

Article

Clash Categorization and Optimization in a Federated BIM Workflow for Integrating Temporary Shoring Systems and Permanent Structures in High-Rise Excavations

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Abstract

The integration of temporary support systems with permanent structural frameworks remains a complex challenge in high-rise construction, where traditional building information modeling (BIM) workflows often lack the coordination needed to optimize both simultaneously. This study addresses that gap through a federated BIM workflow using Tekla Structures, Revit, Navisworks, and Dynamo on a fourteen-story building with a five-level basement. The temporary shoring, permanent concrete frame, and formwork were modeled at Level of Development (LOD) 300–350. A parameter-driven methodology in Dynamo managed large-scale clash detection. Steel cutting-list optimization reduced sheet-cutting waste from 4.5% to below 3% across 18 tons of steel. Clash detection between the truss guard and permanent rebar initially returned over 6000 conflicts; categorizing these via Dynamo made resolution tractable. This data optimized plywood formwork, reducing requirements by 15% (3350 to 2850 square meters), and refined rebar scheduling, recovering 51 of 103 additional tons, 32.8 tons of which are directly attributable to the truss-rebar interaction-zone workflow presented in this study. The study demonstrates that federating temporary and permanent models generates reusable coordination data, yielding savings beyond simple clash avoidance. It offers a transferable workflow for temporary-to-permanent structural integration that the current literature has not yet examined quantitatively.

Keywords: building information modeling (BIM); clash detection; temporary shoring structures; resource optimization; quantity takeoff; truss guard system



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1. Introduction

The increasing complexity of urban construction projects, particularly those involving high-rise buildings and deep excavation, has intensified the demand for integrated digital approaches to design and construction management. Building Information Modeling (BIM) has emerged as a transformative platform enabling multidisciplinary coordination, virtual clash resolution, and resource optimization across all project phases [1]. In this context, modeling temporary structural support systems, such as truss-based guard structures used to stabilize underground retaining walls during excavation, presents a distinctive challenge. These systems are transient by nature, yet their integration with permanent structural elements must be precisely managed to ensure structural safety, the integrity of

construction sequencing, and efficient use of resources [2]. The simultaneous modeling and coordination of temporary and permanent structural systems within a single federated BIM environment introduces specific challenges in clash detection, level-of-development (LOD) definition, and material quantification.

Nevertheless, the existing literature has only partially addressed these challenges. A review by Ko et al. [3] in *Automation in Construction* highlights several BIM applications in high-rise buildings. They identified structural design, clash coordination, and geotechnical integration as the three most underdeveloped application domains. These are precisely the areas that the present study aims to address in combination. These parallel threads of development underscore that the integration challenge examined here is not merely a technical issue. It reflects a broader gap between the capabilities of BIM platforms and the complexity of real construction scenarios. These scenarios involve both permanent and temporary structural systems operating within a shared, phase-sensitive model environment.

1.1. BIM for High-Rise Structural Integration

BIM has been widely adopted as an integrative platform for structural design in complex building projects. Autodesk Revit has become the dominant authoring tool for structural modeling, frequently coupled with analysis environments such as ETABS and coordination platforms such as Navisworks [1]. This toolchain enables a closed-loop adaptive workflow in which parametric modeling, structural simulation, and clash detection operate in continuous feedback, producing more efficient and better-coordinated structural designs. Research by Sherif et al. [4] demonstrated that automated BIM-based structural design workflows, when applied to reinforced concrete buildings, can reduce material costs by up to 15% per floor without compromising spatial requirements—a finding that underscores the quantitative value of BIM-driven optimization beyond geometric coordination alone. Gomes et al. [5] conducted a comprehensive review of integration challenges between BIM and structural analysis software, identifying Industry Foundation Classes (IFC)-based data exchange as both the most standardized and most problematic interface, with frequent loss of analytical relationships and structural constraints during translation. Their findings are particularly pertinent to projects in which temporary structures, modeled outside the primary BIM environment, must be merged into a federated model without losing load-path information or phasing metadata. The reliability-constrained dimension of structural optimization in BIM environments has received growing attention. Yavan et al. [6], in *Applied Sciences*, developed a reliability-constrained structural design optimization framework using visual programming within Revit. This framework integrates probabilistic structural analysis with evolutionary optimization algorithms. Their work demonstrated that BIM-embedded optimization can achieve target reliability indices while reducing steel consumption by up to 18%. This finding is particularly significant for temporary truss systems where reliability requirements are time-bounded, and member sizing directly governs both cost and the feasibility of eventual dismantling. The emergence of AI-integrated BIM workflows represents the current frontier of structural design automation. Similarly, Mudondo et al. [1] demonstrated that an adaptive parametric BIM system integrating Revit, ETABS, Navisworks, and statistical validation in a mutually adjusting design loop can reduce structural material costs while satisfying code compliance. This workflow can be applied directly to the iterative optimization of truss guard configurations in the present project's BIM environment. In the domain of truss structure optimization in BIM environments, Yavan et al. [7] proposed a workflow that combines parametric modeling in Dynamo, finite element analysis using Robot Structural Analysis, and genetic algorithm optimization. This approach demonstrates that integrating visual programming with BIM significantly reduces material consumption while maintaining structural performance tar-

gets. This methodology is directly transferable to the optimization of steel truss shoring systems, where member sizing and connection detailing directly affect both material costs and the ease of eventual removal. Liu et al. [8] further developed layout optimization algorithms for truss structures with modular constraints. Their research demonstrated that topology-driven design approaches can achieve substantial reductions in steel volume while preserving required stiffness characteristics. This insight is particularly applicable to the geometry-constrained design environment typical of deep-excavation shoring within urban building footprints. Figure 1 summarizes the BIM-based integration workflow for high-rise buildings.

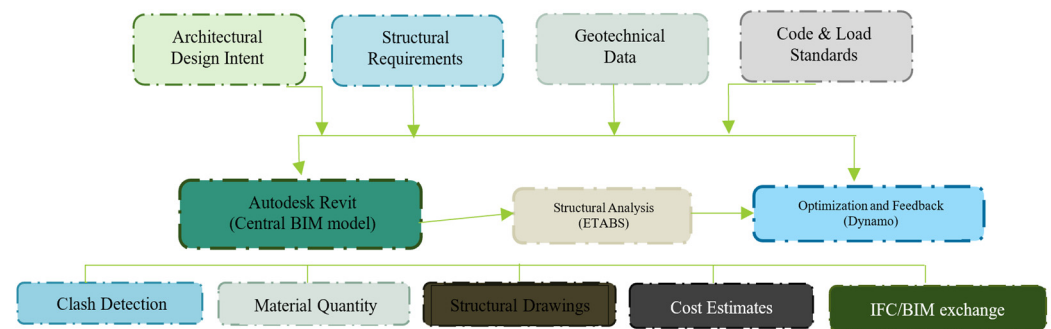


Figure 1. BIM-based structural integration workflow for high-rise buildings (Adapted from [1] and [2]).

