within a floor are modeled to allow quantity consolidation at the terminal item level (i.e., floor-based concrete or formwork items), ensuring traceability between BIM, cost, and schedule without introducing unnecessary geometric detail.

EDT*	Código	NatC*	Nat*	Resumen	CanPres	Ud
	0		Raíz	Estructura de Itemizado tipo	1	
	01		Capítulo	OBRA GRUESA	1	
	1.1		Capítulo	PISO 3	1.00	
	1.1.1		Capítulo	HORMIGONES PISO 3	1.00	
	1.1.1.1		Partida	HORMIGON DE MUROS	m3	
	1.1.1.2		Partida	HORMIGON DE LOSA	m3	
	1.1.1.3		Partida	HORMIGON DE VIGAS	m3	
	1.1.2		Capítulo	MOLDAJE PISO 3	1.00	
	1.1.2.1		Partida	MOLDAJE MUROS	m2	
	1.1.2.2		Partida	MOLDAJE LOSA	m2	
	1.1.2.3		Partida	MOLDAJE VIGAS	m2	

Note (translation of Spanish labels in the figure): *Raíz* = Root; *Capítulo* = Chapter; *Partida* = Item; *Obra Gruesa* = Structural Works; *Piso 3* = Level 3; *Hormigones Piso 3* = Concrete Works Level 3; *Moldaje Piso 3* = Formwork Level 3; *Hormigón de Muros / Losa / Vigas* = Wall / Slab / Beam Concrete; *Moldaje Muros / Losa / Vigas* = Wall / Slab / Beam Formwork.

Figure 3: Example of a Common Itemized Structure (CIS) and its mapping to BIM elements, cost items, and scheduling activities

STAGE III - DESIGN SCIENCE RESEARCH ARTIFACT DEVELOPMENT

At this stage, the results demonstrate (view table 4) that the BIM prototype, by incorporating the common itemized structure, enables a direct linkage between geometry, quantities, and costs, with automated information extraction. Figure 4 illustrates the BIM prototype structured under the common itemized logic, showing the alignment between geometry, quantities, and cost-related data. The model exhibits operational capacity to support automated 5D workflows, reducing the dependence on manual adjustments.

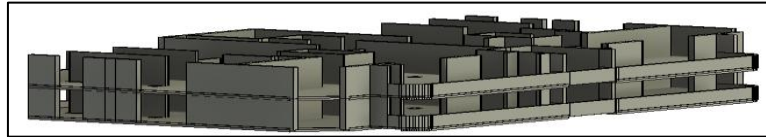


Figure 4: BIM model structured according to the OTM logic

To complement the aggregated performance indicators, Table 3 summarizes the main sources of mismatch identified during the iterative development phase. These mismatches reflect the need for adjustments in modelling, coding, and itemization to achieve stable traceability between BIM elements, cost items, and scheduling activities. It also documents the corrective actions implemented across iterations, evidencing how targeted methodological refinements resolved these issues and reduced automation frictions.

Table 3: Main sources of mismatch and corrective actions during OTM implementation

Cause of mismatch	Systems	Origin	Corrective action implemented
Ambiguous differentiation between structural elements and formwork	Walls/Formwork	Iteration 1	Definition of explicit differentiation rules within the common itemized structure to separate concrete elements from formwork
Non-unique identification and excessive geometric granularity	Walls/Slabs/Beams	Iteration 2	Enforcement of unique item codes per element and floor, consolidating geometry into single measurable units aligned with the itemized structure
Parametric misalignment between modeled and control quantities	Slabs	Iteration 1–2	Standardization of measurement parameters (e.g., thickness, effective area, exclusion rules) to ensure consistency between modeled and control data
Inconsistent unit definitions between model and cost structures	Walls/Slabs	Iteration 2–3	Alignment of measurement units (m^3 , m^2) with the common itemized structure to ensure compatibility with cost estimation workflows
Over-segmentation of model elements not aligned with executable work units	Walls/Beams	Iteration 2	Aggregation of elements into operational units based on construction logic and scheduling requirements, reducing unnecessary geometric fragmentation

As part of the corrective actions described in Table 3, Figure 5 presents a representative script implementation used to resolve unit inconsistencies during cost extraction.

```
// Script for Cost-it: separate structural walls and formwork
// Author: Presto GPT

function onExportElement(element) {
  // Read the element name/type
  var type = element.TypeName;

  // If the name contains "MOLD.", export area (m²)
  if (type.indexOf("MOLD.") >= 0) {
    // Assign the area to the quantity field
    element.Quantity = element.Area;
    element.MeasureUnit = "m2";
  }
  else {
```

Figure 5: JavaScript snippet used for unit normalization during cost extraction

The consolidated modeling principles summarized in Table 4 emerged from the iterative resolution of mismatches identified during the prototyping process.

