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BIM-Based Quantity Takeoff for Stage-Based Payment in High-Rise Construction: A Semi-Automation Approach

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Abstract

Building Information Modeling (BIM) is increasingly used to support quantity takeoff (QTO), yet commercial BIM tools remain limited to whole-element quantification, preventing the extraction of staged or partial quantities required for progress-based payment under unit-price contracts. This limitation is particularly critical in high-rise reinforced concrete projects, where structural components are executed in multiple pours across distinct contractual stages. This study addresses this gap by developing and validating a semi-automated workflow that enables stage-based QTO through element segmentation, contract-aware parameterization, and parameter-filtered scheduling. Using a real high-rise residential building in Vietnam, the workflow was applied to restructure the design-phase model into a stage-aware quantity model in which each BIM element corresponds to a single payment unit. The results demonstrate that the workflow can systematically generate contract-aligned staged quantities for columns, beams, slabs, and walls with high traceability and minimal deviation from manual QTO. The findings highlight the importance of combining geometric restructuring and information enrichment to overcome BIM's native whole-element logic. The study contributes a reproducible operational workflow suitable for developing BIM environments, offering a practical pathway for integrating BIM-derived staged quantities into progress-payment administration. Future work may further automate segmentation and integrate the workflow with 4D and reality-capture tools to enhance construction-phase verification.

1. Introduction

Progress-based payment is a fundamental mechanism for ensuring cash flow stability, managing financial risks, and promoting fairness between contractors and owners [1, 2]. However, accurately measuring progress in high-rise projects is inherently challenging due to repetitive floor cycles, dense structural systems, and multi-stage sequencing [2]. In many developing countries, including Vietnam, progress certification still relies on manual quantity measurement using site inspections and 2D drawings [3]. This practice often leads to inconsistency, delays in certification, and payment-related disputes [1].

Building Information Modeling (BIM)-based quantity takeoff (QTO) has shown strong potential in improving accuracy, transparency, and traceability in construction measurement workflows [4, 5]. Studies have demonstrated that model-based extraction reduces human error, enhances consistency, and supports more reliable decision-making compared with traditional manual methods [4]. Despite these advantages, most commercial BIM tools—including Autodesk Revit—are designed around *whole-element representation*, meaning they extract quantities for full components [5]. This inherent limitation prevents BIM from producing *partial* quantities required for progress-based or unit-price payments, especially when elements such as beams, slabs, and columns are constructed in multiple pours [6]. Although the literature repeatedly highlights this limitation, no existing study provides a practical, operational workflow capable of producing contract-compliant staged quantities directly from BIM models.

In parallel, digital progress-monitoring research has focused on visualization techniques, including 4D simulation, automated tracking using 3D scanning or point clouds, and other computer-vision-based methods [7-9]. While these approaches effectively support status monitoring and as-built vs. as-planned comparison [7], they do not address the core requirement of a stage-based quantity breakdown needed for contractual payment [6, 7]. This creates a methodological gap between progress visualization technologies and the granular, stage-based measurement required in practice.

In Vietnam, these challenges are exacerbated by inconsistent BIM maturity levels [10], incomplete model inheritance across design–tender–construction phases [2, 10], and limited parameterization for downstream uses such as QTO or payment certification [2, 11]. As a result, contractors frequently resort to hybrid BIM–manual workflows, undermining the potential benefits of digital modeling. Existing studies on BIM implementation in Vietnam acknowledge these constraints but do not offer concrete technical workflows for transforming design-oriented models into stage-based QTO models suitable for payment administration.

To address these gaps, this study aims to develop and validate a semi-automated BIM workflow capable of generating contract-aligned partial quantities for staged payment in high-rise construction. The workflow enables (1) segmentation of BIM elements according to construction stages, (2) assignment of custom payment-related parameters, and (3) extraction of stage-specific quantities through parameter-based scheduling. A high-rise residential project in Vietnam is used to validate the approach, demonstrating that partial quantities of beams, slabs, columns, and other structural elements can be accurately extracted and aligned with contractual payment structures.

By formalising this operational workflow, the study provides a pragmatic pathway for integrating BIM into progress-payment administration under unit-price contracts, particularly in contexts where full automation is neither feasible nor desirable.

To guide the research and evaluate the applicability of the proposed workflow, the following research questions are formulated:

RQ1: How can BIM elements be segmented to reflect partial quantities required for stage-based payment in high-rise construction?

RQ2: What parameters and schedule configurations are necessary to align BIM-derived quantities with unit-price contract requirements?

RQ3: How effectively does the proposed semi-automated workflow improve accuracy, transparency, and efficiency under typical Vietnamese project constraints?

By addressing these questions, this study makes four contributions:

(1) it proposes a reproducible BIM workflow for stage-based QTO that operationalizes segmentation, metadata structuring, and staged scheduling;

(2) it introduces the concept of a "stage-aware" BIM model in which elements correspond to payment units rather than whole components;

(3) it offers a semi-automated strategy suited to BIM maturity conditions in developing countries; and

(4) it provides empirical validation through a real high-rise project, demonstrating contractual compliance and practical feasibility.

Accordingly, the primary contribution of this study lies not in proposing new algorithms or automation techniques, but in formalising a reproducible, contract-aware workflow that restructures BIM information to support stage-based payment certification.

2. Background and Related Work

2.1 BIM for Quantity Takeoff

Building Information Modeling has become an essential tool for digital QTO, enabling direct extraction of geometric and material information from 3D models. Compared with manual measurement from 2D drawings, BIM-based QTO improves accuracy, reduces human error, and enhances traceability [5, 12]. A comprehensive review by Abanda, et al. [13] confirms that BIM supports structured, transparent, and repeatable QTO workflows, offering substantial benefits for cost estimation and construction management.

However, authoring tools such as Autodesk Revit generate quantities based on whole-element representation—that is, quantities are computed for an object as a complete element. Monteiro and Martins [4] show that this logic is suitable for early-stage estimation but becomes problematic during construction, where structural components (e.g., beams, slabs, columns) are often executed in multiple pours across staged progress cycles. Because BIM tools lack native support for extracting partial-element quantities, practitioners frequently resort to duplicated elements or hybrid BIM–manual workflows, undermining the advantages of model-based extraction.

Recent advances in IFC-based QTO still require post-model segmentation and metadata enrichment to align with real project needs, especially for reinforced concrete structures [14]. These limitations indicate that existing BIM platforms cannot directly produce staged quantities, motivating the need for workflow-level solutions rather than software-level adjustments.

Overall, prior studies acknowledge BIM's limitations for partial QTO but do not provide an operational mechanism to overcome whole-element quantification for staged payment.

2.2 Digital Progress Monitoring and Its Limitations for Payment Certification

A parallel stream of research has focused on digital progress-monitoring technologies—including 4D BIM, laser scanning, photogrammetry, and point-cloud analysis—to automate as-built status tracking [6, 15]. These technologies can detect construction progress visually or geometrically, offering value for schedule control and project monitoring.

However, most digital progress-monitoring systems focus on completion verification, not on quantifying staged partial quantities required for contractual payment. For example:

- 4D BIM visualizes construction sequences but does not distinguish how much of a beam or slab belongs to each payment stage.
- Point-cloud verification identifies whether an element exists but does not generate stage-specific quantities [15].

