Next Scientists
Journal of Management and Economics

TYPE Original Research
PAGE NO. 23-29

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Enhancing Early-Stage Construction Cost Estimation: A BIM-Driven Framework for Accurate Quantity Take-Off and Decision Support

OPEN ACCESS

SUBMITTED 12 September 2025
ACCEPTED 20 September 2025
PUBLISHED 25 September 2025
VOLUME Vol.05 Issue 09 2025

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Maria L. Fernandez

School of Construction Management and Economics, University of Texas at Austin

Abstract:

Background: Early-stage cost estimation and quantity take-off (QTO) are critical determinants of project feasibility, budgetary control, and lifecycle outcomes in the built environment. Traditional estimating methods frequently suffer from fragmentation, human error, delayed feedback, and limited interoperability with design and construction workflows (Matipa et al., 2008; Sattineni & Bradford, 2011). Building Information Modeling (BIM) offers parametric, semantic, and interoperable mechanisms that can transform how quantities and costs are produced, validated, and iterated during design (Eastman et al., 2011; Lee et al., 2006).

Objectives: This research article develops a theoretically grounded and practice-oriented framework for integrating BIM-enabled quantity take-off, IFC standard extensions, Virtual Design and Construction (VDC), and lean project delivery principles to optimize cost estimation accuracy, traceability, and decision-support at the design stage. The framework addresses interoperability, parametric object behavior, data quality, and multi-criteria decision-making in quantity estimation.

Methods: A mixed-methods synthesis was undertaken, drawing on canonical BIM literature, empirical studies on IFC-based estimating in China, surveys of industry adoption, and contemporary integrations of VDC and lean delivery. The methods section articulates a descriptive computational pipeline—without code—highlighting object modeling, mapping to cost libraries, rule-based quantity extraction, uncertainty propagation, and AHP-based decision modules for alternative selection (Zhiliang et al., 2011; Choi et al., 2015; Darko et al., 2019).

Results: The framework demonstrates how parametric object behavior and IFC extensions enable early, automated QTO with traceable change logs, enabling rapid generation of scenario-based cost envelopes. Integration with VDC and lean practices reduces rework risk and supports continuous value alignment between design intent and constructability (Aslam et al., 2021; Fosse et al., 2017). The paper elaborates on limitations—data quality, skill gaps, and organizational inertia—and prescribes mitigations.

Conclusions: When applied as an integrated socio-technical system, BIM-based QTO coupled with VDC and lean delivery materially improves early-stage cost management, transparency, and adaptive decision-making. Future research should empirically validate the framework in multi-region pilots and elaborate automated uncertainty quantification techniques.

Keywords: Building Information Modeling, quantity take-off, IFC, Virtual Design and Construction, lean construction, parametric objects, cost estimation

INTRODUCTION

The capacity to generate accurate, timely, and actionable quantity take-off (QTO) and cost estimates in the early stages of a construction project fundamentally shapes project viability, financing decisions, stakeholder negotiations, and downstream performance (Matipa et al., 2008). Historically, QTO has been a labor-intensive, manual, and siloed activity—relying on 2D drawings, spreadsheets, and the estimator's experience. Such processes are prone to errors of omission, inconsistent assumptions, and difficult-to-trace revisions, which can cascade into substantial budget overruns and contentious contractual disputes (Sattineni & Bradford, 2011). Over the past two decades, Building Information Modeling (BIM) has emerged as both a technological paradigm and a process reorientation that promises to address these structural weaknesses by embedding semantic information into digital building representations (Eastman et al., 2011).

Despite the promise of BIM, research and practice reveal a wide spectrum of adoption levels and functional maturity: from organizations using BIM primarily for visualization to those integrating parametric object behavior and IFC-based data exchange into automated estimating and tendering workflows (Arayici et al., 2011; Lee et al., 2006; Zhiliang et al., 2011). This heterogeneity generates important research questions: How can BIM be harnessed to produce reliable early-stage QTO that balances speed and accuracy? What technical and organizational configurations ensure that IFC and parametric object specifications translate into trustworthy quantities and costs? How do contemporary practices like Virtual Design and Construction (VDC) and lean project delivery systems synergize with BIM-enabled estimating to reduce waste and improve constructability?

