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Accuracy assessment of BIM 5D-based quantity take-off for concrete and reinforcement works: A case study of a three-story building project

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Abstract

Accurate quantity take-off is essential for construction cost estimation, procurement, and project control, particularly for reinforced-concrete structural works. This study evaluates the accuracy of BIM 5D-based quantity take-off generated by Tekla Structures and Cubicost for concrete and reinforcement works in a three-story building project in Surakarta, Indonesia. A quantitative comparative case-study design was applied using the same structural drawings, reinforcement details, manual calculation recapitulations, and consultant bill of quantities (BOQ). Manual calculation was treated as a controlled analytical reference rather than an error-free ground truth, while the consultant BOQ was used as a secondary practical benchmark. The analysis used absolute deviation, percentage deviation, mean absolute percentage error (MAPE), root mean square error (RMSE), mean bias, Bland-Altman limits of agreement, and R^2 as supporting exploratory indicators. Based on the corrected element-level quantities, Tekla Structures and Cubicost produced concrete deviations of 1.803 m^3 (0.30%) and 3.341 m^3 (0.55%), respectively. For reinforcement, Tekla Structures and Cubicost produced deviations of 9,879.109 kg (9.07%) and 1,379.923 kg (1.27%), respectively. Deviations relative to the consultant BOQ ranged from 11.83% to 12.36% in the project-documentation comparison. The findings indicate that concrete quantities were relatively stable because they were primarily geometry-based, whereas reinforcement quantities were more sensitive to modelling assumptions, detailing rules, and extraction settings. The contribution of this study is a case-specific BIM 5D validation framework that separates analytical accuracy from BOQ agreement and highlights the importance of work-item sensitivity in structural quantity estimation.

Keywords: BIM 5D, Quantity take-off, Accuracy metrics, Validation framework, Tekla structures, Cubicost

1. Introduction

Accurate quantity take-off (QTO) plays a central role in construction project delivery because it supports cost estimation, material procurement, tender preparation, and project control. In structural works, quantity information is particularly important because concrete and reinforcement represent major cost components and directly affect budgeting accuracy, purchasing decisions, and planning reliability. When quantity estimates deviate from actual project needs, the consequences may include procurement mismatch, cost overrun, delayed decision-making, and inefficient resource allocation [1-4].

Despite its widespread use, conventional QTO based on two-dimensional drawings remains vulnerable to recurring technical and procedural limitations. Incomplete or ambiguous drawings may lead to omission, duplication, or misinterpretation of quantities, especially when revisions are not fully reflected in the latest quantity documents [1, 3]. Manual measurement is also prone to human error and estimator variability, which become more pronounced in large or geometrically complex projects [2, 4]. In addition, fragmented measurement practices and inconsistent application of measurement rules can reduce the reliability and comparability of manually prepared quantity documents across projects and regions [1, 3]. Conventional take-off procedures are also time-intensive, which can delay cost updates and increase the risk of using outdated quantity information during tendering and construction planning [1, 3, 4].

Building Information Modeling (BIM) has been increasingly adopted as an alternative approach for improving quantity extraction by linking project information within a coordinated digital model. In BIM-based workflows, quantities can be generated directly from model objects rather than repeatedly interpreted from 2D drawings, thereby reducing manual effort and improving data consistency [3, 5, 6]. The development of 5D BIM extends this capability by integrating geometric representation with quantity and cost information, enabling dynamic cost updating and closer linkage between design changes and cost control throughout the project lifecycle [5, 7, 8]. Previous studies have shown that BIM-based QTO can improve speed, transparency, collaboration, and traceability compared with conventional estimation procedures [3-5]. In addition, 5D BIM can support broader cost management functions, including design-stage comparison, lifecycle cost consideration, and more responsive decision-making when design revisions occur [9-11].

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However, BIM adoption does not automatically guarantee accurate quantity outputs. The reliability of BIM-generated quantities depends on model completeness, object definition, level of development, interoperability, and the rules used to map model elements into measurable cost items [3, 5, 12]. Quantity discrepancies may still arise from hidden or non-modeled elements, overlap treatment, inconsistent parameter assignment, and software-specific extraction logic [1, 3]. Several studies therefore emphasize that BIM-based QTO accuracy is strongly shaped by modelling governance, data standardization, and the adequacy of measurement protocols rather than by software automation alone [10, 12, 13]. In other words, BIM is not a self-validating system; its output quality remains dependent on how the model is structured, detailed, and translated into quantity information.