Thus, although digital progress monitoring enhances transparency in project control, it does not address the need for a structured workflow that computes stage-based quantities aligned with unit-price payment rules. This disconnect highlights a methodological gap between visual progress monitoring and the detailed QTO requirements of staged payment. It is important to distinguish the problem addressed in this study from Scan-to-BIM and point-cloud-based segmentation research. While Scan-to-BIM approaches aim to reconstruct as-built geometry or detect construction progress through automated geometric processing, they do not inherently address contractual measurement logic, payment-stage definitions, or BOQ alignment. As a result, automated geometric segmentation does not necessarily produce quantities that correspond to legally certifiable payment units under unit-price contracts.

2.3 Practical and Contractual Challenges in Vietnam's BIM Environment

In Vietnam, BIM adoption is expanding due to governmental policies and increasing demand for digital transformation, yet practical implementation remains uneven. Several studies identify systemic constraints that hinder the use of BIM for progress-based QTO:

(1) Uneven BIM competencies

Construction stakeholders exhibit varying BIM skill levels, leading to inconsistent modeling practices and limited capability to generate QTO-ready models [16].

(2) Lack of clear BIM requirements

Many projects lack clearly defined Employer's Information Requirements or Exchange Information Requirements (EIR) or BIM Execution Plans (BEP), resulting in models that are insufficiently structured for downstream tasks such as QTO and progress certification [11].

(3) Poor model inheritance across project phases

International studies [17] and domestic observations [10] show that models transferred from design to tender or construction phases frequently lack the structured attributes required for field-level tasks such as staged payment measurement.

(4) Models not QTO-ready

Local studies show that Vietnamese BIM models are typically not parameterized or structured to support automated QTO; issues include inconsistent naming, insufficient LOD, and absence of work-package metadata [16, 18].

(5) Contractual mismatch

Unit-price contracts in Vietnam require quantities aligned to actual work executed in each payment period [19], yet BIM schedules cannot natively represent partial-element quantities needed for staged certification.

These issues collectively illustrate that Vietnam's BIM environment lacks the model structure, metadata, and segmentation required to support stage-based QTO in real projects. As a result, a workflow is needed to adapt existing BIM models—originally developed for design—to become stage-aware quantity models suitable for payment certification.

2.4 Research Gaps and Motivation

From the reviewed literature, several gaps remain unresolved:

- Technical gap: BIM tools lack built-in mechanisms for staged or partial-element segmentation.
- Methodological gap: Progress-monitoring research does not provide stage-specific quantity extraction.
- Practical gap: Vietnam's BIM models often require significant post-processing before they can support QTO.
- Contractual gap: BOQ structures and payment-stage rules are not embedded in BIM models.

Although these gaps are well recognized, no study has developed and validated a practical workflow capable of producing contract-aligned staged quantities directly from BIM models. Therefore, this study proposes a semi-automated workflow integrating (1) structural element segmentation, (2) contract-aware parameterization, and (3) stage-filtered scheduling to generate staged quantities suitable for unit-price payment in high-rise construction.

3. Research Process

The process consisted of iterative prototyping, testing, and refinement—an approach commonly applied in technical BIM research where the objective is to develop and evaluate a functional workflow rather than test statistical hypotheses. This study followed a structured research process designed to translate the limitations identified in Section 2 into a workable BIM-based workflow for stage-based QTO. Rather than repeating the literature gaps, this section explains how the research problem was formulated, how the workflow was developed, and how it was validated through a real construction project. In line with a research-by-design paradigm, the study relied on iterative prototyping cycles in which technical insights were progressively refined to converge toward a deployable workflow. The overall research process is illustrated in Fig. 1.

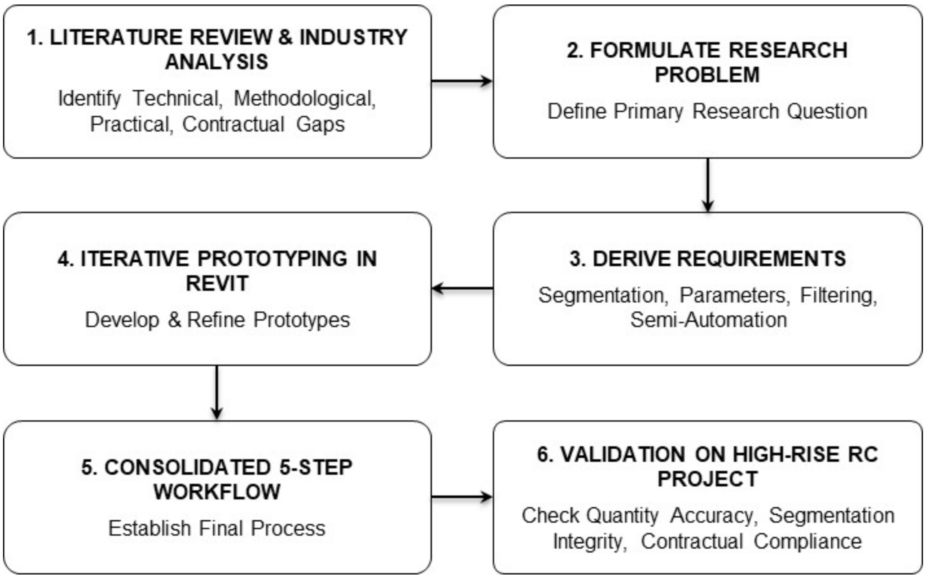

Fig. 1 *Overall research process*

3.1 Formulating the Research Problem

The literature review and industry analysis revealed a recurring challenge: although BIM provides accurate whole-element quantities, current authoring tools do not support the extraction of partial-element quantities required for staged payment under unit-price contracts. At the same time, digital progress-monitoring technologies cannot supply stage-specific quantities, and Vietnamese BIM models often lack the structured information needed for downstream cost management.

Drawing on these insights, the research problem was formulated as follows:

- How can BIM be adapted to generate stage-based, contract-compliant quantities for progress payment certification in high-rise construction projects?

This problem statement guided the research toward developing a workflow that restructures BIM data—through segmentation, parameter assignment, and filtered scheduling—to enable stage-specific QTO without requiring major changes to existing modeling practices. This formulation explicitly positioned the research to extend existing BIM-QTO practices into the domain of staged payment certification, where partial-element measurement remains unresolved.

3.2 Approach for Developing the Workflow

To address the research problem, the study adopted a gap-bridging strategy that translated conceptual limitations in current BIM-QTO practice into a set of actionable technical requirements. The workflow was developed through iterative experimentation with representative structural elements in Autodesk Revit. This research-by-design approach involved three key steps:

(1) Deriving technical requirements from the problem context

From the identified limitations, the study extracted four essential requirements:

- elements must be segmented according to staged execution,
- models must include payment-related parameters,
- QTO must be derived through parameter-based filtering, and
- the overall workflow must remain semi-automated, given current BIM maturity levels.
- These requirements formed the foundation for the proposed technical solutions (S1–S4).