1.2. Clash Detection in Multi-Discipline BIM Models

Clash detection, the identification of spatial and functional conflicts between building components from different disciplines, is one of the most operationally critical functions of BIM in construction. Studies have consistently demonstrated that BIM-based clash detection can reduce design conflicts by up to 80% and accelerate project schedules by 10% to 30% when applied proactively during the design phase [9]. Clashes are commonly categorized into hard clashes (physical geometric intersections), soft clashes (proximity violations within defined tolerance zones), and workflow clashes (sequencing conflicts arising from the timing of construction activities) [10]. In the context of a project integrating temporary shoring with permanent structural elements, all three clash types are relevant: hard and soft clashes arise where shoring members approach permanent columns, foundations, or slabs; workflow clashes emerge when the schedule for shoring removal conflicts with the progression of the permanent structural frame. Akponeware et al. [11] argued that a proactive clash avoidance strategy—establishing spatial rules and modeling standards before design begins—produces substantially better outcomes than reactive detection and resolution workflows. Their work is particularly relevant to the integration of truss shoring systems, where the geometry of temporary elements is typically defined after the permanent structural layout is established, creating an inherently reactive coordination context. More recent work by Bitaraf et al. [10] introduced a clash prioritization framework using the Best-Worst Method, assigning weights to structural and (Mechanical, Electrical, and Plumbing) MEP elements to focus resolution efforts on the most impactful conflicts. This type of priority-driven approach is scalable to multi-phase projects with large numbers of potential clashes, including those arising between temporary shoring members and permanent structural components at different construction stages. Koo et al. [12], developed a risk-and-relevance-based clash resolution framework that addresses the problem of false positives—clashes flagged by automated software that do not represent real coordination problems. Their study demonstrated that combining geometric clash data with semantic building information (element type, function, construction phase) substantially reduces the manual review burden and focuses coordination effort on genuine design conflicts. This se-

mantic enrichment of the clash detection process is directly applicable to federated models in which temporary and permanent elements coexist and must be distinguished by phase and function rather than purely by geometry. Complementing this, Yin et al. [13], presented a BIM-based tool for detecting and resolving spatial-temporal clashes in underground construction, defining a two-category clash taxonomy that accounts for both geometric and time-dependent conflicts—a framework well suited to the sequential nature of temporary shoring installation and removal. From a software interoperability perspective, Colajanni et al. [14] demonstrated that federated BIM models assembled from multiple software environments can successfully preserve clash detection accuracy when IFC-based data exchange is carefully managed. Their findings highlight the importance of controlled modeling and federation workflows, particularly in projects where the temporary shoring model and the permanent building model may originate from different design teams. Two more recent studies extend this trajectory toward automating the clash-review process itself. Hasannejad et al. [15] proposed an automated clash-detection improvement method that reduces the manual effort of filtering geometrically trivial or duplicate flags from federated model outputs, a capability directly relevant to the volume of raw clashes typically generated when a temporary shoring system is coordinated against a permanent structural frame. Shehadeh et al. [16] extended this direction with a modified extreme gradient boosting model that predicts and classifies clashes across architectural, structural, and MEP disciplines with high accuracy, indicating that machine-learning-based prioritization is becoming a viable complement to the parameter-driven and semantic-enrichment strategies discussed above. BIM-based clash detection taxonomy is summarized in Figure 2.

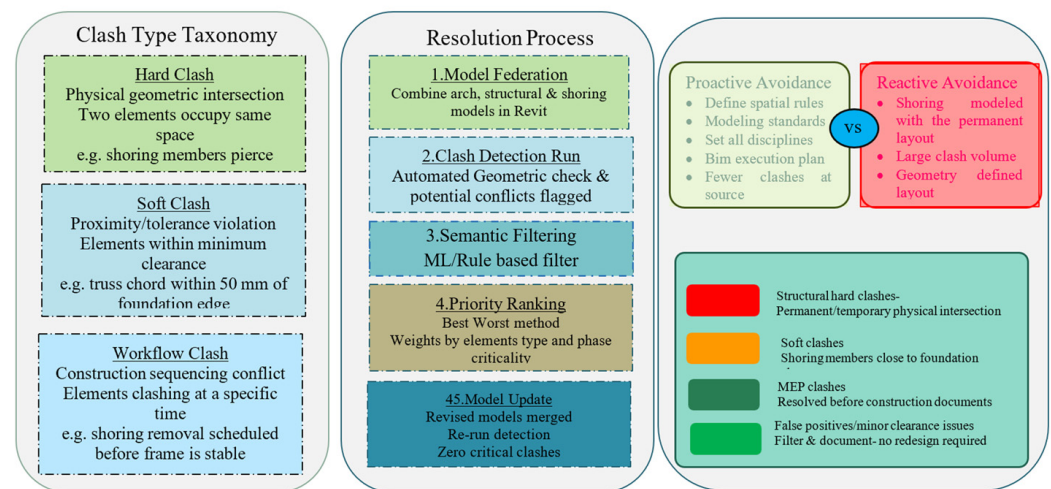


Figure 2. BIM clash detection taxonomy and priority-driven resolution framework, distinguishing hard, soft, and workflow clash types and contrasting proactive avoidance with reactive detection workflows.

1.3. Geotechnical BIM and Temporary Shoring Systems

The integration of geotechnical information into BIM models represents one of the more demanding frontiers of the technology, particularly for projects involving deep excavations in complex urban environments. The standard IFC schema, which serves as the primary open data format for BIM interoperability, does not natively include detailed entity definitions for excavation retaining structures or geological information. This limitation restricts the extent to which shoring design can be fully captured and exchanged within conventional BIM workflows [17]. This gap has been identified as a critical barrier to the broader adoption of BIM in underground construction. It has motivated several recent research efforts to extend the IFC standard and automate design generation for excavation

support systems. Zhang et al. [18] developed a semantic IFC data model for automatic safety risk identification in deep excavation projects, linking BIM elements with risk factors, construction parameters, and dynamic construction phases within a central database. Their framework demonstrated that BIM-based risk identification, when structured around a semantic data model, can significantly accelerate the detection of safety-critical conditions compared to manual review. Their finding has direct implications for projects involving temporary shoring, permanent foundations, and underground walls. Building on this direction, a study published in *Underground Space* [17] presented a novel automated design framework that integrates an extended IFC standard with mechanical analysis and BIM for excavation retaining structures. This framework directly generates 3D models and enables structural optimization and rebar detailing. This work represents the current frontier of BIM application to retaining structures and provides a methodological precedent for the automated modeling approach adopted in the present study. Menaka and Babu [19] examined the application of BIM in deep excavation projects in geotechnically complex environments in South India. They found that the implementation of geotechnical BIM remains limited in many developing regions due to the irregular nature of soil layers and the absence of standardized data models. Despite this, the study demonstrated that BIM offers significant advantages in visualizing the spatial relationships between excavation support systems and adjacent permanent structures, as well as in communicating phased construction sequences to project stakeholders. Their case study highlighted that even a partial BIM implementation offered substantial coordination benefits over traditional 2D documentation, particularly in resolving spatial conflicts between foundation elements and shoring components. Complementing this, Fabozzi et al. [20] developed an infrastructure-BIM framework for automatic numerical analysis of large-scale excavations, linking 3D geometric models with finite element solvers to produce continuous feedback loops between design and geotechnical performance. While their study focused on tunnel excavation, the methodological framework—using BIM as a bridge between geometric modeling and geotechnical simulation—is equally applicable to foundation pit shoring for high-rise buildings. At the level of construction safety management, Hire et al. [21] proposed a conceptual framework for BIM-based site safety practice applicable to deep foundation and excavation works. This framework integrates BIM model data with safety regulation checks and hazard identification protocols. Their framework explicitly addressed the lifecycle of temporary structures, noting that the installation, active service, and removal phases of shoring systems each present distinct hazard profiles that can be proactively managed through BIM-enabled visualization and rule-checking. This safety-through-BIM perspective is particularly relevant to the present study, where the truss guard system must be removed in stages as the permanent structure is constructed, and where premature or poorly sequenced removal could compromise the stability of the underground retaining walls. More recently, Yang et al. [22] demonstrated that explainable artificial intelligence models can accurately estimate ground settlement during foundation excavation directly from monitoring data, offering a data-driven complement to the geometry- and rule-based BIM frameworks reviewed above for managing the geotechnical risks associated with temporary shoring. Table 1 is a Summary of Key Studies on Geotechnical BIM and Temporary Shoring Systems.