Previous BIM-QTO studies have contributed valuable evidence on workflow efficiency, model-based cost integration, and the comparison between BIM-derived and conventional quantity documents [3, 5, 6, 14, 15]. Nevertheless, the literature remains uneven in how it defines accuracy. Some studies report agreement with BOQ documents without clearly separating project-document concordance from analytical validation, while others emphasize time savings without explaining whether quantity deviations are caused by measurement rules, modelling scope, software extraction logic, or reference-data uncertainty [14, 16-19]. This creates a conceptual gap: BIM-QTO accuracy is often discussed as a software-output problem, although it is actually a combined problem of reference definition, measurement protocol, work-item characteristics, and model governance.

This gap is especially important for reinforced-concrete structural works because concrete and reinforcement do not respond equally to modelling assumptions. Concrete quantities are primarily derived from the geometry of major structural components, whereas reinforcement quantities depend on detailing assumptions such as bar diameter, spacing, hooks, laps, overlap treatment, segmentation, and layered arrangements. Prior studies have shown that reinforcement quantity extraction becomes more reliable when reinforcement is explicitly or consistently represented at an appropriate level of model detail and aligned with quantity classification rules [6, 20, 21]. Conversely, deviations tend to increase when reinforcement is simplified, incompletely represented, or inconsistently mapped to BOQ items and measurement standards [22-24].

Accordingly, this study does not seek to rank Tekla Structures and Cubicost universally. Instead, it evaluates how the two platforms perform under the same project data, structural-element scope, and validation basis. The originality of the study lies in its validation logic: it distinguishes between a controlled analytical reference and a practical BOQ benchmark, evaluates concrete and reinforcement separately, and supplements percentage deviations with additional exploratory validation metrics. This framing helps clarify where quantity differences originate and why similar BIM workflows may produce different levels of reliability across work items.

This study evaluates the accuracy of BIM 5D-based quantity take-off for structural concrete and reinforcement works using Tekla Structures and Cubicost in a three-story building project. Manual calculation derived from the same structural drawings is used as the primary controlled analytical reference, while the consultant BOQ is used as a secondary practical benchmark. The objectives are: (1) to evaluate concrete-quantity deviations generated by Tekla Structures and Cubicost relative to the controlled manual reference, (2) to evaluate reinforcement-quantity deviations generated by both platforms relative to the same reference, and (3) to analyze the agreement of BIM-generated quantities with the consultant BOQ. The numerical findings are case-specific, but the validation framework is intended to support more transparent BIM 5D quantity assessment in structural cost-estimation practice.

2. Materials and methods

2.1 Research design

This study employed a quantitative comparative case study design to evaluate the accuracy of BIM-based quantity take-off (QTO) for structural works. Quantitative case-based designs are commonly used in BIM-QTO research because they enable direct comparison between BIM-generated quantities and reference quantities such as manual calculations, contractor estimates, or project BOQs using explicit deviation metrics and agreement indicators [14, 18, 25]. In the present study, the object of analysis was the quantity take-off of structural works in a three-story building project. A comparative design was selected because the study aimed to assess how two BIM platforms, namely Tekla Structures and Cubicost, generated quantity outputs under the same project conditions, based on the same design documents, and evaluated against the same reference basis. The study is therefore interpreted as a controlled case-based validation, not as a universal ranking of the two software platforms.

2.2 Case study project

The case study was conducted on a three-story building construction project located in Surakarta, Indonesia. The project was selected because it provided a complete set of structural drawings, reinforcement detailing documents, manual quantity calculation recapitulations, and consultant BOQ documents, which enabled controlled comparison between BIM-generated quantities and project reference data. The scope of analysis was limited to structural work items that typically have substantial quantity and cost implications in reinforced concrete building projects, namely concrete and reinforcement works. The numerical results are specific to this project, although the validation workflow may be adapted for other building or infrastructure cases after further testing.

2.3 Source documents and research data

The research data consisted of six main sources: (1) structural drawings of the project, (2) reinforcement detailing drawings, (3) manual quantity calculation recapitulations, (4) consultant BOQ documents, (5) quantity outputs generated from Tekla Structures, and (6) quantity outputs generated from Cubicost. Structural drawings and reinforcement details served as the principal modelling basis. Manual calculations were used as the primary controlled analytical reference because they were derived from the same drawings and were independent of the internal extraction logic of either BIM platform. The consultant BOQ was retained as a secondary practical benchmark to examine agreement with project documentation used in practice.