(2) Iterative development through prototyping

Prototype models were developed to test segmentation, parameterization, and scheduling strategies. Each iteration focused on improving clarity, repeatability, and compatibility with typical Vietnamese contract structures. Failures and inefficiencies observed during prototyping informed refinements to the workflow steps.

(3) Consolidation into a generalized workflow

The insights from iterative testing were synthesized into a five-step workflow that supports:

- defining information requirements,
- segmenting elements,
- assigning custom parameters,
- extracting stage-based schedules, and
- reconciling BIM quantities with contractual BOQ structures.

This development approach ensured that the workflow was both technically feasible and adaptable to real-world project environments. By grounding the workflow in iterative testing against typical contract structures, the development phase ensured that the resulting methodology directly addressed the technical and contractual gaps identified in Section 2.

3.3 Approach for Validating the Workflow

The workflow was validated using a real high-rise residential project, selected for its representative reinforced concrete structure and multi-stage payment scheme. The validation aimed to verify not only the technical operation of the workflow but also its contractual compatibility and practical usefulness.

The validation comprised three components:

(1) Segmentation and parameter integrity check

All segmented elements were reviewed to ensure that:

- segmentation followed actual stage boundaries,
- each element instance was assigned correct payment and BOQ parameters, and
- no element overlapped across multiple stages.

This ensured internal consistency and auditability.

(2) Comparison between BIM-derived and manual quantities

Stage-based quantities extracted from the BIM model were compared with traditional manual QTO prepared according to Vietnamese measurement standards. Differences were analyzed to identify causes such as rounding, geometric tolerances, or boundary interpretations.

(3) Alignment with contractual BOQ structure

Extracted quantities were reviewed against the project's unit-price BOQ and staged payment rules to confirm contractual compliance. The validation assessed whether the workflow produced quantities that could be directly used for payment certification without further manual manipulation.

Together, these validation steps ensured that the proposed workflow was not only technically functional but also suitable for real project administration and audit processes. A high-rise reinforced concrete building with repetitive floor layouts and staged construction cycles was selected because its structural regularity and clear stage boundaries provided an effective environment for assessing the accuracy and practicality of segmentation-based QTO.

4. Proposed Workflow for Stage-Based BIM Quantity Takeoff

While prior studies acknowledge the difficulty of extracting partial-element quantities from BIM models, no operational workflow currently integrates segmentation, contract-aware parameterization, and staged schedule filtering into a unified, reproducible method. This section presents such a workflow and explains how it enables stage-based QTO suitable for unit-price payment certification. The proposed workflow addresses the core limitation of BIM's whole-element quantification by restructuring how model elements are represented, annotated, and extracted for staged payment measurement. It consists of two complementary layers: (1) four technical solutions (S1–S4) that enable partial-element quantity representation, and (2) a five-step implementation framework that operationalizes these solutions in practice. Fig. 2. summarizes the relationship between the four technical solutions (S1–S4) and the five-step implementation workflow.

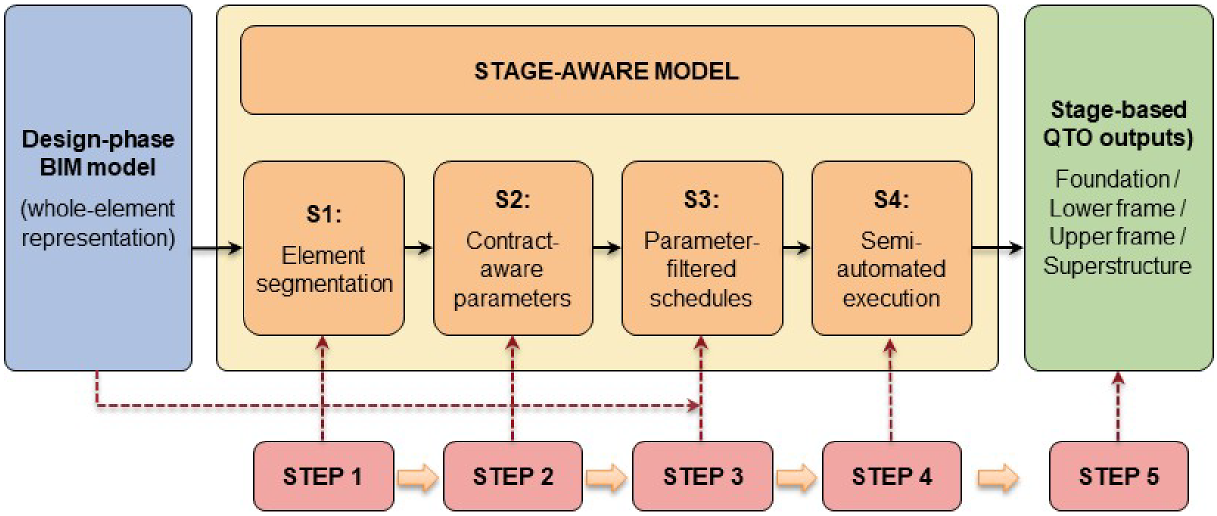

Fig. 2 *Conceptual workflow: from whole-element BIM to stage-aware QTO*

4.1 Technical Solutions

Based on the research problem identified in Section 3 and the constraints of unit-price contracts in Vietnam, the technical solutions S1–S4 were developed to adapt BIM models for stage-based QTO.

4.1.1 S1 - Segmentation of Structural Elements According to Payment Stages

Commercial BIM authoring tools such as Autodesk Revit quantify components as full elements, which prevents alignment with staged construction sequences. To overcome this limitation, the model must represent partial elements, not whole objects.

Two segmentation approaches were used:

(a) Manual re-modeling of simple vertical elements

Columns, short walls, and other discrete vertical components were manually redrawn into separate elements, each corresponding to one contractual payment stage. This approach provides geometric clarity and full control of segment boundaries.

(b) SPLIT-based segmentation for continuous horizontal elements

Continuous components such as beams, slabs, and diaphragms were segmented using Revit's SPLIT tool. This method maintains geometric accuracy while enabling precise division according to floor levels, work zones, or contractor-defined stage boundaries.

Segmentation ensures that BIM quantities represent the actual constructed portion during each payment period, preventing duplicate or overlapping measurements. This segmentation transforms the BIM model into a stage-aware representation, enabling partial quantities that are not natively supported by Revit's whole-element logic.

4.1.2 S2 – Contract-Aware Parameterization

To enable filtering, grouping, and aggregation during QTO, custom shared parameters were introduced. These parameters act as the metadata bridge between the BIM model and contractual structures.

The key parameters include:

- Payment Phase: Identifies the stage (e.g., Foundation, Frame Stage 1, Frame Stage 2).
- Work Item / BOQ Code: Ensures alignment with the contract BOQ for unit-price payment.
- Location identifiers: Such as Floor, Story Range, or Zone, supporting structured extraction.

Every segmented element must contain all required parameters for the workflow to function deterministically. These metadata fields allow the model to behave not only as a geometric database but also as a structured, query-ready information model aligned with contractual logic.

4.1.3 S3 – Parameter-Filtered Schedule Extraction

Once segmentation and parameterization are complete, stage-based quantities can be generated through Revit's scheduling engine.