This article proposes a unified, theoretically rigorous framework for BIM-based QTO and cost management at the design stage. The approach synthesizes extant studies on IFC extensions for estimating, parametric object behavior specifications, BIM adoption barriers, and the alignment of VDC with lean principles to form a coherent design-stage estimation pipeline (Zhiliang et al., 2011; Lee et al., 2006; Aslam et al., 2021; Fosse et al., 2017). The framework explicitly accounts for uncertainty propagation, multi-criteria decision-making (using Analytic Hierarchy Process, AHP), and feedback loops for continuous improvement. The contribution is twofold: a conceptual architecture for automated, traceable QTO from BIM, and an organizational-playbook to integrate VDC and lean workflows that support improved cost outcomes.

By drawing on empirical findings and theoretical constructs across the referenced literature, the article aims to provide practitioners, researchers, and educators with a robust roadmap for transforming early-stage cost management—reducing risk, increasing transparency, and enabling evidence-based design decisions (Gholizadeh et al., 2018; Garcés & Peña, 2022). The remainder of the article elaborates the methodology underpinning the framework, outlines the proposed QTO pipeline, presents descriptive findings on expected performance enhancements, discusses limitations and implementation challenges, and outlines concrete directions for future empirical testing.

METHODOLOGY

This research adopts a theory-building and integrative synthesis approach rather than primary field experimentation. The methodology is intentionally descriptive and prescriptive—assembling technical constructs and process interventions from authoritative BIM, VDC, and lean construction literature, and reconciling them into a single coherent framework for early-stage QTO and cost control.

Literature synthesis and conceptual integration: The first methodological step involved a systematic reading and thematic synthesis of canonical BIM texts, IFC-based estimating studies, parametric object behavior literature, and recent works on VDC and lean integration (Eastman et al., 2011; Zhiliang et al., 2011; Lee et al., 2006; Aslam et al., 2021). The synthesis focused on extracting: (a) core technical mechanisms relevant to QTO (object geometry, parametric behavior, IFC data schemas); (b) workflow designs that integrate estimating within design feedback loops; and (c) process-alignment practices that leverage VDC and lean principles for waste minimization and value optimization.

Construct specification: Based on the synthesis, we specify the primary components of the proposed framework as logical modules: object parametrization and behavior modeling, IFC schema extension and mapping to cost items, rule-based quantity extraction, uncertainty modeling and propagation, decision-support via multi-criteria AHP modules, and VDC-lean operational alignment. Each module is described in prose to avoid code or mathematical notation per the task constraints.

Traceability and validation rationale: The methodology emphasizes traceability—maintaining a chain of custody for every quantity extracted from BIM elements through the mapping to cost libraries and assumptions recorded. Validation mechanisms are described in process terms: cross-referencing IFC-derived quantities with independent measurements, using rule-based sanity checks, and employing expert review cycles to reconcile anomalies (Zhiliang et al., 2011; Choi et al., 2015).

Stakeholder role mapping and organizational strategy: Recognizing that technology alone does not guarantee impact, the methodology articulates human and organizational roles—quantity surveyors, BIM modelers, cost engineers, and VDC coordinators—and prescribes collaboration patterns, hand-off protocols, and training emphasis to manage knowledge gaps and resistance to change (Matipa et al., 2008; Arayici et al., 2011).

Performance expectation modeling: Without empirical data collection in this article, performance expectations are described qualitatively through scenario analysis—contrasting outcomes for projects adopting the integrated framework versus those using traditional estimating. Expected benefits—reduced error rates, faster scenario generation, superior traceability, and enhanced decision quality—are grounded in cited literature and reasoned argumentation (Sattineni & Bradford, 2011; Gholizadeh et al., 2018).

Ethical and governance considerations: The methodology includes governance prescriptions for data stewardship, version control, and contractual clarity over model-based quantities to manage liability concerns and foster trust among stakeholders (Eastman et al., 2011).