2.4 Structural elements analyzed

The structural elements analyzed in this study comprised footplat or pile cap, sloof, columns, beams, and slabs. In this manuscript, sloof refers to reinforced-concrete ground beams or tie beams commonly used in Indonesian building practice to connect foundation and column systems. These elements were selected because they represent the principal reinforced-concrete components of the building

structure and provide a suitable basis for comparing concrete volumes and reinforcement quantities across software platforms [14, 26, 27]. By restricting the analysis to the same structural elements across the two software environments, the study maintained comparability in object coverage and reduced bias associated with inconsistent scope definition.

2.5 BIM modelling procedure and assumptions

The BIM modelling procedure was carried out separately in Tekla Structures and Cubicost using the same project drawings and reinforcement details. In Tekla Structures, concrete elements were modelled using object-based components such as pad footing, concrete column, concrete beam, and concrete slab, while reinforcement was represented using reinforcement tools such as Pile Cap Reinforcement, Rectangular Column Reinforcement, Beam Reinforcement, Slab Bar, and Rebar Set editing when adjustment was required. In Cubicost, concrete quantity take-off was conducted using Cubicost Takeoff for Architecture and Structure (TAS), while reinforcement take-off was conducted using Cubicost Takeoff for Rebar (TRB). The TAS model provided the principal concrete-geometry basis and TRB was used to define reinforcement by structural element. Reinforcement modelling was guided by the structural details, including bar diameter, spacing, cover, hooks, bends, and lap/overlap assumptions where these were represented in the software workflow. No separate formal LOD certificate was available; therefore, the model detail is described by its quantity-relevant content rather than by a certified LOD label. Table 1 summarizes how Tekla Structures, Cubicost TAS, and Cubicost TRB were standardized in terms of modelling basis, structural element scope, reinforcement representation, calculation rules, output extraction, and validation reference. Table 1 also reports the verified software versions and key modelling assumptions. Complete exportable configuration files for all internal software settings were not available in the supplied project records; therefore, exact replication of every hidden software default remains a reproducibility limitation.

Table 1 BIM modelling and quantity-extraction protocol used to standardize Tekla Structures and Cubicost outputs.

Aspect	Tekla Structures	Cubicost	Standardization / control
Concrete modelling	Pad footing, concrete column, concrete beam, and concrete slab objects	Cubicost TAS structural-element modules	Same drawings, dimensions, levels, and element scope
Reinforcement modelling	Pile Cap Reinforcement, Rectangular Column Reinforcement, Beam Reinforcement, Slab Bar, and Rebar Set editing	Cubicost TRB rebar definition by element	Same reinforcement drawings and detailing assumptions
Measurement rules	Model properties and organizer/report extraction	Indonesian measurement environment and TRB calculation rules	Common work-item grouping and units
Detailing variables	Cover, bar diameter, spacing, bends, hooks, and laps/overlaps where modelled	Cover, bar diameter, spacing, hooks, laps/overlaps according to TRB settings	Checked against manual calculation recapitulations
Output format	Exported quantity reports / spreadsheets	View Quantity, View Quantity by Category, and spreadsheet export	Common comparison table by element and work item
Software versions and unavailable settings	Tekla Structures 2021 Student License	Cubicost TAS 2021 Cubicost TRB 2021	Concrete cover, lap splice, hooks, and overlaps followed the structural drawings and SNI 2847:2019. No additional waste allowance was applied during BIM quantity extraction. Bar-length rounding followed the default software calculation rules.

2.6 Measurement framework and quantity extraction

The comparison was standardized by aligning the same drawings, element scope, work-item grouping, units, and structural-element classification across manual calculation, Tekla Structures, and Cubicost. The concrete and reinforcement calculations were interpreted within the Indonesian project-measurement context. Reinforcement detailing followed the project drawings and the relevant SNI 2847:2019 provisions on concrete cover, hooks, bends, development length, and lap splice requirements where applicable to quantity modelling. Cubicost TAS was set within an Indonesian measurement environment, while Cubicost TRB used Indonesian calculation rules for rebar take-off. Tekla quantities were extracted through model properties and organizer/report outputs, whereas Cubicost quantities were extracted through View Quantity, View Quantity by Category, and spreadsheet export. These outputs were then reorganized into a common comparison format.

2.7 Reference and benchmark definition

Two comparison bases were used. First, manual calculation derived from the same structural drawings and reinforcement details was defined as the primary controlled analytical reference. This does not imply that manual calculation is an error-free true value; rather, it provides an independent baseline outside the extraction algorithms of both BIM platforms. Second, the consultant BOQ was defined as a secondary practical benchmark. This distinction is important because BOQ values may reflect project-specific recapitulation rules, classification decisions, rounding, allowances, and measurement conventions that are not necessarily identical to the analytical quantity model [14, 18, 19].