The schedule configuration includes:

- applying filters using Payment Phase,
- grouping items by structural type, floor, or zone,
- verifying consistency with Vietnamese measurement rules (e.g., m^3 for concrete, m^2 for slabs),
- exporting structured schedules for contractual verification.

This filtering mechanism eliminates the need for manual sorting or cross-referencing, ensuring transparency and repeatability. The use of parameter-based filtering ensures that quantities for each stage can be regenerated consistently, even if the underlying model evolves.

4.1.4 S4 – Semi-Automated Workflow Suitable for Vietnam's BIM Maturity

Although BIM has advanced significantly, full automation of segmentation and parameter assignment remains unrealistic in typical Vietnamese project conditions. Therefore, a semi-automation strategy was adopted:

- tasks requiring judgment (segmentation, parameter assignment) remain human-controlled but highly standardized,
- tasks ideal for automation (scheduling, filtering, calculation) are fully automated within Revit.

This approach balances feasibility, precision, and replicability while respecting current industry capabilities. By combining human judgment for geometry restructuring with automated information extraction, the workflow becomes both implementable and scalable in environments where BIM maturity is still uneven.

4.2 Five-Step Workflow Description

The four technical solutions were consolidated into a five-step workflow suitable for application in high-rise projects. These processes collectively transform the original design-phase model into a stage-aware BIM model in which each element corresponds to a single payment unit.

4.2.1 Step 1: Define Information Requirements

Information needs for staged payment are identified, including:

- structural elements subject to staged certification,
- contractual stage definitions,
- measurement rules and units of measure,
- BOQ coding structures.

This step establishes the data requirements for downstream processing. It ensures that the workflow begins with explicit alignment between model information and contractual obligations, preventing ambiguities in later extraction stages.

4.2.2 Step 2: Segment Model Elements According to Payment Stages

Structural elements are segmented along boundaries derived from drawings, contract documents, or construction sequences.

- Manual re-modeling is applied to simple elements.
- The SPLIT tool is applied to beams, slabs, and continuous walls.

Each resulting element belongs to exactly one payment stage. This guarantees a one-to-one relationship between BIM elements and staged quantities, forming the structural basis of the workflow.

4.2.3 Step 3: Create Custom Parameters for QTO Classification

Custom shared parameters are created to capture stage affiliation, contractual coding, and spatial location. These parameters form the classification backbone for multidimensional QTO reporting.

Together, these parameters transform the segmented model into an information-rich dataset that can be interrogated programmatically during schedule extraction.

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4.2.4 Step 4: Assign Parameters to Segmented Elements

All segmented elements are populated with the appropriate parameter values. This step ensures that the model becomes a structured, query-ready dataset from which stage-based quantities can be extracted directly. Parameter completeness is essential for deterministic behavior during the schedule filtering stage.

4.2.5 Step 5: Extract Stage-Based Quantities

Revit schedules are configured with filters based on the *Payment Phase* parameter. Quantities are aggregated by element type and location and exported for contractual verification. This enables consistent, repeatable extraction across payment cycles without modifying the underlying model. This step enables deterministic regeneration of staged quantities across payment cycles, even when the model undergoes revisions.

The following section demonstrates how the five-step workflow was implemented in a real high-rise project to evaluate its technical feasibility, accuracy, and alignment with contractual payment requirements.

5. Case Study Implementation and Results

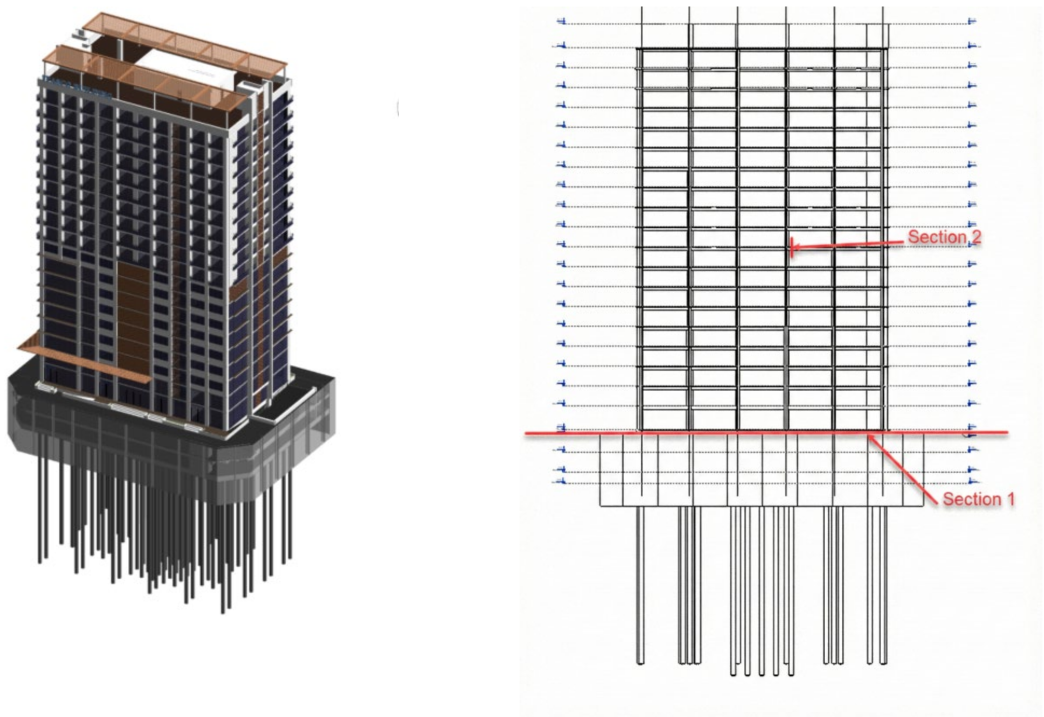
This study proposes a concise BIM-enabled workflow to support quantity takeoff aligned with stage-based payment requirements in high-rise construction projects. The workflow integrates model segmentation, parameter customization, and structured data extraction to ensure that quantities reflect the actual scope completed in each payment cycle. The steps are described as follows.

5.1 Project Overview

The proposed workflow was applied to a reinforced concrete high-rise residential project in Hanoi, Vietnam. The building comprises one basement and multiple above-ground floors arranged around a central reinforced concrete core, featuring repetitive floor layouts typical of high-rise residential developments (Fig. 3). The primary structural system consists of cast-in-place columns, beams, slabs, shear walls, and core walls. The contract scope covers only structural works; no other trades are included.

The project's contract adopts a unit-price payment mechanism, with work certified in discrete stages including: (1) foundation works, (2) lower-frame structure (from 1st floor to 8th mid-floor), (3) the remaining upper-frame structure. These staged boundaries provided a suitable basis for evaluating segmentation and stage-based QTO performance. These clearly defined construction stages, together with the repetitive nature of the RC structural system, made the project an appropriate choice for validating the segmentation-based workflow, as it provides distinct boundaries for staged quantities and sufficient geometric regularity for assessing accuracy and consistency.

In addition to these general limitations, the illustrative model used in the case study exhibited characteristics typical of design-phase authoring practices. Columns had been modeled as floor-by-floor segments, but most other structural elements—such as beams, slabs, bored piles, and walls—were created as single continuous objects from end to end. Moreover, the model did not contain parameters indicating the payment stage to which each object belonged, nor any parameter representing its payment status. These conditions required adjustments before the workflow could be applied, reinforcing the practical relevance of the case study.