Table 1. Summary of Key Studies on Geotechnical BIM and Temporary Shoring Systems.

Author(s)	Study Focus	Key Finding	Relevance to Present Study
Zhang et al. [18]	Semantic IFC model for safety risk identification in deep excavation	Linking BIM elements to risk factors and construction phases via a central database accelerates automatic safety risk identification	Provides a framework for phase-aware risk management of the truss guard structure during installation and removal
Fabozzi et al. [20]	I-BIM approach for geotechnical and numerical modelling of tunnel excavation	BIM models can serve as a bridge between 3D geometric design and finite element geotechnical simulation, enabling continuous design-analysis feedback	Establishes precedent for coupling BIM-based shoring geometry with geotechnical performance evaluation
Menaka & Babu. [19]	Geotechnical BIM for deep excavation case study in South India	Even partial BIM implementation for retaining systems offers significant coordination benefits; geotechnical BIM adoption remains limited in developing regions	Highlights the gap in systematic BIM-based modeling of excavation support systems alongside permanent structures
Hire et al. [21]	Conceptual framework for BIM-based site safety practice in deep foundation works	Installation, active service, and removal phases of temporary structures carry distinct hazard profiles manageable through BIM-enabled rule-checking	Directly supports the safety rationale for BIM of truss removal sequencing in the present study
Waqar et al. [2]	BIM implementation for geotechnical offshore construction projects	BIM adoption in geotechnical projects significantly improves construction coordination but faces barriers related to data standardization and underground element representation	Reinforces the importance of explicit BIM-based coordination between temporary underground works and the permanent structural system

1.4. BIM-Driven Resource Optimization and Material Quantification

Resource optimization is among the most tangible and measurable benefits of BIM adoption in construction projects. Central to this is the automated quantity takeoff (QTO) capability embedded in BIM authoring tools such as Revit, which enables the extraction of accurate material quantities directly from the three-dimensional model. Valinejadshoubi et al. [23] developed an integrated framework for automated, high-accuracy QTO from BIM models, incorporating a Quantity Precision Check (QPC) module to validate model consistency prior to extraction. The study demonstrated that automated QTO significantly outperforms traditional manual methods in both speed and accuracy. That rule-based validation detects parameter inconsistencies that would otherwise propagate as estimation errors. The system was critically validated in an infrastructure project, which identified a 39% inconsistency in wall-element quantities.

Additionally, resolving design changes resulted in a 10% reduction in calculated steel quantities. This performance is directly relevant to projects involving non-standard structural systems such as temporary truss shoring, where standard quantity schedules may not exist, and manual verification of model accuracy is particularly difficult. The quality and consistency of the underlying model strongly influence the accuracy of BIM-based QTO. Sampaio et al. [24] examined the BIM-based QTO methodology in structural and architectural models. They found that BIM offers substantially greater precision in material quantification than conventional 2D-based approaches. Moreover, the phased visibility of BIM models allows resource requirements to be tracked and managed independently for each construction stage. This phased perspective is particularly valuable in projects with temporary structural systems, where the material scope of the shoring works, including steel sections, connection hardware, and bracing elements, must be tracked separately from the permanent building elements. This separation allows for accurate procurement scheduling and cost control for each phase. Their study also identified specific modeling guidelines required to align BIM model outputs with quantity surveying standards, providing a replicable methodology for structuring models intended for QTO. Mohammed et al. [25] demonstrated that bill-of-quantities outputs from Revit models can be used to accurately estimate volumes and weights for each structural design scenario in steel structures. This provides actionable data to optimize procurement and minimize construction waste. Their methodology involves using BIM-embedded material schedules as the primary input to

a design-for-deconstruction scoring framework. This approach is directly applicable to temporary steel truss systems, where optimizing member sizes and connection details affects both the initial material cost and the efficiency of eventual removal and reuse. The study found that BIM-enabled QTO reduced material estimation error to less than 3% compared to manual takeoff, while simultaneously enabling scenario comparisons between alternative design configurations that would be prohibitively time-consuming to produce manually. Parallel developments in formwork and reinforcement optimization further reinforce the value of BIM-based material tracking demonstrated above. Wu et al. [26] proposed an automated quality-inspection method that uses 3D point cloud data to verify formwork member spacing against design tolerances, extending BIM-based formwork management from quantity extraction into installation-stage quality control. In the domain of reinforcement, Widjaja et al. [27] and Wang et al. [28] independently developed BIM-integrated cutting-pattern optimization algorithms that reduced rebar cutting waste to near-zero levels through special-length prioritization and multiobjective optimization, respectively, corroborating the scale of savings achievable when BIM-derived cutting data is coupled with a dedicated optimization routine—the same principle underlying the steel and rebar optimization approach adopted in the present study. Beyond quantity extraction, BIM supports broader resource management through integration with cost estimation and procurement workflows. The level of development (LOD) assigned to temporary structural elements within a BIM model has a direct bearing on the accuracy of resource optimization outputs. When shoring components are modeled at LOD 300 or above—capturing exact geometry, material specifications, and connection details—the resulting QTO and cost estimates are sufficiently accurate to inform procurement decisions. Conversely, lower-LOD representations, while adequate for clash detection purposes, introduce unacceptable levels of uncertainty into material schedules. This LOD-accuracy relationship, documented in the context of permanent structural works by Yavan et al. [7], applies with equal force to temporary systems and underscores the importance of modeling the truss guard structure with sufficient geometric fidelity to support reliable quantity extraction from the outset of the project. Some of the current literature and their application to this study is summarized in Table 2.

Table 2. Summary of Key Studies on BIM-Driven Resource Optimization and Material Quantification.

Author(s)	Tool/Method	Key Quantitative Finding	Application to Present Study
Sherif et al. [4]	Automated BIM-based structural design and cost optimization (RC buildings)	Reduces structural material cost by up to 15% per floor without compromising spatial requirements	Benchmarks the cost-reduction potential of BIM-driven structural optimization applicable to both permanent frame and temporary truss design
Valinejadshoubi et al. [23]	Automated QTO framework with Quantity Precision Check (QPC) module—Revit + Power BI	Identified 39% inconsistency in wall material quantities; reduced steel takeoff by 10% after design change resolution	Provides the QTO validation methodology for extracting accurate steel quantities from the truss guard structure model
Sampaio et al. [24]	BIM-based QTO methodology for structural and architectural models	BIM QTO outperforms 2D methods in precision and enables phase-by-phase material tracking for independent cost control per stage	Supports the separation of temporary shoring quantities from permanent structural quantities within a single federated model
Mohammed et al. [25]	Revit bill-of-quantities for steel structure deconstruction analytics	BIM-enabled QTO reduces material estimation error to less than 3%; enables scenario comparison across alternative steel configurations	Directly applicable to truss member sizing optimization and removal-phase planning for the guard structure
Yavan et al. [7]	BIM + Dynamo + Genetic Algorithm for truss optimization; LOD-accuracy analysis	LOD 300+ required for reliable QTO; genetic algorithm optimization reduced steel volume while maintaining target stiffness	Defines the LOD requirement for the truss guard model and offers an optimization pathway for member sizing

1.5. Research Gaps and Contribution

The reviewed literature demonstrates substantial progress in BIM for structural coordination, clash detection, geotechnical applications, and resource optimization; but these threads have largely developed in parallel. Studies addressing temporary shoring systems

focus predominantly on geotechnical behavior and system selection, without systematically examining how such systems should be modeled, integrated, and coordinated within a BIM environment alongside the permanent structure. BIM research on clash detection has advanced significantly in terms of automation and semantic enrichment, but has rarely been applied to the specific challenge of phased temporary-to-permanent structural transitions, where the clash landscape changes continuously as construction progresses. Research on BIM-based resource optimization and QTO is well developed for permanent structural systems but has not been extended to temporary steel works with stage-dependent removal sequences. No study identified in this review explicitly examines the BIM integration of a truss-based temporary guard structure with a multi-story building's structural system, incorporating multi-phase clash detection, automated quantity takeoff, and resource optimization of the temporary works within a single Revit-based modeling framework. the precise gap that the present study aims to address.