The manual calculation was prepared from the approved structural drawings and reinforcement detailing sheets using spreadsheet-based quantity recapitulation. It was checked against the element schedule, reinforcement drawings, and consultant BOQ recapitulation to identify inconsistencies in element scope, unit use, and work-item grouping. When discrepancies were identified, the quantities were rechecked against the original drawings and aligned to the same structural-element scope used in the BIM models. A fully independent

third-party audit was not available in the supplied records; therefore, the manual calculation is used as a controlled analytical reference rather than an error-free ground truth.

2.8 Accuracy evaluation metrics

The primary indicators used to evaluate QTO accuracy were absolute deviation and percentage deviation. Deviation-based indicators are among the most widely used measures in BIM-QTO validation studies because they directly express the difference between software-generated quantities and reference quantities [14, 28-30]. The absolute deviation was calculated using Equation (1):

$$D = |Q_BIM - Q_ref| \quad (1)$$

where D is the absolute deviation, Q_BIM is the quantity generated by the BIM software, and Q_ref is the reference quantity obtained from manual calculation or consultant BOQ, depending on the comparison basis.

The percentage deviation was calculated using Equation (2):

$$PD = (|Q_BIM - Q_ref| / Q_ref) \times 100\% \quad (2)$$

where PD is the percentage deviation between the BIM-generated quantity and the reference quantity. These metrics provide a direct and interpretable basis for comparing output accuracy across different structural elements and quantity magnitudes.

2.9 Supporting validation

To address the limitation of relying on R^2 alone, supporting exploratory validation indicators were calculated at the structural-element level. Because only four structural-element groups were available, these indicators are interpreted cautiously as exploratory supporting evidence rather than as a full robustness analysis.

$$MAPE = (1/n) \Sigma_i |(Q_BIM,i - Q_ref,i) / Q_ref,i| \times 100\% \quad (3)$$

$$RMSE = \sqrt{[(1/n) \Sigma_i (Q_BIM,i - Q_ref,i)^2]} \quad (4)$$

$$\text{Mean bias} = (1/n) \Sigma_i (Q_BIM,i - Q_ref,i) \quad (5)$$

$$LoA = \bar{d} \pm 1.96 s_d \quad (6)$$

$$R^2 = [r(Q_ref,i, Q_BIM,i)]^2 \quad (7)$$

In Equations (3)–(7), Q_BIM,i is the BIM-generated quantity for structural-element group i, Q_ref,i is the corresponding manual reference quantity, n is the number of structural-element groups, $d_i = Q_BIM,i - Q_ref,i$, $\bar{d}$ is the mean bias, s_d is the sample standard deviation of the paired differences, and r is the Pearson correlation coefficient. R^2 was therefore calculated as the squared Pearson correlation coefficient between the element-level manual reference quantities and the corresponding BIM-generated quantities, not as an independent accuracy measure.

2.10 Data analysis workflow

The data analysis was conducted in six sequential stages. First, manual calculations were compiled as the controlled reference for all analyzed structural elements. Second, concrete and reinforcement quantities were extracted from Tekla Structures. Third, equivalent quantity data were extracted from Cubicost TAS and TRB. Fourth, absolute deviation, percentage deviation, MAPE, RMSE, mean bias, Bland-Altman limits, and squared Pearson correlation values were calculated as supporting exploratory indicators. Fifth, BIM-generated totals were compared with the consultant BOQ as a practical benchmark. Sixth, deviation patterns were interpreted according to platform, work-item characteristics, modelling assumptions, and practical cost-estimation implications. The overall workflow is shown in Figure 1.