(a) Structural model **(b) Staged sections for payment**

Fig. 3 *The case study building*

5.2 Workflow Steps

The five-step workflow developed in Section 4 was applied across Sections 5.2 to 5.4 to transform the design-phase BIM model into a stage-aware QTO model capable of generating contract-aligned partial quantities. In the case study, Steps 1–4 (information preparation, segmentation, parameter assignment, and schedule configuration) were executed as follows, while Step 5 (extraction of stage-based quantities) is presented in Section 5.4.

Information preparation

Contract documents, BOQ schedules, and structural drawings were reviewed to determine:

- which elements required certification under each payment stage,
- the location of stage boundaries (e.g., top of foundation, floor ranges),
- the measurement units and conventions applicable to concrete, formwork, and reinforcement.

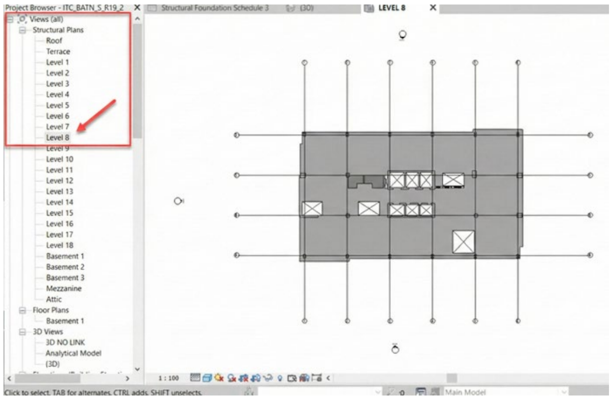
This review also clarified where model adjustments were necessary. For example, basement elements—already separated from above-ground components—were suitable for direct quantity extraction for Stage 1. However, at higher levels such as Level 8, beams and slabs remained continuous and did not align with the owner's payment milestones. This mismatch meant that the number and granularity of BIM elements did not correspond to the contract's staged QTO requirements, mandating further segmentation before quantities could be computed.

Model segmentation

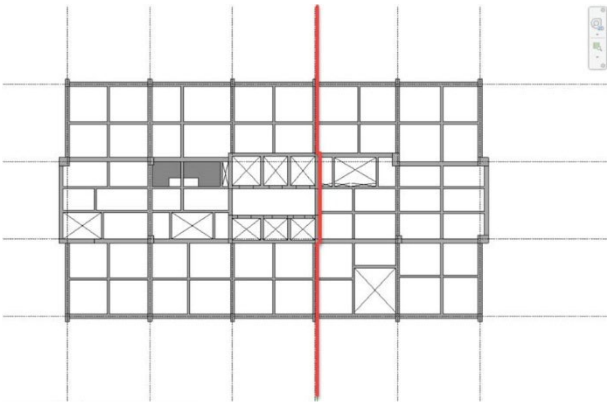
Structural elements that extended across stage boundaries were subdivided.

- Columns were re-modeled into separate segments aligned with each floor or stage boundary.
- Beams and slabs were divided using geometric splits corresponding to floor elevations and work zones.

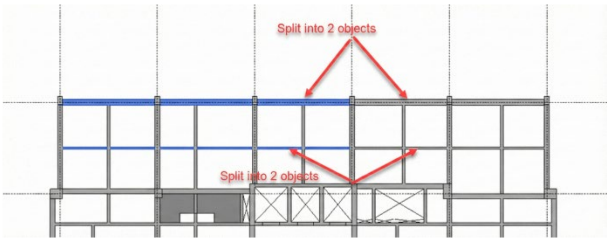
This process addressed the initial condition in which non﹣column elements had been modeled as monolithic objects. By defining cut planes aligned with the owner’ s payment stages, the contractor ensured that each resulting BIM element corresponded to exactly one payment period. The following figures illustrate (Fig. 4,) the re-modeling of elements that required subdivision according to the contractor's payment stages, beginning with a beam element.



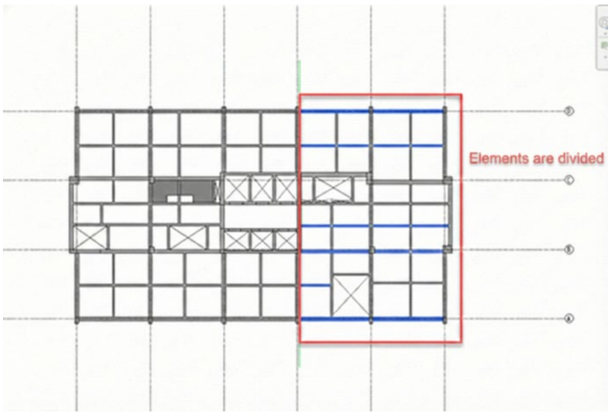
(1) Select the floor slab



(2) Draw a line to distinguish the payment stages



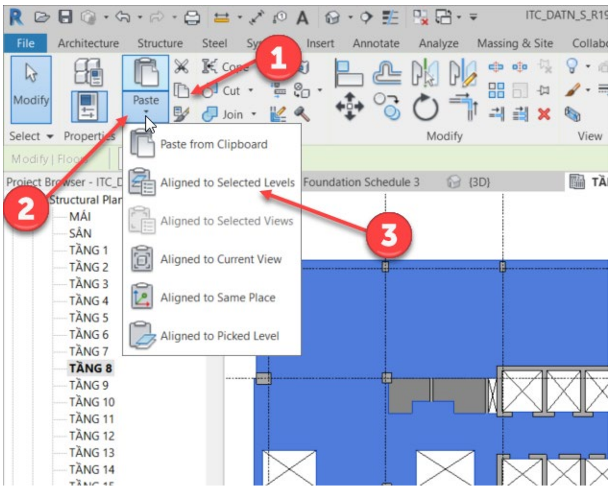
(3a) Re-model the element and split it into two separate objects (manually)



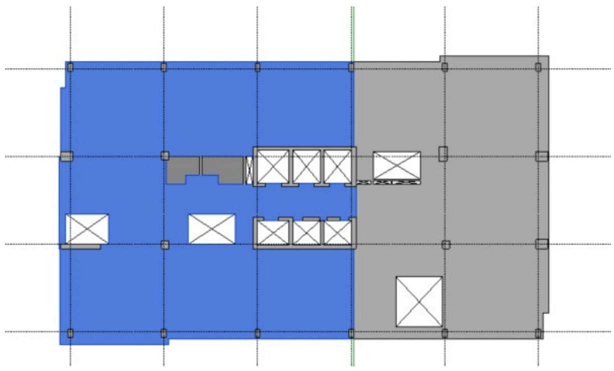
(3b) Use Revit's SPLIT command to divide the element

Fig. 4 *Segmentation of a beam element through re-modeling and SPLIT operations aligned with contractual stage boundaries*

For slab elements, the SPLIT command cannot be used. Instead, the slab must be re-modeled or handled using an alternative method. In this approach, the slab element is duplicated, as illustrated in Fig. 5.