2. Methodology

2.1. Research Design Overview

This section presents the methodological framework adopted to achieve the research objectives: (i) the development of an integrated BIM model incorporating both the permanent structural system of a fourteen-story commercial building and its temporary truss-based guard shoring system; (ii) the systematic detection and resolution of spatial and functional clashes between the temporary truss members and the permanent structural elements, including formwork and reinforcement; and (iii) the optimization of rebar placement within the spatial constraints imposed by the active truss guard configuration. The research follows a case-study methodology grounded in a real construction project, enabling both qualitative assessment of the modeling and coordination workflow and quantitative measurement. The overarching methodological approach is process-driven, focusing on documenting the sequence of decisions for modeling, analysis, and resolution. The research uses Autodesk Revit as the central BIM authoring platform and employs Navisworks Manage to detect clashes in the federated model. Figure 3 illustrates the phased workflow of the research.

2.2. Steel Modeling via Tekla & Optimization via Plus 2D

To minimize steel consumption at the procurement stage, the Tekla Structures 2025 model was exported into Plus 2D version 10.52, an industrial cutting-list optimization application. The complete member list and associated steel plate geometries were imported into the platform, and standard sheet sizes available in the local market were defined as the nesting boundaries. More than ten alternative nesting configurations were evaluated for each available sheet size, with the primary objective of minimizing offcut and scrap weight. The truss guard structure is a temporary system that is dismantled in its entirety once the permanent building frame reaches grade level. Because of this, minimizing steel consumption at the procurement stage directly reduces both project cost and the volume of waste generated at the point of removal. Figure 4 illustrates the imported shoring structure and the Plus 2D nesting platform.

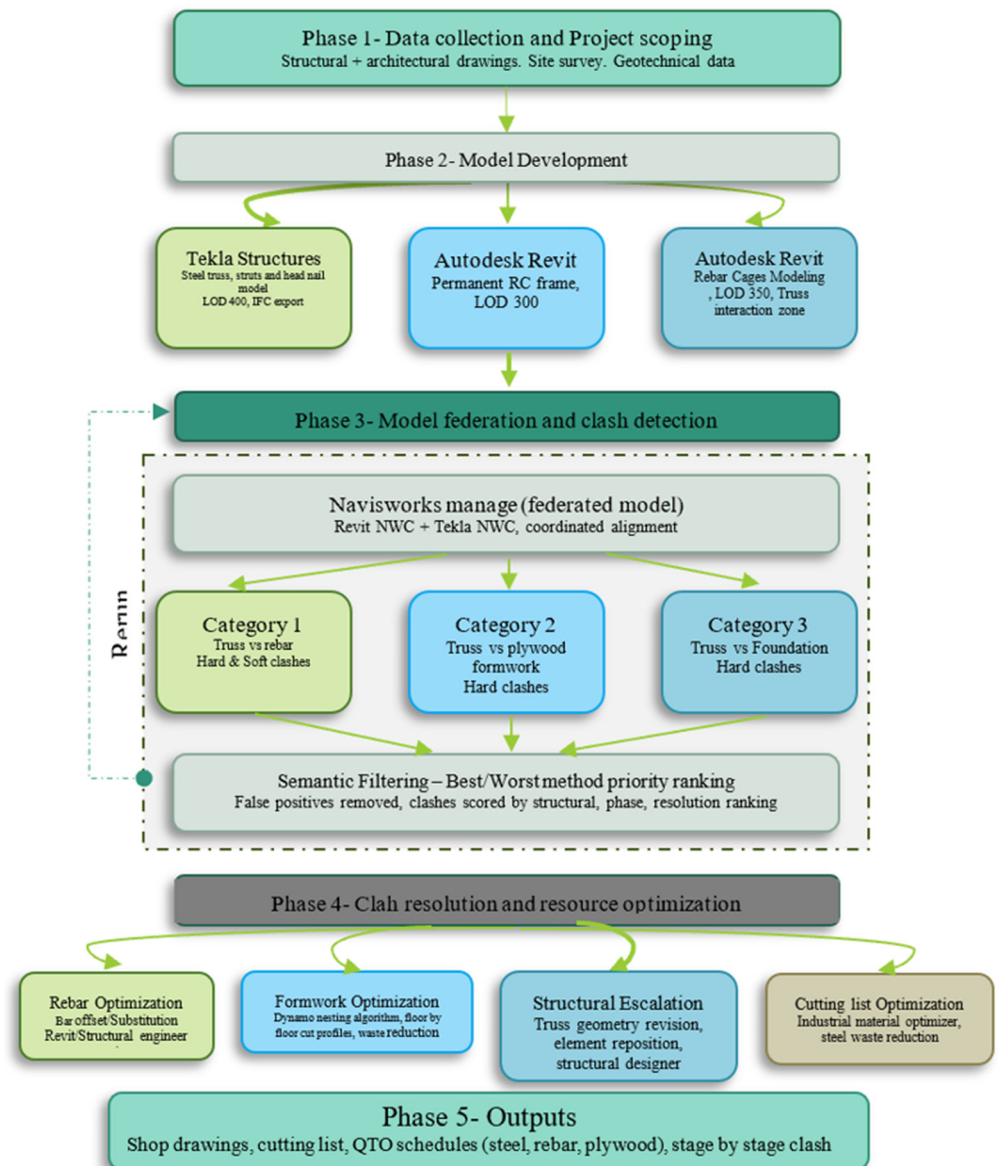


Figure 3. BIM performance framework for geotechnical shoring systems in high-rise buildings.

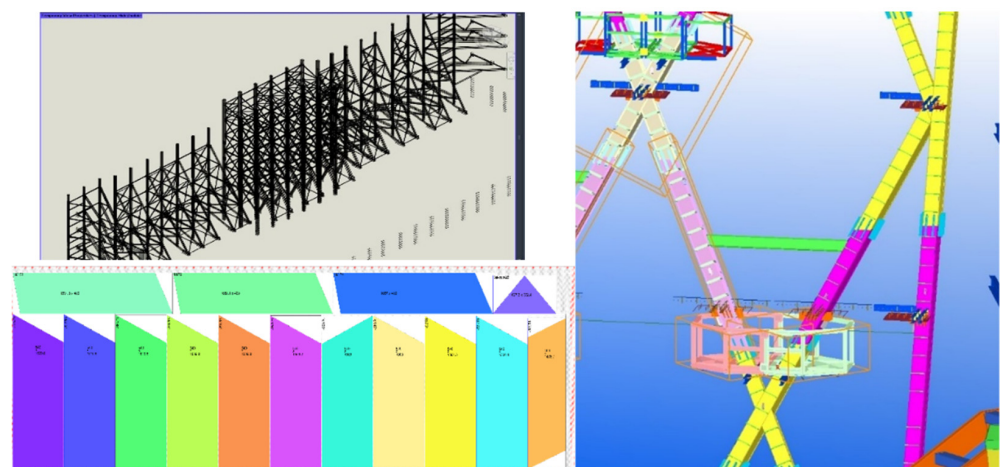


Figure 4. Tekla structures steel truss model and Plus 2D sheet cutting plan.