By synthesizing technical and organizational elements into a descriptive, implementable framework, this methodology aims to offer a practical yet theoretically grounded pathway for transforming early-stage cost estimation through BIM, IFC, VDC, and lean integration.

RESULTS

This section presents the descriptive outcomes of applying the prescribed framework—articulating what the integrated system produces, how it behaves under typical design-stage workflows, and the kinds of improvements stakeholders can expect relative to traditional estimating methods. These results are inferential and constructed from the literature synthesis and theoretical modeling performed in the methodology.

Automated quantity extraction with parametric fidelity: When building objects are specified with parametric object behavior (BOB) and detailed semantic attributes—in line with the specifications of parametric building object behavior—the BIM model becomes a robust source for automated QTO extraction (Lee et al., 2006). The framework demonstrates that by enforcing consistent object naming, parameter schemas, and unit conventions, estimators can reliably extract quantities such as gross floor area, wall surface area, linear lengths of structural members, and aggregated material volumes. Using IFC extensions that map object properties to tendering cost items, the model produces machine-readable quantities that can be exported directly to cost engines and tender documents (Zhiliang et al., 2011).

Scenario-driven cost envelopes: The framework supports the rapid generation of multiple design scenarios by leveraging parametric model variants. For example, a change in a wall assembly thickness or finish standard propagates through the parametric geometry to update material volumes and associated costs automatically. This capability enables cost envelope generation at different confidence levels: base estimates for concept approval, refined estimates for schematic design, and probabilistic envelopes for risk-aware budgeting. The literature supports that early-stage schematic estimation benefits significantly from parametric BIM workflows that link object geometry to quantity take-off engines (Choi et al., 2015; Sattineni & Bradford, 2011).

Traceable change logs and auditability: The framework mandates that every quantity reported includes metadata linking it to the model object, parameter revision, author, and timestamp. This traceability feature addresses a recurrent industry problem: unidentified sources of variance between successive estimates (Matipa et al., 2008). Traceability enhances contractual clarity and reduces disputes by allowing parties to audit how a particular cost figure was derived from a specific model element.

Interoperability via IFC and controlled extensions: The IFC standard, when appropriately extended and applied, provides the neutral interchange format necessary for transferring model-derived quantities into estimating platforms and tendering systems (Zhiliang et al., 2011). The framework elaborates guidelines for extending IFC schemas with cost-relevant properties in a controlled manner—preserving interoperability while embedding the additional semantics necessary for estimating. Practitioners in China have demonstrated the feasibility of such IFC-based estimating pipelines for tendering workflows, indicating practical viability (Zhiliang et al., 2011).

Integration with VDC and lean delivery: Marrying BIM-derived QTO with VDC practices enables a continuous loop where constructability insights—3D sequencing, clash detection, and offsite fabrication potential—inform the cost baseline. Lean principles applied through VDC (e.g., target value design, just-in-time workflows) sharpen the focus on value and reduce costly rework (Aslam et al., 2021; Fosse et al., 2017). The framework articulates how early identification of coordination issues via the BIM model prevents downstream cost escalation and supports the alignment of design choices with client-defined value metrics.

Decision-support enriched by AHP: The framework integrates a descriptive decision-support module using Analytic Hierarchy Process (AHP) to rank design alternatives not purely by lowest first-cost but by multiple criteria including lifecycle cost, constructability, schedule impact, sustainability metrics, and stakeholder preferences (Darko et al., 2019; De Paris et al., 2022). The AHP module ingests quantities, cost implications, and qualitative assessments from stakeholders to produce a prioritized recommendation for design decisions. This multi-criteria orientation addresses the common pitfall of single-criterion cost minimization.

Qualitative improvements in accuracy and productivity: While quantitative validation is outside the scope of this article, the literature suggests realistic improvements in estimation accuracy and productivity when BIM-based QTO is institutionalized — reductions in manual entry errors, faster iterative costing, improved change management, and a closer alignment between design intent and contractual quantity definitions (Sattineni & Bradford, 2011; Matipa et al., 2008; Gholizadeh et al., 2018).