(1) Select the floor with object to duplicate



(2) Adjust the floor plan according to the payment stage

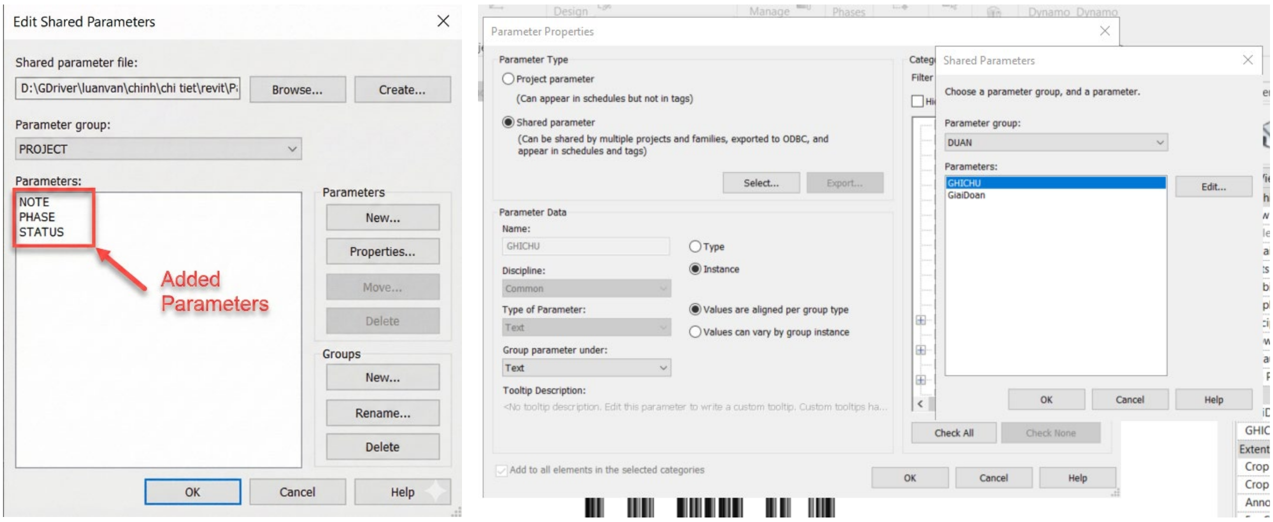
Fig. 5 *Duplicate the slab element*

The segmentation output created a one-to-one relationship between BIM elements and payment stages, allowing quantities to correspond precisely to actual executed work in each period.

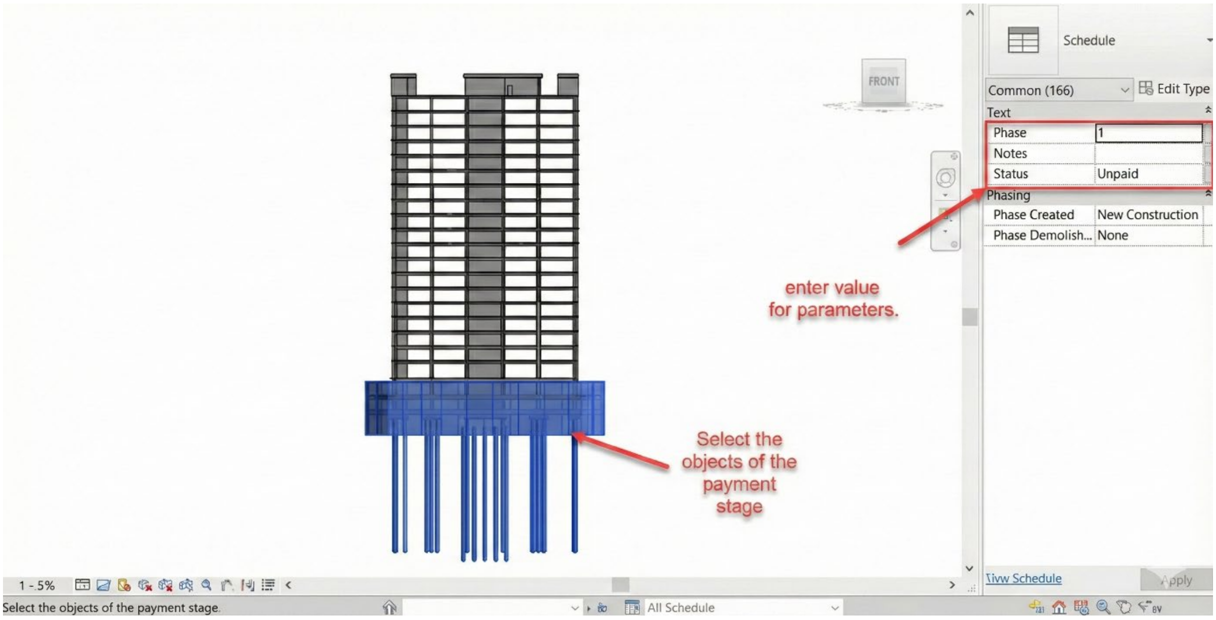
Parameter assignment

Custom parameters—including *Payment Phase*, *BOQ Code*, and *Location*—were added to all segmented elements. Parameter population followed a structured mapping derived from the contract BOQ, ensuring that each element could be traced directly to contractual line items.

Because the original model lacked attributes indicating payment stages or payment status, new parameters were introduced to encode both the stage to which each object belonged and whether it had been certified for payment. This enriched metadata enabled reliable filtering, aggregation, and auditability during staged QTO. Fig. 6 illustrates the process of assigning parameters to elements in the model.



(1) Create Shared Parameters **(2) Assign the newly created parameters to Revit elements**



(3) Input values into the newly created parameters

Fig. 6 *Steps for parameter assignment*

Schedule configuration

Stage-filtered schedules were created for columns, beams, slabs, and walls. These schedules aggregated volumes and areas according to the assigned parameters and followed Vietnamese measurement practices (e.g., m^3 for concrete, m^2 for formwork).

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5.3 Segmentation Outputs

The segmentation process significantly increased the granularity of the model. Continuous components such as core walls, which originally existed as single elements spanning multiple floors, were subdivided into multiple instances aligned with payment stages. Similarly, long-span beams and large slab panels were divided to reflect the contractor's planned sequence of execution.

Element proliferation

- Columns: increased from a single instance per stack to separate elements per floor, producing clear stage-wise quantities.
- Beams and slabs: segmentation introduced multiple horizontal slices corresponding to construction cycles.
- Walls: core and shear walls were subdivided at stage levels to support partial-volume quantification.

Boundary accuracy

Segmentation boundaries matched contractual definitions using floor elevations and drawing-based geometric control. Visual and geometric checks were conducted to ensure:

- no overlapping segments,
- no gaps between adjacent segments,
- consistent alignment with stage boundaries.

This segmentation structure ensured that each model instance represented an unambiguous portion of work, forming the technical basis for reliable stage-based QTO.

5.4 Stage-Based Quantities

Stage-filtered schedules produced quantities for each payment phase without manual recalculation or re-modeling. Concrete volumes, slab areas, and wall volumes were aggregated by structural category and floor location. Key observations:

- Foundation stage: quantities reflected only the segmented pile caps, raft slabs, and lower walls belonging to Stage 1.
- Lower-frame stage: extracted volumes matched the expected concrete works from the 1st to the designated intermediate floors.
- Upper-frame stage: segmentation allowed clear isolation of works executed in higher floors, a common challenge when using whole-element models.