Table 4: Consolidated modeling principles established in Stage III

Modelling principle	Effect on 5D traceability
Floor-based and uniquely instantiated modeling	Each floor is modeled as an independent unit with floor-specific element instances, preventing duplication and enabling one-to-one correspondence between BIM elements, itemized structure, and scheduled activities.
Operationally oriented element definition	Modeling is limited to valuated and schedulable elements, with consistent item codes and measurement units (e.g., m ³ , m ² , kg), ensuring coherence with the hierarchical itemized structure and supporting automated 5D calculations.
Standardized parameterization and export rules	The use of system families, shared parameters, and standardized export configuration ensures consistent quantity measurement and reliable data transfer to cost management platforms, closing the BIM–cost–schedule traceability loop.

STAGE IV - BEFORE–AFTER QUANTITATIVE INDICATOR EVALUATION

Quantitative performance evaluation demonstrates substantial improvements of the BIM prototype compared to the ERP baseline in terms of traceability, automation, and data consistency. The comparative indicators confirm the superior performance of the OTM, empirically validating its effectiveness against conventional methods. Figure 6 below present the results obtained.

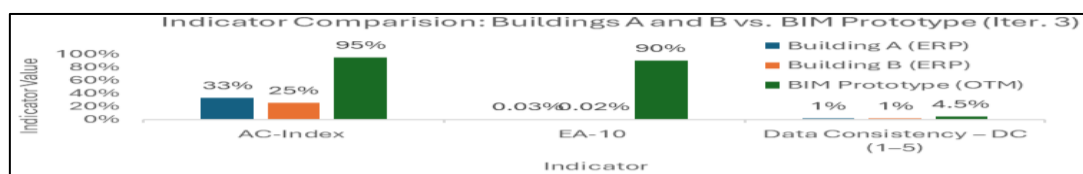


Figure 6: Comparison of indicators: Buildings A and B (baseline) vs. OTM prototype

Figure 6 shows that the OTM substantially outperforms the ERP-based baseline, increasing traceability to above 95%, automation to above 90%, and data consistency to more than 4.5, while the conventional approach remains limited by low coverage, minimal automation, and poor coherence. These results indicate that the OTM transforms the BIM model into an operational backbone for 5D integration. From a Lean-oriented perspective, the method aligns modeling decisions with information flow efficiency rather than visual representation, reducing informational waste by restricting geometry and parameters to those required for cost-schedule automation. Table 5 summarizes the relationship between the main OTM mechanisms, Lean Construction constructs, and their effects on 5D integration performance.

Table 5: Mapping between OTM mechanisms and Lean Construction contributions

OTM mechanism	Lean construction	Waste	Effect on 5D integration
CIS and hierarchical coding embedded in the BIM model	Standard work and flow reliability	Rework Waiting	Standardizes modeling rules and stabilizes BIM–cost–schedule data exchange
Modeling based on measurable and schedulable units	Variability reduction	Overprocessing	Aligns model granularity with cost-schedule items, reducing deviations and manual adjustments
Early standardization and simplified geometry.	System-level waste reduction	Overproduction Duplication	Minimizes downstream corrections and stabilizes quantity extraction for 5D automation

DISCUSSION

The outcomes indicate that operational 5D BIM remains constrained by non-standardized modeling practices and weak alignment between BIM models and cost–schedule structures. As reported in previous studies, this misalignment reduces traceability, fragments control, and increases reliance on manual interpretation (Fan et al., 2015; Parsamehr et al., 2023; Safaa Eldin et al., 2024). In contrast, the OTM achieved traceability above 95% and data consistency greater than 4.5/5, suggesting that semantic structuring through hierarchical itemization can significantly improve the operational use of BIM for cost–schedule integration (Giménez et al., 2025; Safaa Eldin et al., 2024). These findings support the view that effective 5D integration depends less on increasing geometric detail and more on modeling standardization, parameter consistency, and alignment with measurable work units. From a Lean Construction perspective, this also suggests that the OTM contributes to more stable information flow and to the reduction of informational waste, rework, and overprocessing (Eldeep et al., 2022; ElMenshawly & Marzouk, 2021; Michaud et al., 2019; Pishdad & Onungwa, 2024).