Implementation enablers and constraints: The framework identifies critical enablers—standardized object libraries, calibrated cost databases, skilled BIM-QTO practitioners, and contractual language recognizing model-based estimates. It also enumerates constraints: incomplete or inconsistent model data, lack of IFC compliance, cultural resistance within organizations, and regulatory or procurement frameworks not adapted for model-based tendering (Arayici et al., 2011; Eastman et al., 2011).

In summary, the proposed framework yields automated, traceable QTO, scenario-based cost envelopes, interoperability through IFC extensions, and decision-support enhanced by VDC and lean integration. These outcomes collectively address the core problems identified in the introduction: fragmentation, error-proneness, and lack of early-stage decision support in traditional estimating practices.

DISCUSSION

This section provides an in-depth interpretation of the results, exploring theoretical implications, practical trade-offs, counter-arguments, limitations, and recommended directions for implementation and future research. The discussion synthesizes diverse strands of the literature to reason about the socio-technical realities of deploying the framework.

Theoretical implications: The framework reframes early-stage estimating as an evidence-based, parameter-driven decision process embedded in a socio-technical system rather than a solitary human judgment activity. The adoption of parametric BOB specifications and IFC-based data exchange moves estimation from an analog artifact to a digitally native product of the design model. This shift has theoretical implications for how value is constructed in the design phase: quantities and costs become malleable outputs of design parameters, enabling designers to reason about cost as an object property rather than an external estimate (Lee et al., 2006; Eastman et al., 2011). The integration with AHP extends this by recognizing that cost is one dimension among many in design decision-making, necessitating structured multi-criteria frameworks to reflect stakeholder values (Darko et al., 2019).

Interoperability trade-offs: Extending IFC schemas to encode cost properties enhances the precision of QTO but introduces risks around portability and vendor neutrality. The framework advocates for controlled extensions—documented, reversible, and aligned with prevailing IFC development practices—to balance expressiveness with interoperability (Zhiliang et al., 2011). A counter-argument is that proprietary extensions could lock users into specific vendor ecosystems; the response is that careful governance, open documentation, and adherence to community best practices mitigate lock-in while addressing real-world estimating needs.

Parametric modeling versus early conceptual uncertainty: Parametric BIM delivers agility in scenario modeling, but early conceptual design is characterized by high uncertainty and incomplete information. Critics argue that detailed parametric modeling at very early stages may produce spurious precision, resulting in false confidence. The framework addresses this by advocating for graded modeling fidelity—lightweight parametric objects for schematic phases (capturing dominant dimensions and assembly-level properties), with fidelity increasing as design decisions are confirmed. Additionally, uncertainty-aware reporting (presenting cost envelopes and confidence bounds) counters the illusion of deterministic accuracy (Choi et al., 2015).

Human factors and role evolution: The shift to BIM-driven QTO redefines roles. Quantity surveyors and cost engineers evolve from manual measurers to model interpreters, rule authors, and validation specialists (Matipa et al., 2008). Training and cultural change become as important as technology. Organizations must invest in upskilling and redefine responsibilities to avoid tokenistic adoption where tools are used but core practices remain unchanged (Arayici et al., 2011). Resistance may arise from perceived threats to professional discretion; the framework addresses this by emphasizing complementary roles and enhanced professional judgment enabled by better data and traceability.

VDC and lean integration—synergy and friction: Integrating VDC and lean practices with BIM-based QTO optimizes for value and reduces waste; however, friction can occur where lean-driven process changes conflict with traditional contractual arrangements or procurement milestones. The framework proposes contractual and governance modifications: early collaborative contracting, shared risk-reward arrangements, and explicit recognition of model-derived data in tendering documentation. These changes are non-trivial but are supported by documented gains in projects that align VDC and lean principles with digital workflows (Aslam et al., 2021; Fosse et al., 2017).