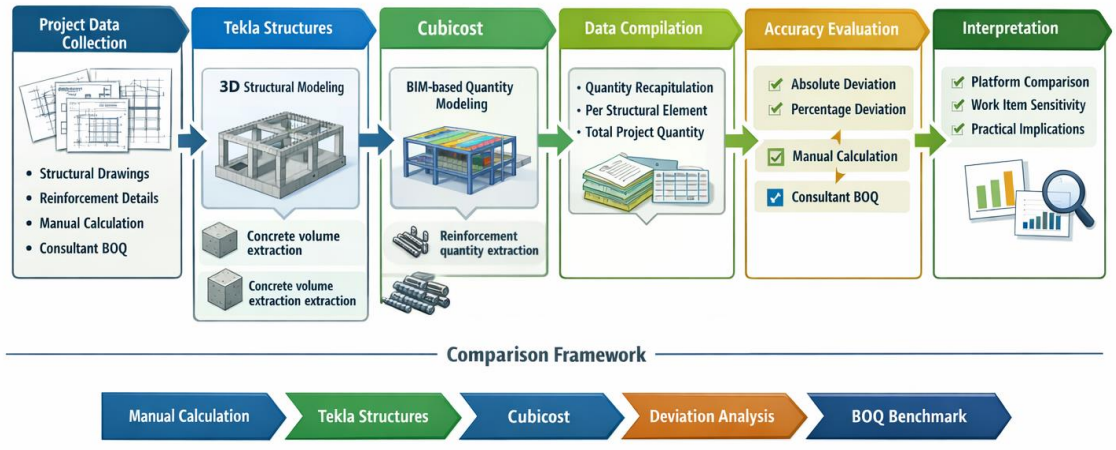

Figure 1 Research workflow for BIM-based quantity take-off accuracy evaluation.

3. Results

3.1 Concrete quantity results

Table 2 presents the concrete quantity comparison by structural element based on manual calculation, Tekla Structures, and Cubicost. Based on the corrected element-level quantities, the total concrete volume was 605.975 m³ for the manual reference, 607.778 m³ for Tekla Structures, and 609.316 m³ for Cubicost. Both BIM totals were close to the manual reference, indicating that concrete quantity extraction was comparatively stable under the tested project conditions. The most visible difference occurred in slab quantities, where both BIM platforms generated slightly higher volumes than the manual calculation.

This pattern is consistent with previous studies reporting that BIM-based quantity take-off for concrete generally achieves high agreement with manual or BOQ-based references when model geometry is sufficiently complete and aligned with measurement rules [22, 31-34]. However, the result should be interpreted within the selected structural scope and should not be generalized to all project types.

Table 2 Concrete quantity comparison by structural element.

Structural Element	Manual Calculation (m³)	Tekla Structures (m³)	Cubicost TAS (m³)
Footplat / Pile Cap	40.728	40.728	40.728
Sloof and Beams*	220.589	219.485	220.351
Columns	158.178	157.959	158.043
Slabs	186.480	189.606	190.194
Total	**605.975**	607.778	609.316

3.2 Reinforcement quantity results

Table 3 presents the reinforcement quantity comparison by structural element. In contrast to the concrete results, reinforcement quantities showed a wider difference across the two BIM platforms. Based on the element-level quantities, the total reinforcement quantity was 108,893.920 kg for the manual reference, 99,014.811 kg for Tekla Structures, and 107,513.997 kg for Cubicost TRB. The largest differences were found in the grouped sloof and beam category and in slab reinforcement, particularly for Tekla Structures.

These results support the interpretation that reinforcement quantity extraction is detail-sensitive. Reinforcement quantities depend not only on gross structural geometry but also on how each platform represents bar diameter, spacing, hooks, bends, laps, segmentation, support conditions, and embedded extraction rules. Previous studies similarly note that reinforcement quantity take-off is strongly affected by detailing assumptions, bar modelling strategy, overlap treatment, and classification consistency [6, 20, 21, 24, 35].

Table 3 Reinforcement quantity comparison by structural element.

Structural Element	Manual Calculation (kg)	Tekla Structures (kg)	Cubicost TRB (kg)
Footplat / Pile Cap	3,790.520	3,916.410	3,794.458
Sloof and Beams*	36,906.479	31,803.448	35,535.695
Columns	37,669.291	36,326.165	37,667.750
Slabs	30,527.630	26,968.788	30,516.094
Total	108,893.920	99,014.811	107,513.997

3.3 Accuracy comparison based on manual calculation

The total-level accuracy comparison relative to the controlled manual reference is summarized in Table 4. Tekla Structures produced a corrected concrete deviation of 1.803 m³ (0.30%), while Cubicost produced 3.341 m³ (0.55%). For reinforcement, Tekla Structures produced a deviation of 9,879.109 kg (9.07%), whereas Cubicost TRB produced a deviation of 1,379.923 kg (1.27%). Under the tested project conditions, both platforms were close for concrete, while Cubicost TRB was closer to the manual reference for reinforcement.

Table 4 Overall quantity take-off accuracy relative to manual calculation.