2.3. Integration of the Permanent Structural Model

The permanent structural system was modeled in Autodesk Revit, leveraging the platform's ability to integrate steel and concrete structural elements into a single coherent model. The Tekla-derived shoring model was linked into Revit as an external reference, creating a federated, multi-discipline environment in which both the temporary and permanent systems were simultaneously visible and queryable. The outputs of the three modeling tracks—structural design, shoring geometry, and material optimization—converge at the Integrated Performance Assessment layer. This layer combines the results into a unified set of performance metrics: clash resolution rate and stage-by-stage approval status. These metrics collectively govern the transition from one construction phase to the next. Figure 5 presents the building model developed in Revit, including the imported steel shoring structure in contact with the reinforced concrete (RC) frame, as well as the overall project plan. A summary of the project data and scope is provided in Table 3.

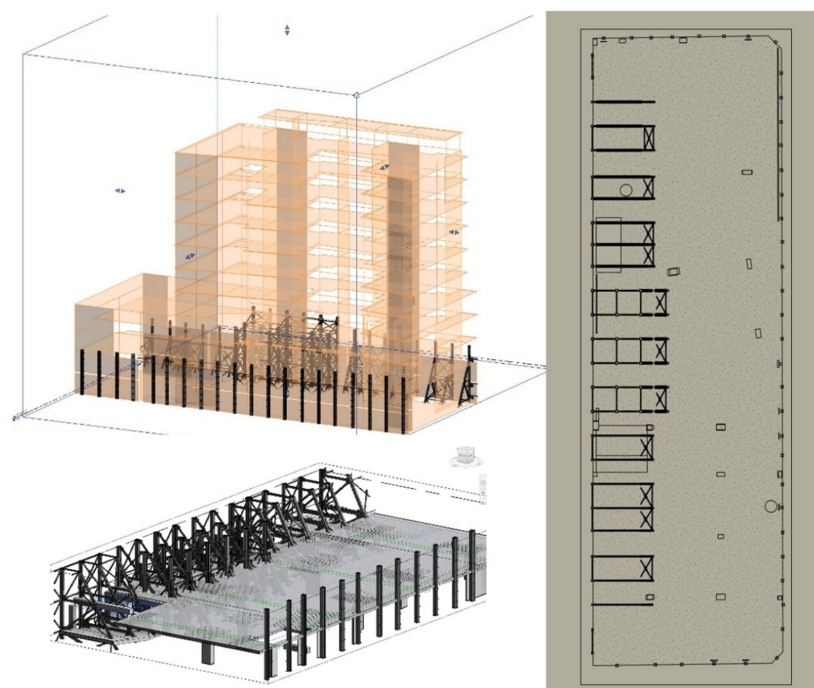


Figure 5. Permanent vs temporary structure model in Revit.

Table 3. Summary of projects data and scoping.

Project Parameter	Value/Description
Building height	14 stories above grade
Underground levels	5 basement levels
Excavation depth	18 m below ground surface
Shoring steel mass	Approximately 18 tons
Primary shoring system	Truss-based guard shoring—temporary, removed after frame completion
Permanent structural system	Reinforced concrete frame (columns, slabs, shear walls)
BIM platform	Tekla Structures (Main steel truss and strut system modeler), Plus 2D (Industrial cutting list preparation), Autodesk Revit (structural authoring); Navisworks Manage (clash detection), Dynamo (Optimization platform)
Clash types identified	Hard clashes (rebar–truss, Plywood or formwork–truss), soft clashes (clearance), workflow clashes (phasing)

2.4. Clash Categorization and Resolution Strategy

The federated model revealed a comprehensive set of spatial conflicts, which were subsequently classified into three categories: (i) clashes between the truss guard members

and the structural reinforcement system; (ii) clashes between the plywood formwork panels and the truss and strut guard system; and (iii) clashes between the steel structure and the permanent foundation network. The first and third categories were modeled and examined in the Navisworks platform, and detailed feedback was provided to the structural designer to inform decisions on resolving conflicts that necessitated structural redesign. The second category was converted to the Dynamo scripting environment, where it served as the geometric input for a formwork-cutting optimization workflow.

The cross-sectional profile of the truss guard varies at each floor level, so the required cut geometry for the plywood formwork panels is unique to each story. In the absence of model-informed optimization, the contractor would have been required either to cut formwork panels individually for each floor—generating substantial material waste—or to over-order panels and absorb the resulting cost. By exporting the floor-by-floor geometric boundaries from the Revit model into Dynamo, the cutting geometry was systematically optimized across all levels, reducing both material waste and overall project costs.

The structural model encompasses all cast-in-place concrete elements across the full building height: columns, beams, floor slabs, shear walls, and foundation components spanning the five basement levels and the fourteen above-grade stories. All permanent structural elements were modeled at Level of Development (LOD) 300, ensuring that element geometry, material specifications, and structural properties were captured with sufficient precision to support reliable quantity takeoff and clash detection. Construction phasing was embedded into the model using Revit’s built-in Phase parameter, assigning each structural element to the construction stage in which it would be built. This phase assignment was critical to enabling stage-sensitive clash detection for the temporary shoring system, since the spatial relationships between truss members and permanent elements evolve at each construction phase. The truss guard shoring model, developed in Tekla Structures and described in Section 2.2, was linked into the Revit model as an external reference. This integration established a federated multi-discipline environment in which both systems remained visible and queryable within a unified authoring space.

Material schedules and quantity takeoff (QTO) were configured in Revit to extract steel and concrete quantities independently for the temporary and permanent systems. Separate schedules were produced for each construction phase, enabling the procurement team to track material requirements on a stage-by-stage basis. This approach aligns with the phased QTO methodology established by Sampaio et al. [24], who demonstrated that BIM-based phased material tracking supports independent cost control across each stage of a multi-phase project. The LOD assignments and key modeling parameters applied to the primary element categories are summarized in Table 4.

Table 4. BIM Parameters and LOD Assignments by Element Category.

Element Category	LOD	Key Modeled Properties	Purpose
RC Columns, Beams, Slabs	300	Exact geometry, concrete grade, phase	QTO, clash detection, phased scheduling
Shear Walls and Foundation	300	Geometry, reinforcement cover zones, openings	Foundation-to-truss clash detection
Rebar (Reinforcement Cages)	350	Bar diameter, spacing, cover, hooks, lap splices	Rebar–truss hard clash detection
Steel Truss Guard (linked from Tekla)	350	Section profiles (HSS/WF), connections, installation phase [HSS = Hollow Structural Section; WF = Wide Flange]	Multi-type clash detection, removal sequencing
Formwork (Plywood Panels)	300	Panel dimensions, floor-by-floor geometry	Formwork–truss clash detection, plywood cut optimization

2.5. Reinforcement Modelling and Interaction Zone Definition

Reinforcement modeling was carried out in Autodesk Revit using the native rebar tool, complemented by Dynamo scripting to automate repetitive bar placement across multiple structural elements. Rebar elements were modeled at LOD 350 throughout the basement levels, capturing bar diameter, spacing, concrete cover, hook geometry, and lap splice positions. Particular attention was paid to the basement-level columns and slab-edge zones—the regions closest to the truss guard members—as these locations define the primary rebar–truss interaction zone where hard clashes were most likely to occur.