Stage-based schedules effectively isolated exact quantities for each payment period, supporting contract-aligned certification and eliminating ambiguity inherent in whole-element QTO. The data from the illustrative project are presented in Fig. 7.

<Substructure Schedule>

A	B	C	D	E	F
Component Name	Quantity	Volume	Stage	Status	NOTE
800 Pile	6	89.78 m³	1	Unpaid	
800 Pile	67	1012.60 m³	1	Unpaid	
Barret Pile	2	82.56 m³	1	Unpaid	
Barret Pile	1	51.84 m³	1	Unpaid	
Barret Pile	20	1113.60 m³	1	Unpaid	
Barret Pile V1	1	67.86 m³	1	Unpaid	
Barret Pile V5.2	1	62.40 m³	1	Unpaid	
Barret Pile V5.2	1	66.24 m³	1	Unpaid	
Barret Pile V5.3	1	67.86 m³	1	Unpaid	
Barret Pile V5.4	1	64.70 m³	1	Unpaid	
Barret Pile V5.5	1	60.86 m³	1	Unpaid	
Footing 3800x3800x1400	16	180.48 m³	1	Unpaid	
Footing 3800x3800x3800	1	30.18 m³	1	Unpaid	
Footing 3800x3800x3800	3	91.44 m³	1	Unpaid	
Grand total: 122	122	3042.39 m³			

Substructure schedule for payment stage 1 with the "unpaid" status

<Substructure Schedule>

A	B	C	D	E	F
Component Name	Quantity	Volume	Stage	Status	Note
Pile 800	6	89.78 m³	1	Paid	
Pile 800	67	1012.60 m³	1	Paid	
Barret Pile	2	82.56 m³	1	Paid	
Barret Pile	1	51.84 m³	1	Paid	
Barret Pile	20	1113.60 m³	1	Paid	
Barret Pile V1	1	67.86 m³	1	Paid	
Barret Pile V5.2	1	62.40 m³	1	Paid	
Barret Pile V5.2	1	66.24 m³	1	Paid	
Barret Pile V5.4	1	64.70 m³	1	Paid	
Barret Pile V5.4	1	64.70 m³	1	Paid	
Barret Pile V5.5	1	60.86 m³	1	Paid	
Foundation 3800x3800x14(	16	180.48 m³	1	Paid	
Foundation 3800x3800x38(	1	30.18 m³	1	Paid	
Foundation 3800x3800x38(	3	91.44 m³	1	Paid	

Substructure schedule for payment stage 1 with the “paid” status

Basement Schedule | Column Concrete Schedule | Beam Concrete Schedule | Column Schedule Phase 2

<Column Schedule Phase 2>

A	B	C	D	E	F	G
Family and Type	Quantity	Volume	Column Location	Phase	Status	NOTES
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_800x800	1	1.54 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_500x800: 12	12	18.48 m³				
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_700x1000	1	2.43 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_700x1000	1	2.43 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_700x1000	1	2.43 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_700x1000: 3	3	7.28 m³				
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_700x1250	1	3.37 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_700x1250: 1	1	3.37 m³				
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_800x1000	1	3.08 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_800x1000	1	3.08 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_800x1000	1	3.08 m³	CONCRETE COLUMN T1	2	Unfinished	
M_Concrete-Rectangular-Column: ITC_S_CL_REC_CON_800x1000: 3	3	9.24 m³				

Column schedule for payment stage 2

<Beam Schedule Phase 2>

A	B	C	D	E	F	G	H
Member Name	Member Location	Quantity	Total Volume	Status	Note	Phase	Length
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_220x300	BT BEAM T 1	1	0.16 m^2	Unpaid		2	2580
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_220x500	BT BEAM T 1	17	18.76 m^2	Unpaid		2	
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_400x650	BT BEAM T 1	14	24.18 m^2	Unpaid		2	
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_400x1000	BT BEAM T 1	8	39.58 m^2	Unpaid		2	
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_450x650	BT BEAM T 1	1	1.60 m^2	Unpaid		2	7800
			84.27 m^2				
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_220x300	BT BEAM T 2	1	0.16 m^2	Unpaid		2	2690
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_220x500	BT BEAM T 2	23	18.47 m^2	Unpaid		2	
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_400x650	BT BEAM T 2	21	47.45 m^2	Unpaid		2	
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_450x650	BT BEAM T 2	1	1.60 m^3	Unpaid		2	8000
			67.67 m^2				
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_220x300	BT BEAM T 3	1	0.16 m^2	Unpaid		2	2590
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_220x500	BT BEAM T 3	23	18.47 m^2	Unpaid		2	
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_400x650	BT BEAM T 3	21	47.46 m^2	Unpaid		2	
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_450x650	BT BEAM T 3	1	1.73 m^2	Unpaid		2	8000
			67.82 m^2				
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_220x300	BT BEAM T 4	1	0.16 m^2	Unpaid		2	2690
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_220x500	BT BEAM T 4	23	18.47 m^2	Unpaid		2	
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_400x550	BT BEAM T 4	21	47.45 m^2	Unpaid		2	
M_Concrete-Rectangular Beam: ITC_S_BM_REC_CON_450x650	BT BEAM T 4	1	1.60 m^2	Unpaid		2	8000
			67.67 m^3				

Beam schedule for payment stage 2

<Slab Schedule Phase 2>

A	B	C	D	E	F	G	H
Element Location	Element Type	Quantity	Volume	Phase	Note	Status	Family and Type
FLOOR	Slab 100	1	136.74 m^2	2		Chuathanhtoan	Floor: ITC_S_FL_200
			136.74 m^3				
FLOOR 1	Slab 100	1	1.30 m^2	2		Unpaid	Floor: ITC_S_FL_100
FLOOR 1	Slab 150	1	137.91 m^2	2		Unpaid	Floor: ITC_S_FL_CON_150
			139.21 m^3				
FLOOR 2	Slab 100	1	1.30 m^3	2		Unpaid	Floor: ITC_S_FL_100
FLOOR 2	Slab 150	1	131.46 m^2	2		Unpaid	Floor: ITC_S_FL_CON_150
			132.76 m^3				
FLOOR 3	Slab 100	1	1.30 m^2	2		Unpaid	Floor: ITC_S_FL_100
FLOOR 3	Slab 150	1	131.46 m^3	2		Unpaid	Floor: ITC_S_FL_CON_150
			132.76 m^3				
FLOOR 4	Slab 100	1	1.30 m^2	2		Unpaid	Floor: ITC_S_FL_100
FLOOR 4	Slab 150	1	134.49 m^2	2		Unpaid	Floor: ITC_S_FL_CON_150
			135.79 m^2				
FLOOR 4	Slab 100	1	1.30 m^2	2		Unpaid	Floor: ITC_S_FL_100
FLOOR 5	Slab 150	1	134.63 m^2	2		Unpaid	Floor: ITC_S_FL_CON_150
			135.93 m^2				
FLOOR 6	Slab 100	1	1.31 m^2	2		Unpaid	Floor: ITC_S_FL_100
FLOOR 6	Slab 150	1	134.62 m^2	2		Unpaid	Floor: ITC_S_FL_CON_150
			135.92 m^2				
FLOOR 7	Slab 100	1	1.31 m^2	2		Unpaid	Floor: ITC_S_FL_100
FLOOR 7	Slab 150	1	134.62 m^2	2		Unpaid	Floor: ITC_S_FL_CON_150
			135.92 m^3				
MEZZANINE	Slab 100	1	1.31 m^2	2		Unpaid	Floor: ITC_S_FL_100
MEZZANINE	Slab 150	1	134.74 m^2	2		Unpaid	Floor: ITC_S_FL_CON_150