Work Item	Tekla Structures Total	Cubicost Total	Tekla Absolute Deviation	Tekla Percentage Deviation	Cubicost Absolute Deviation	Cubicost Percentage Deviation
Concrete (m³)	607.778	609.316	**1.803**	0.30%	**3.341**	0.55%
Reinforcement (kg)	99,014.811	107,513.997	9,879.109	9.07%	1,379.923	1.27%

3.4 Comparison with consultant BOQ

After evaluating the software outputs against the controlled manual reference, the analysis was extended to the consultant BOQ to examine agreement with project documentation used in practice. Table 5 presents a verification-oriented comparison that reports the consultant BOQ quantities, BIM-generated quantities, signed deviations, absolute deviations, and percentage deviations. For concrete, Tekla Structures and Cubicost TAS produced deviations from the consultant BOQ of 85.716 m³ (12.36%) and 84.271 m³ (12.15%), respectively. For reinforcement, Tekla Structures and Cubicost TRB produced deviations of 13,450.899 kg (11.96%) and 14,425.435 kg (11.83%), respectively.

The larger BOQ gap suggests that disagreement between BIM outputs and consultant BOQ documents cannot be attributed solely to software behavior. Differences may also reflect classification rules, measurement standards, recapitulation procedures, rounding,

under-modelled or excluded elements, and project-specific assumptions embedded in BOQ preparation [3, 36-38]. Therefore, the BOQ comparison is interpreted as a practical benchmark rather than as the sole analytical reference.

Table 5 Verification-oriented comparison of BIM-generated quantities with consultant BOQ.

Work item	Platform	Consultant BOQ quantity	BIM-generated quantity	Signed deviation (BIM−BOQ)	Absolute deviation	Deviation from BOQ (%)
Concrete	Tekla Structures	693.494 m³	607.778 m³	−85.716 m³	85.716 m³	12.36%
Concrete	Cubicost TAS	693.587 m³	609.316 m³	−84.271 m³	84.271 m³	12.15%
Reinforcement	Tekla Structures	112,465.710 kg	99,014.811 kg	−13,450.899 kg	13,450.899 kg	11.96%
Reinforcement	Cubicost TRB	121,939.432 kg	107,513.997 kg	−14,425.435 kg	14,425.435 kg	11.83%

3.5 Supporting validation

Table 6 presents supporting exploratory validation indicators. The R^2 values were recalculated as squared Pearson correlation coefficients based on the element-level data in Tables 2 and 3. These values indicate linear consistency across element-level quantities, but they are not interpreted as proof of accuracy because high R^2 may coexist with systematic bias. MAPE, RMSE, mean bias, and Bland-Altman limits provide additional information on error magnitude and direction. Because the calculations use only four structural-element groups, the Bland-Altman limits and related agreement indicators are exploratory and should be interpreted cautiously.

Table 6 Supporting exploratory validation indicators based on four structural-element groups.

Work item	Platform	MAPE	RMSE	Mean bias	LoA	R^2
Concrete	Tekla Structures	0.58%	1.661 m³	0.451 m³	-3.168 to 4.069 m³	0.999447
Concrete	Cubicost TAS	0.55%	1.862 m³	0.835 m³	-2.931 to 4.602 m³	0.999440
Reinforcement	Tekla Structures	8.09%	3,183.006 kg	-2,469.777 kg	-7,014.121 to 2,074.566 kg	0.986959
Reinforcement	Cubicost TRB	0.96%	685.420 kg	-344.981 kg	-1,685.422 to 995.461 kg	0.998417

Note: Positive mean bias indicates overestimation relative to the manual reference; negative mean bias indicates underestimation. R^2 was calculated as the squared Pearson correlation coefficient between element-level manual and BIM quantities. Because only four structural-element groups were available, MAPE, RMSE, mean bias, and Bland-Altman limits are interpreted as exploratory supporting indicators rather than a full robustness analysis.