The interaction zone was defined as a three-dimensional envelope extending 300 mm outward from the surface of any truss member. This area encompasses the region within which permanent reinforcement bars, connection hardware, and formwork elements are most susceptible to spatial conflict. This zone definition was derived from the minimum clearance requirements specified in the project's structural design basis. It was encoded as a Navisworks selection rule to ensure consistent application during the automated clash detection described in Phase 3. Within this zone, rebar scheduling was configured to flag any bar whose centroid fell within 50 mm of a truss member surface. This threshold indicates a soft-clash condition that requires review, even in the absence of a direct geometric intersection. The 300 mm and 50 mm thresholds were established by the structural designer as the critical points distinguishing conflicts resolvable within normal field tolerances from those requiring formal design input. Deviations below the 50 mm threshold were considered correctable through standard shop-drawing measures, such as minor rebar repositioning, displacement, or local bending, without affecting the design's structural intent. Above this threshold, the designer determined that the conflict could no longer be resolved through such field-level adjustments. Instead, formal notification to the design team was required for a decision on how to proceed, whether through structural redesign, truss offset, or another intervention. The 300 mm envelope was set correspondingly as the outer boundary of the zone within which such designer-defined interaction conflicts were considered plausible. This ensured that the automated clash detection captured the full range of elements the designer would need to review.

The complex shape and structure of the steel truss, along with its interaction with the main RC frame, made the clash detection process challenging. Over 6000 clashes were identified for just one of the underground slabs interacting with the steel truss, thus making the categorization of the clashes quite difficult. To overcome this challenge, it seemed best to first group the elements in Revit according to specific parameters, then use Dynamo to define selection sets based on these parameters before transferring them to Navisworks. Therefore, the clashes were categorized by their resolution. Modeling errors were first detected and resolved. Clashes related to the rebars and their intersection with the steel truss were sent back to the structural engineers and the designer's team to review. The rebar model also served as the primary geometric input for the Dynamo-based formwork-cutting optimization workflow. Because the truss guard's cross-sectional profile varies at each floor level, the outline of the interaction zone—and therefore the required cut geometry for the plywood formwork panels—is unique to each story. The floor-by-floor geometric boundaries exported from the federated Revit model served as input for this optimization step. Figure 6 summarizes the data flow from Navisworks into Dynamo and back into the main model, followed by a clash re-run that reduced the total number of outstanding conflicts and improved overall waste management outcomes.

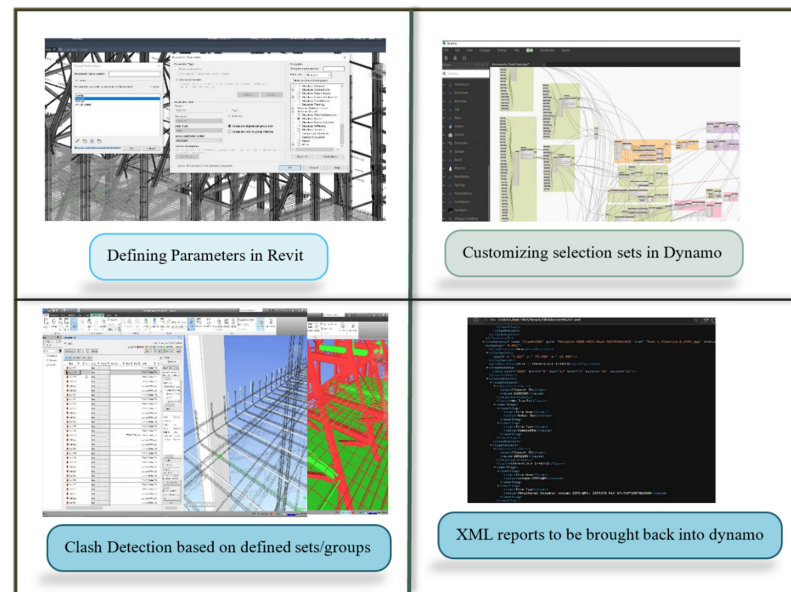


Figure 6. Data flow and feedback loop of categorized clash management.

All detected clashes were exported to structured Navisworks Clash Detective reports in HTML and XML formats, with each clash record capturing: a unique clash identifier, the element GUIDs of both conflicting components, the clash centroid coordinates, the clash depth (for hard clashes), and the construction phase in which the conflict occurs. Table 5 summarizes the clash classification matrix applied to the verified conflict set, demonstrating the three clash categories, their associated element pairs, the typical resolution pathway for each, and the responsible party for implementing the correction.

Table 5. Clash Classification Matrix—Element Pairs, Resolution Pathways, and Responsible Parties.

Clash Category	Element Pair	Priority	Resolution Pathway	Responsible Party
Category 1	Truss guard member vs. rebar cages of permanent RC elements	High (3)	Rebar repositioning within structural design constraints, or truss member offset; escalated to structural engineer	Structural engineer + BIM coordinator
Category 2	Plywood formwork panels vs. truss and strut guard system	Medium (2)	Dynamo-based plywood cutting optimization; floor-by-floor panel profiles revised	BIM coordinator + site engineer
Category 3	Steel truss structure vs. permanent foundation network (pile caps, ground beams, retaining walls)	High (3)	Truss geometry revision or foundation element repositioning; escalated to structural designer for formal decision	Structural engineer

The three-tier resolution protocol operates as a severity classification cutting across, rather than replacing, the Category 1/2/3 element-pair classification in Table 5: a Category 1 or Category 3 clash requiring structural redesign is handled as Tier 1, a Category 2 clash is handled as Tier 2 via the Dynamo optimization workflow, and any clash within Categories 1 or 3 that is minor enough to require no model revision—a soft-clash clearance violation, for instance, is handled as Tier 3 regardless of which category it originated from. Tier 1 clashes, those involving structural redesign of either the truss guard system or the permanent RC elements, were escalated to the structural design team for formal assessment. The BIM coordinator prepared a clash report for each Tier 1 conflict, containing the clash location (in global coordinates), the element identifiers of the conflicting components, the construction phase, and a rendered view from the Navisworks model showing the geometric relationship of the conflicting elements. This report formed the basis for the structural engineer’s

decision on whether to adjust the truss geometry, modify the permanent element layout, or accept the clash with a field-implemented mitigation measure. Tier 2 clashes, formwork-to-truss conflicts, were routed to the Dynamo optimization workflow. These conflicts were resolved not by redesigning elements but by generating optimized cut geometries for the plywood panels at each affected floor level, allowing the panels to fit precisely around the truss profile without requiring excessive on-site trimming. Tier 3 items, minor clearance violations and soft clashes that do not require geometry changes were documented with field notes and assigned to the site engineer for monitoring during construction, without triggering a BIM model revision. Following all model revisions for a given construction phase, the updated NWC (NavisWorks Cache) files were reloaded into the Navisworks federated model, and the three clash detection tests were re-run. Resolution was considered complete for a given phase when the clash count for Tier 1 and Tier 3 category conflicts within that phase reached zero. Before starting construction activity in any phase zone, the target resolution rate was set at 100% for Category 1 and Category 3 clashes, and 95% for Category 2 clashes (permitting a small number of minor formwork adjustments to be addressed as a controlled on-site activity under supervision).

2.6. Plywood Cutting Optimization and Waste Management

Category 2 clashes—conflicts between the plywood formwork panels and the truss guard profile—were resolved not through structural redesign but through computational optimization of the panel cutting geometry at each floor level. Because the cross-sectional envelope of the truss guard system varies between basement levels due to the changing lateral load demand at each excavation depth, the cut-out profile required in the formwork panels is unique to each story. Without BIM-enabled optimization, the conventional on-site approach would have been to procure full standard-size plywood sheets and cut each panel to shape manually. This approach would lead to significant material waste and require skilled on-site carpentry at every floor level of the five-story building.