Slab schedule for payment stage 2

Fig. 7 *Quantity schedules extracted from the model (All figures have been translated from the Vietnamese version)*

6. Discussion

The findings reveal how the proposed workflow extends current BIM-QTO capabilities and addresses limitations that remain unresolved in prior work, particularly the inability of commercial BIM tools to generate staged or partial-element quantities for payment certification. The implementation results demonstrate that adapting BIM for stage-based QTO requires modifications not only to model geometry but also to the underlying information structure. The proposed workflow provides a systematic way to overcome BIM's whole-element quantification constraints and to align model outputs with staged payment requirements commonly found in Vietnam's unit-price contracts.

A key insight is that segmentation serves as the foundational mechanism enabling partial-element quantification. Without converting whole objects into stage-specific units, neither parameter filtering nor schedule automation can produce quantities that correspond to actual work executed at each payment period. This aligns with prior observations that BIM's native quantity logic is well-suited for design but insufficient for construction-phase certification. The case study confirms that segmentation—when executed consistently—restores the correspondence between modeled objects and contractual scopes of work. This stage-aware modeling approach constitutes a conceptual shift from conventional whole-element BIM practices, demonstrating that QTO accuracy can be increased without altering core software functionality.

A second implication concerns the role of metadata. The introduction of parameters such as *Payment Phase* and *BOQ Code* transforms the BIM model into a structured dataset that can support automated, stage-aware extraction. This reinforces the argument that QTO accuracy depends as much on information organization as on geometric fidelity. In contexts where BIM models are often developed without downstream measurement needs in mind, the parameterization strategy provides a practical method for retrofitting existing models for payment-based applications. From this perspective, the key innovation lies in how BIM information is structured and governed to support payment certification, rather than in the specific modelling commands used.

The results also underscore the practical rationale for adopting a semi-automated approach. In the proposed workflow, automation is intentionally limited to schedule generation, filtering, and quantity aggregation, while segmentation remains a manual but rule-based task. This reflects the fact that defining stage boundaries and contractual scopes requires engineering judgment that cannot be reliably automated under current practice. This hybrid strategy is particularly suitable for Vietnam, where BIM adoption is growing but modelling practices and inter-organizational coordination remain uneven.

From a broader methodological perspective, the proposed workflow should not be interpreted as an alternative to automated Scan-to-BIM or point-cloud-based segmentation techniques. Those approaches primarily address geometric reconstruction and progress detection, whereas the present study focuses on structuring BIM information to support contract administration. In this context, segmentation is guided by payment logic and contractual scope rather than by purely geometric criteria, highlighting the distinction between technical automation and legal-operational applicability.

From an efficiency and scalability perspective, the workflow should be understood as introducing an upfront modelling effort followed by substantial downstream benefits. While it does not necessarily reduce initial modelling time, it significantly improves repeatability, traceability, and auditability across payment cycles. In particular, the ability to consistently reproduce stage-based quantities from a single structured model reduces reliance on repeated manual measurement, limits subjective interpretation during certification, and lowers the risk of disputes in high-rise projects with repetitive structural systems.

From a contractual standpoint, the workflow enhances transparency and auditability by ensuring that every quantity is traceable to a model element and every element is linked to a BOQ item and payment phase. This is particularly critical in staged payment scenarios involving partial completion of repeated structural components.

Despite its demonstrated feasibility, the workflow has several limitations. Segmentation increases the number of BIM elements, potentially affecting model manageability in large-scale projects. The approach also assumes relatively stable stage definitions; in fast-track projects with frequent design changes, repeated segmentation may reduce efficiency. In addition, the construction-oriented quantity model may be partially detached from the original design model, creating coordination challenges during late design revisions.

These limitations suggest directions for future research, including rule-based automation using BIM APIs or Dynamo, extension of the workflow to reinforcement and MEP systems, and tighter integration between design, analytical, and quantity models to support continuous updating across project phases. For the workflow to scale to very large or mega-projects, future research should investigate replacing manual SPLIT-based segmentation with rule-based automation using Dynamo scripts or BIM API plugins, while preserving the contract-driven logic of stage definition.

7. Conclusion

This study developed and validated a BIM-based workflow that enables the extraction of contract-compliant staged quantities for progress payment in high-rise construction projects. By integrating element segmentation, contract-aware parameterization, and parameter-filtered scheduling, the workflow overcomes a central limitation of commercial BIM tools: the inability to compute partial-element quantities aligned with staged execution. Application to a real reinforced-concrete high-rise project demonstrated that the workflow produces accurate, traceable, and repeatable staged quantities that correspond to the contractual BOQ structure.

Importantly, the contribution of this study does not lie in automating element segmentation or proposing new computational techniques. Instead, it formalises a reproducible, contract-aware operational workflow that restructures existing BIM information into a stage-aware quantity model, in which each model element corresponds to a single payment unit. In this workflow, automation is limited to schedule-based quantity extraction and regeneration, while segmentation and parameter assignment remain manual but standardised engineering tasks. This demonstrates that staged quantities can be produced without modifying BIM software logic, relying on structured segmentation and metadata enrichment to support contract administration.

Based on the findings, the study makes four main contributions. First, it proposes a practical workflow for stage-based QTO that operationalises segmentation, parameterisation, and schedule filtering for payment certification. Second, it introduces the concept of a stage-aware BIM model, clarifying how design-phase models can be systematically restructured into payment-ready representations. Third, it develops a semi-automated strategy that balances engineering judgment with automated extraction, making the approach suitable for developing BIM environments such as Vietnam. Finally, it provides empirical validation through a real high-rise project, confirming the workflow's feasibility, contractual alignment, and auditability.

Rather than claiming productivity gains at the modelling stage, the value of the workflow lies in its ability to reduce repetitive manual effort, improve consistency across multiple payment cycles, and strengthen transparency in certification processes. Future research should explore rule-based or API-driven support for segmentation (e.g., scripting/visual programming), integration with 4D or reality-capture data, and extension of the workflow to reinforcement and MEP systems, as well as tighter coordination between design and quantity models. By formalising this operational workflow, the study offers a pragmatic pathway for integrating BIM into progress-payment administration under unit-price contracts, particularly in contexts where full automation is neither feasible nor desirable.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *VAN, VM;* ***data collection:*** *VAN;* ***analysis and interpretation of results:*** *VNA, VYN, HBN;* ***draft manuscript preparation:*** *VAN, VYN, VM, HBN. All authors reviewed the results and approved the final version of the manuscript.*

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