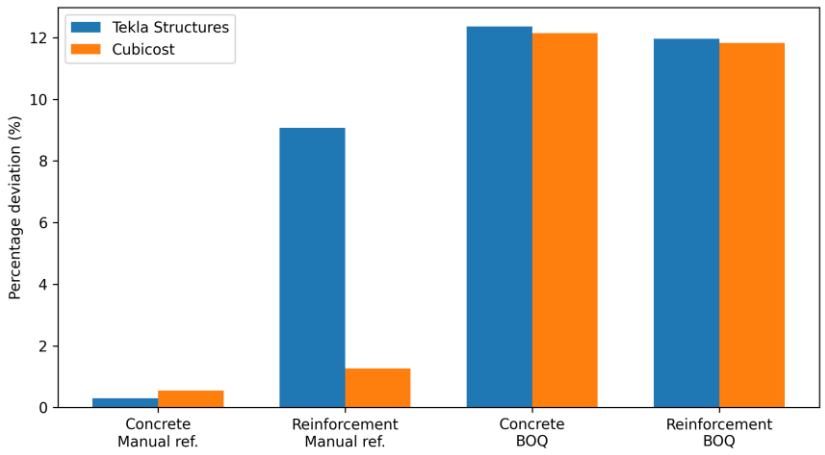

Figure 2 Percentage deviation of BIM-generated quantities relative to the controlled manual reference and consultant BOQ.

As illustrated in Figure 2, the manual-reference comparison and the BOQ comparison convey different validation meanings. The manual-reference comparison evaluates analytical accuracy under controlled scope and drawing-based assumptions, whereas the BOQ comparison reflects practical agreement with project documentation. Therefore, the larger BOQ-related deviations should not be interpreted solely as BIM modelling error, but as an indication that consultant BOQ quantities may have been prepared using different measurement conventions, grouping rules, or project-specific allowances.

4. Discussion

The findings indicate that BIM 5D quantity take-off accuracy varied by work item. Concrete quantities generated by Tekla Structures and Cubicost were close to the controlled manual reference, whereas reinforcement quantities showed a wider platform-dependent difference. This distinction is methodologically important because it demonstrates that BIM reliability should not be judged only at the software level. The nature of the measured item, the modelling protocol, and the extraction rules are equally important.

The stronger consistency of concrete quantities can be explained by their geometry-based character. For structural elements such as footplat or pile cap, beams, columns, and slabs, concrete volume depends mainly on the dimensions and boundaries of the modelled objects. When these boundaries are defined consistently, quantity extraction tends to remain stable across software platforms. This interpretation is consistent with prior studies reporting that BIM-based concrete QTO often produces low deviation when model geometry and item mapping are adequately controlled [32-34].

Reinforcement quantities require a different interpretation. Rebar take-off depends on bar diameter, spacing, hooks, bends, lap splices, overlap treatment, support conditions, segmentation, and software-specific extraction logic. Small differences in these inputs

can produce substantial differences in total reinforcement mass. In the present case, Tekla Structures underestimated reinforcement relative to the manual reference more strongly than Cubicost TRB, particularly in the sloof/beam and slab categories. This result should not be interpreted as a universal software ranking; it only indicates that Cubicost TRB aligned more closely with the manual reference under the tested project documents, modelling assumptions, and extraction settings.

The conceptual difference between concrete and reinforcement quantity sensitivity is illustrated in Figure 3. Concrete extraction is mainly governed by stable volumetric boundaries, while reinforcement extraction is detail-sensitive and more dependent on modelling assumptions and software rules. This finding supports the view that QTO validation should separate geometry-based and detail-based work items instead of treating all structural quantities as a single category.

Another important finding concerns the difference between manual-reference accuracy and consultant BOQ agreement. Although the BIM outputs were relatively close to the controlled manual reference, the deviations relative to the consultant BOQ were much higher. This suggests that BOQ discrepancy cannot be explained by software performance alone. BOQ values may include different measurement conventions, item classifications, recapitulation procedures, rounding practices, allowances, and project-specific assumptions that are not directly visible in the BIM model [3, 36-38]. The revised validation framework therefore separates analytical accuracy from practical BOQ concordance.

The supporting exploratory indicators strengthen this interpretation, but their limited element-group basis requires caution. R^2 values were high for all platform-work-item combinations, but the MAPE, RMSE, mean bias, and Bland-Altman indicators show that high linear consistency does not necessarily mean low error. For example, reinforcement in Tekla Structures retained a high squared Pearson correlation value but showed larger MAPE, RMSE, and negative mean bias. Deviation and bias metrics are therefore more informative when the objective is to determine quantity reliability for cost-estimation practice.

The study also highlights the need for explicit modelling governance. Quantity outputs are only as reliable as the modelling rules, object definitions, measurement framework, and extraction logic used to produce them. For reinforcement, project teams should define bar spacing, hook treatment, lap splice assumptions, cover rules, overlap handling, and report settings before relying on model-derived quantities for procurement or cost control. For concrete, teams should still verify object boundaries, openings, intersections, and element classification, even when deviations appear small.