The optimization workflow was implemented in the Dynamo visual programming environment and linked to the Revit model, which contained both the floor-by-floor formwork geometry and the truss profile. For each basement level, Dynamo extracted the boundary geometry of all formwork panels as two-dimensional polylines. It computed the intersection of each panel boundary with the plan projection of the truss guard cross-section at that level. For each panel, the algorithm evaluated the proportion of the panel's total area that would be removed by this intersection with the truss profile. Where the required cutout exceeded 80% of the panel's area, the panel was excluded from the plywood scope entirely and reassigned to steel formwork or infill, on the basis that cutting a standard plywood sheet down to less than one-fifth of its usable area is not an efficient use of material regardless of nesting strategy. This substitution rule was applied uniformly across all five basement levels and was the primary mechanism by which the total plywood requirement was reduced relative to the unoptimized baseline (Section 3.3), rather than the nesting step described below. The resulting cut geometry for each remaining panel, inclusive of the 3 mm kerf and 15 mm edge/trim allowance defined in Section 3.3, was then nested algorithmically, panel by panel, within the available standard plywood sheet sizes sourced from the local market (typically 1220 × 2440 mm), with the algorithm tracking offcut and scrap area at each sheet to determine the total number of sheets required. The nesting algorithm evaluated multiple cutting configurations to minimize both the total number of sheets required and the residual offcut area, maximizing material utilization across the full basement formwork scope. This approach mirrors the multi-alternative nesting methodology used for steel sheet cutting optimization in Plus 2D. It extends the resource minimization philosophy from the temporary steel structure to the associated tem-

porary works. The outputs of the Dynamo optimization were a set of dimensioned cutting layout drawings for each floor level, suitable for direct use in the off-site pre-fabrication of the formwork panels. Pre-cutting panels to the correct profile before delivery to the site eliminates unplanned trimming, reduces on-site waste, and enables more predictable formwork installation schedules. These benefits are consistent with the waste-minimization objectives of BIM-enabled design-for-construction frameworks documented by Mohammad et al. [25]. The quantified waste-reduction outcomes—expressed as the percentage reduction in plywood offcut area relative to the unoptimized baseline—are reported in Section 3 as part of the project’s overall resource-optimization results. Table 6 summarizes the three resource optimization streams addressed in Phase 4, indicating the BIM platform used for each, the optimization objective, and the method used to quantify outcomes for comparative analysis.

Table 6. Summary of Resource Optimization Streams.

Resource Stream	BIM Platform	Optimization Objective	Quantification Method	Phase
Steel truss guard—cutting list optimization	Tekla Structures + Plus 2D	Minimize steel sheet offcut and scrap weight across 10+ nesting alternatives	Offcut weight (kg) vs. unoptimized baseline; % savings	Phase 2
Rebar—repositioning within truss constraint zone	Autodesk Revit + Navisworks	Resolve Category 1 clashes while maintaining code-compliant steel area; minimize design change impact	Clash count before and after resolution; rebar QTO comparison	Phase 4
Plywood formwork—panel cutting optimization	Revit + Dynamo	Minimize plywood offcut area per floor by nesting panel cut geometries within standard sheet sizes	Offcut area (m ²) per level vs. unoptimized baseline; total sheet count reduction	Phase 4

3. Results and Discussion

3.1. Steel Truss Cutting List Optimization

The cutting list optimization workflow described in Section 2.2 was applied to the complete steel truss guard structure, totaling approximately 18 tons of steel across all basement levels. The baseline waste rate of 4.5% is the contractor’s actual reported cutting waste (offcut plus scrap) from the project’s initial, unoptimized nesting arrangement—the layout that would have been used had the Tekla-exported member geometries been sent directly to fabrication against standard market sheet sizes, without the Plus 2D optimization step—rather than a theoretical or software-default estimate. For structural steel cutting generally, a waste rate in the 3–3.75% range is considered normal industry practice; the contractor attributed this project’s elevated 4.5% baseline to its heavy interaction with retained-soil geometry and the correspondingly high proportion of small, non-standard detail members in the truss guard, which reduce nesting efficiency relative to a typical steel frame. This 3–3.75% range reflects contractor and practitioner experience rather than a published industry standard, and is reported here as context rather than as a formally cited benchmark. Following optimization in Plus 2D, in which more than ten alternative nesting configurations were evaluated per sheet size, the total waste rate was reduced to 2.89% of the total steel mass—again the contractor’s measured figure from the optimized cutting list, not a projected estimate. Critically, the composition of this residual waste shifted entirely: offcut weight—material lost as unusable trim between nested parts—was reduced to zero, while scrap weight, consisting of unavoidable material losses inherent to cutting tolerances and sheet edge conditions, was contained to approximately 520 kg. Relative to the scale and geometric complexity of the truss guard structure, a 520-kg residual represents a negligible fraction of the total steel mass and approaches the practical lower bound of achievable waste for a non-standard temporary structure of this kind. This outcome is consistent with the QTO accuracy benchmarks established in the literature: Mohammed et al. [25] reported that BIM-enabled quantity takeoff reduces material estimation error to below 3%

relative to manual methods, and the present result demonstrates that this same threshold is achievable not only in estimation accuracy but in actual realized cutting waste when QTO is paired with industrial nesting optimization. The elimination of offcut waste specifically is significant given that the truss guard is a temporary system intended for full removal once the permanent frame reaches grade (Section 3.4); minimizing material consumption at the procurement stage directly reduces both the embodied cost of a structure that will not remain in the finished building and the volume of waste requiring disposal or recycling at the point of dismantling. Table 7 summarizes the optimization results in Plus 2D. A few samples of the sheet arrangement is also shown in Figure 7.

Table 7. Summary of Optimization Results.

Thickness	10	15	20	20	25	30	35
Saw Width	5	5	4	5	0	5	5
Number of Layouts	42	12	159	3	42	27	24
Number of Stock Used	10	2	18	1	10	5	7
Total Utilization	97.65%	96.09%	95.23%	96.90%	89.45%	91.00%	88.00%
Total Parts Required	90.38	20.23	74.31	0.12	24.32	5.9	2.7
Total Parts Nested	90.38	20.23	74.31	0.12	24.32	5.9	2.7
Reusable Offcuts	0	0	0	0	0	0	0
Total Stock Area	9.96	1.08	42.00	0.74	4.41	3.24	5.10
Total Part Area	8.37	0.90	36.60	0.69	3.87	2.68	4.31
Offcut Area	0	0	0	0	0	0	0
Scrap Area	1.59	1.18	15.40	0.15	1.54	1.56	1.79
Total Part Weight	1553.76	252.72	11,793.60	230.26	1719.90	1516.32	1392.30
Total Offcut Weight	0	0	0	0	0	0	0
Total Scrap Weight	24.82	6.35	336.87	3.69	52.73	22.47	85.77
ScrapWt/PartWt	1.60%	2.51%	2.86%	1.60%	3.07%	1.48%	6.16%
Length	12,000	6000	12,000	12,000	6000	6000	6000
Width	1500	1500	2000	2000	2000	2000	2000
Total stock weight (kg)	18,458.9						
Total scrap + offcut weight (kg)	532.7						
cutting waste loss (%)	2.89%						