The iterative development process also helps explain why the proposed method performed better than the baseline. Ambiguities between structural elements and formwork created rework in quantity take-off, while excessive segmentation and inconsistent unit definitions generated overprocessing and delays. Under the OTM, these issues were reduced through explicit differentiation rules, operational aggregation of elements, and parameter standardization. This indicates that many of the observed inefficiencies were not caused by BIM technology itself, but by the absence of a modeling logic explicitly aligned with cost and scheduling needs.

This interpretation is consistent with recent IGLC literature, which suggests that BIM-based project control is often constrained more by fragmented tools and workflows than by technological limitations alone. Disconnected platforms tend to increase coordination effort and weaken decision reliability (Suarez et al., 2020), whereas BIM should be understood as part of an integrated production and control system rather than as an isolated digital model (Rodriguez et al., 2021). In this sense, the contribution of the OTM is not only technical, but also procedural, since it organizes BIM information in a way that supports more coherent downstream use.

At the same time, the findings should be interpreted with appropriate caution. Although Lean-BIM integration can improve workflow stability when supported by consistent information structuring (Landim et al., 2022), interoperability challenges remain important in practice (Assaf et al., 2023). The results therefore suggest that improved 5D BIM performance depends on semantic information organization that reduces waste and strengthens cost-schedule integration (Gómez-Cabrera et al., 2020), but not that interoperability problems have been fully resolved. In this context, the OTM appears to reduce some of the waste associated with fragmented cost–schedule integration by strengthening the internal consistency of the BIM model and its alignment with control structures.

Although the OTM is not tied to specific structural elements, but rather to the alignment of BIM modeling with measurable work units and cost–schedule structures, its applicability beyond this context still requires further examination. The results indicate potential transferability, but this should be confirmed in other disciplines, project phases, and multidisciplinary environments.

From a systems-integration perspective, the OTM should not be interpreted as a direct BIM-ERP integration mechanism. Instead, its contribution lies in providing a semantic structure that aligns BIM elements with cost and schedule breakdowns, thereby improving traceability across platforms. In that sense, the OTM functions as a bridging structure between BIM models and enterprise systems through semantic consistency rather than direct interoperability. This distinction is important, because it clarifies that the method improves the conditions for reliable data exchange, even though it does not eliminate the need for intermediate platforms or workflow coordination.

The discussion also has practical implications for implementation. Adoption of the OTM may face both interoperability and organizational challenges, especially in firms where ERP-based practices are already well established. The introduction of a Common Itemized Structure requires not only technical adjustments, but also changes in modeling criteria, coding logic, and coordination practices. In addition, the proposed approach demands greater upfront effort than conventional BIM workflows, particularly during early modeling and semantic structuring. However, consistent with the logic of the MacLeamy curve, this early effort may reduce later uncertainty, rework, and data inconsistencies by improving downstream reliability.

From a practical standpoint, one strength of the OTM is that it can be implemented using standard BIM tools without requiring additional software or complex technological infrastructure. Its main requirement is not new technology, but disciplined modeling oriented toward cost and schedule integration. Even so, successful implementation depends on the availability of BIM competencies capable of supporting this type of structured modeling, which creates challenges related to training, process standardization, and organizational readiness. For that reason, the feasibility of the method depends not only on technical adequacy, but also on broader organizational and implementation conditions.

CONCLUSIONS

This study provides empirical evidence that the OTM can improve 5D BIM cost–schedule integration in high-rise structural projects through standardized itemization, BIM coding, and quantity extraction. Results indicate substantial improvements over ERP-based workflows, with traceability exceeding 95%, EA-10 above 90%, and data consistency reaching ≥ 4.5 . These findings suggest that BIM models, when structured under the OTM logic, can support cost–schedule control when aligned with measurable work units.

The study further highlights that semantic structuring appears to be more important than increased geometric detail for effective 5D integration. In this sense, the OTM contributes to Lean-BIM practice by promoting more stable information flows and reducing the need for manual reinterpretation and rework. However, these findings have some limitations. The test of the approach was conducted only in two high-rise residential projects and in the structural phase, which restricts the strength of the generalization. Although the method shows potential for transferability, additional research is needed to test its applicability across other disciplines, project types, and implementation contexts.

Overall, further research should assess its scalability across contexts, BIM–ERP environments, AI-based automation, and real-project validation.

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