This study has several limitations. First, it is based on a single three-story reinforced-concrete building project in Surakarta, Indonesia. The numerical deviations should therefore not be generalized to high-rise buildings, bridges, tunnels, industrial facilities, or other project types. Second, the study evaluates selected structural elements only. Third, the available project records did not allow a full parametric sensitivity rerun for alternative lap, hook, overlap, or spacing assumptions. Fourth, although software versions and general modelling assumptions were identified, complete exportable configuration files for all internal software-specific settings were not available; therefore, exact replication of detailed hidden defaults, particularly internal bar-length rounding parameters and undocumented calculation settings, remains limited. Fifth, because manual calculation is itself subject to human error, it is treated as a controlled analytical reference rather than as an absolute ground truth.

Despite these limitations, the validation framework remains useful. It demonstrates how BIM 5D QTO can be evaluated by separating reference-baseline accuracy from BOQ benchmark agreement, by distinguishing geometry-based and detail-sensitive work items, and by combining deviation metrics with exploratory supporting validation indicators. Future research should apply the same validation logic to multiple projects, different project scales, alternative BIM platforms, and parametric sensitivity scenarios for reinforcement detailing.

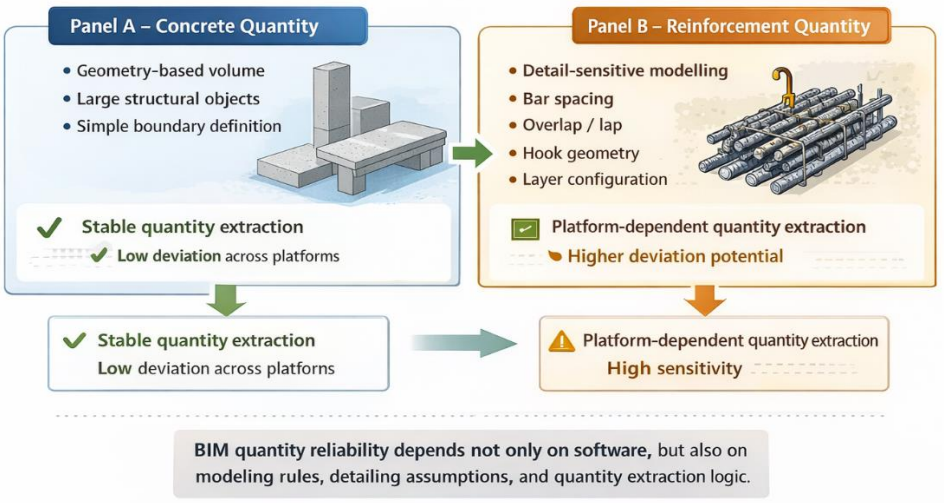

Figure 3 Conceptual explanation of quantity sensitivity in BIM-based estimation.

5. Conclusions

This study evaluated the accuracy of BIM 5D-based quantity take-off for structural concrete and reinforcement works using Tekla Structures and Cubicost in a three-story building project. Manual calculation was used as a controlled analytical reference, while the consultant BOQ was used as a secondary practical benchmark. This distinction was introduced to avoid treating BOQ concordance or manual calculation as an unqualified ground truth.

Based on the corrected element-level quantities, both platforms produced close concrete estimates relative to the manual reference, with deviations of 1.803 m^3 (0.30%) for Tekla Structures and 3.341 m^3 (0.55%) for Cubicost TAS. Reinforcement quantities were more sensitive to modelling and extraction logic, with deviations of 9.07% for Tekla Structures and 1.27% for Cubicost TRB. Under the tested project conditions, Cubicost TRB produced reinforcement quantities closer to the controlled manual reference, but this result should not be interpreted as a universal ranking of the software platforms.

The BOQ comparison showed higher deviations, ranging from 11.83% to 12.36% in the retained project-document benchmark. This indicates that differences between BIM-generated quantities and BOQ documentation may arise from measurement rules, classification, rounding, recapitulation procedures, allowances, or other project-specific assumptions, not only from software behavior.

The principal contribution of the study is a case-specific BIM 5D quantity-validation framework that separates analytical reference accuracy from practical BOQ agreement and highlights the different sensitivity of concrete and reinforcement quantities. Reliable BIM-based quantity estimation therefore requires standardized modelling rules, transparent extraction protocols, explicit reference definitions, and transparent BOQ comparison. Future research should apply the framework to multiple projects and conduct parametric sensitivity testing of reinforcement assumptions such as lap splices, hooks, spacing, cover, and overlap treatment.

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