Quality of model data and libraries: A pivotal dependency is the quality of object libraries and cost databases. Inconsistent or poorly parameterized objects produce erroneous quantities. The framework prescribes rigorous library governance—standard templates, naming conventions, and validation tests—coupled with continuous calibration of cost databases to regional price indices and supplier quotes (Gholizadeh et al., 2018). Organizations must treat libraries as living assets requiring stewardship and version control.

Legal and procurement implications: Model-based quantities influence tendering and contract formation. Traditional procurement frameworks assume discrete, signed-off bills of quantities. Transitioning toward model-based tendering requires explicit contractual language that specifies the role of model-derived quantities, liability for discrepancies, and dispute resolution mechanisms. The experiences documented in IFC-based tendering pilots illustrate the need for pilot projects with contractual experimentation to build confidence (Zhiliang et al., 2011).

Sustainability and lifecycle cost considerations: The framework's multi-criteria orientation encourages moving beyond first-cost toward lifecycle cost and embodied carbon considerations. By integrating quantities with lifecycle assessment libraries, designers can compare alternatives on decarbonization metrics, enabling more sustainable choices that still respect budgetary constraints. This broadens the estimator's remit from price-finding to value analysis across environmental and social dimensions (Garcés & Peña, 2022).

Limitations of the present work: The primary limitation is the conceptual and descriptive nature of the framework without empirical validation in live projects. While each component of the framework is grounded in literature and existing practices, the integrated system's cumulative effects warrant field trials to quantify benefits and identify emergent challenges. Additionally, the framework assumes a baseline level of BIM capability and organizational readiness; organizations starting from minimal BIM maturity will require staged adoption pathways, which the framework discusses but does not quantify.

Future scope and research agenda: Future work should operationalize the framework in longitudinal case studies across regions to measure impacts on estimate accuracy, tendering speed, rework reduction, and stakeholder satisfaction. Research should also develop robust, non-parametric uncertainty quantification techniques that combine expert elicitation with historical data to produce probabilistic cost envelopes. Another promising avenue is automated semantic reconciliation tools that detect and correct inconsistent object parameterization across federated models—a technical challenge with high practical payoff (Gholizadeh et al., 2018). Finally, socio-legal research is needed to craft procurement templates and liability frameworks that support model-based tendering at scale.

CONCLUSION

This article set out to develop an integrated, publication-ready framework that leverages Building Information Modeling, IFC-based interoperability, parametric object behavior, Virtual Design and Construction, and lean delivery principles to enhance early-stage quantity take-off and cost management. The resulting framework positions QTO as a model-derived, traceable, and scenario-capable output that supports multi-criteria decision-making rather than a static, manually compiled artifact. By enforcing parametric fidelity where appropriate, extending IFC schemas responsibly, and embedding decision-support and governance practices, organizations can materially improve estimation accuracy, speed, and alignment between design intent and constructability.

Key practical takeaways include: maintain rigorous object and library governance; use IFC extensions judiciously to preserve interoperability; employ graded modeling fidelity to manage early-phase uncertainty; integrate VDC and lean practices to reduce waste and align value; and institutionalize multi-criteria decision frameworks to avoid narrow cost minimization. The framework acknowledges real-world constraints—data quality, skill gaps, procurement conventions—and prescribes mitigations rather than idealized assumptions.

The theoretical contribution lies in reframing design-stage costing as an integrated socio-technical process enabled by semantic modeling, enabling richer dialogues between designers, estimators, contractors, and clients. The practical contribution is a detailed, implementable architecture for automated, traceable QTO linked to decision-support processes.

To realize the framework's potential, empirical validation is essential: pilot implementations, cross-industry case studies, and quantitative assessments will refine the models, calibrate expected benefits, and evolve contractual and governance mechanisms. The literature indicates substantial promise; the pathway from promise to routine practice lies in disciplined implementation, investment in human capital, and adaptive procurement reform. The resulting transformation promises to reduce the endemic uncertainties of early-stage estimation, improve project value delivery, and support the construction industry's broader digital and sustainability transitions.

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