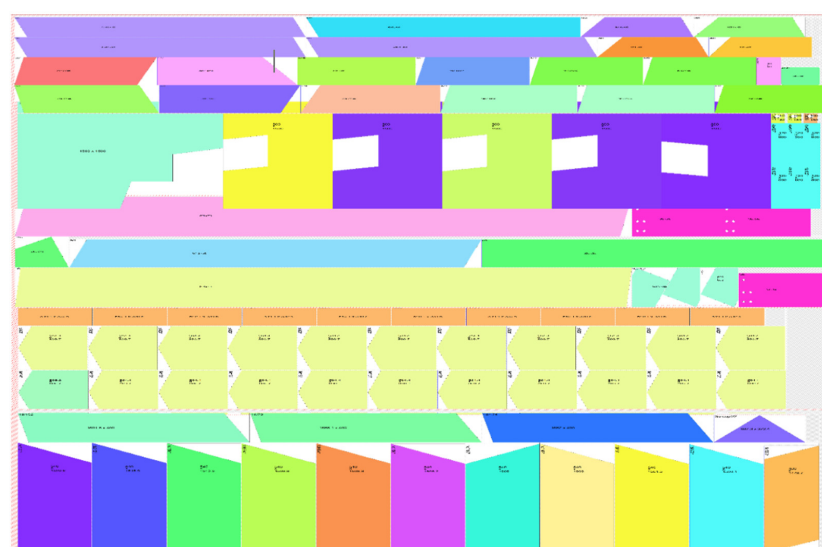


Figure 7. Example of sheet arrangement & layout optimization of steel sheets.

As Table 7 shows, the 2.89% overall cutting-waste loss is driven almost entirely by scrap rather than offcut across every plate thickness, with the 20 mm and 25 mm thicknesses

showing the highest scrap-to-part-weight ratios; the sheet layout underlying this result is illustrated in Figure 7.

3.2. Clash Detection and Resolution in the Truss-Rebar Interaction Zone

Modeling of the interaction zone between the temporary truss guard structure, the rebar cages, and the permanent vertical elements (Section 2.5) confirmed the scale challenge anticipated in the methodology. The federated clash detection run in Navisworks returned raw clash counts ranging from 5712 to 7289 across the five basement levels (B1–B5), for a combined total of 33,547 raw clashes before deduplication; Table 8 reports the full per-level breakdown, including duplicate flags removed and the resulting status distribution. At this volume, manual review and categorization of clashes on a story-by-story basis across the full five-level basement scope proved impractical, as illustrated for a representative story in Figure 8; the sheer number of flagged conflicts made it impossible to reliably track resolution status, assign responsibility, or distinguish genuine design conflicts from geometrically trivial or duplicate flags using conventional clash-list review.

Table 8. Clash Categorization Results by Basement Level (Raw, Duplicate, and Status Breakdown) for category 1 & 3.

Level	Raw Clashes	Duplicates Removed	Unique Clashes	Active	Reviewed	Approved	Resolved	New/Unclassified
B1	7289	532	6757	222	147	1569	5270	81
B2	7012	750	6262	213	141	1509	5071	78
B3	6901	694	6207	210	139	1485	4990	77
B4	6633	451	6182	202	133	1428	4796	74
B5	5712	443	5269	174	115	1229	4130	64
Total	33,547	2870	30,677	1021	675	7220	24,257	374

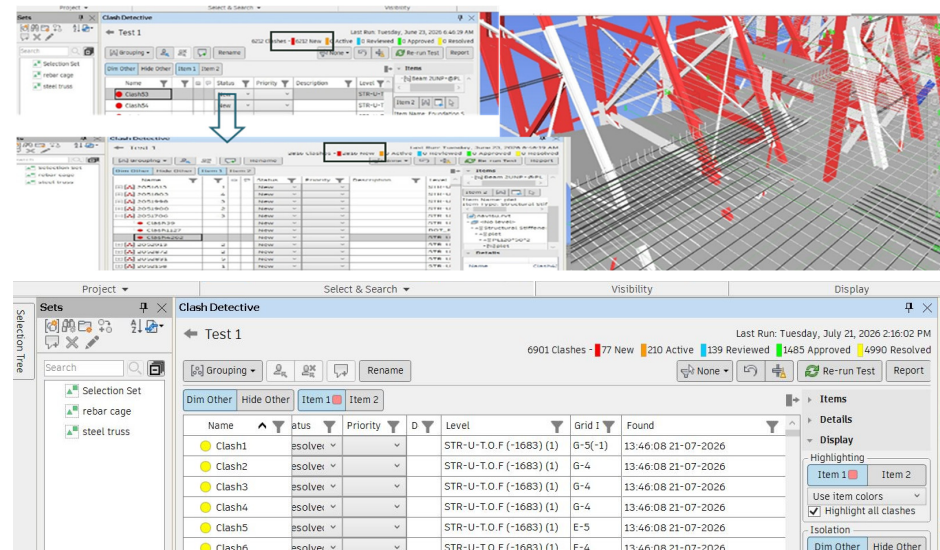


Figure 8. Basic Clash Detection for a basement story.

Within Table 8, clash status is defined as follows: a clash is classified as New/Unclassified when it has been detected but not yet assigned to Category 1, 2, or 3; as Active, once categorized but pending review by the responsible party; as Reviewed, once the responsible party has assessed the clash and determined its resolution pathway (structural redesign, Dynamo-based cutting optimization, or field-level mitigation); as Approved, once that determination has been formally confirmed; either as a genuine conflict requiring a specific corrective action, or as a false positive requiring no action; and as Resolved, once the corresponding model revision has been implemented and the clash cleared on the subsequent Navisworks re-run.

To address this, a parameter-driven grouping strategy was implemented in place of element-by-element review. A defined set of parameters was first established directly on the truss and rebar elements within Revit, encoding attributes such as construction phase, element category, and interaction-zone membership. These parameters were then accessed through Dynamo, which used them to generate structured selection sets corresponding to logical groupings of elements; for example, all rebar within the 300 mm interaction envelope of a given truss segment, or all members belonging to a single floor level. Clashes were grouped by interaction-zone involvement using the same three-category classification established in Table 5: Category 1 (truss guard vs. rebar cages), Category 2 (formwork vs. truss/strut system), and Category 3 (truss vs. foundation network). Seven selection sets were defined by element type, using the POS (position) numbering already assigned to structural and steel elements in Revit and Tekla: (1) floor slab main rebar cage, (2) floor slab top and bottom additional reinforcement, (3) wall reinforcement, (4) column reinforcement, (5) steel truss members, (6) steel struts, and (7) smaller connection plates within the truss. These seven sets were applied independently to each of the five basement levels, yielding 33 discrete coordination groups, not exactly 35 groups, as the steel struts (set 6) had no interaction with the floor slabs at B1 and B3 and therefore returned no clashes at those levels. This categorization served a coordination purpose beyond triage: each category was routed to the team responsible for the corresponding decision—clashes exceeding the designer-defined rebar displacement limit were sent to the structural design team, while clashes involving the truss guard system were returned to the geotechnical modelers. These Dynamo-generated selection sets were exported back into Navisworks, where they replaced the default, ungrouped clash list with a structured set of clash groups aligned to the project's actual coordination logic. This restructuring transformed the clash detection output from an undifferentiated list of over 30,000 raw flags (Table 8) into a manageable set of grouped conflicts that could be reviewed, prioritized, and assigned by category, team, and phase, consistent with the three-category resolution protocol and clash classification matrix described earlier. Once grouped in this way, clashes were identified and resolved more efficiently than would have been possible under direct, unstructured review, as illustrated in Figure 9; review and processing time were reduced by this restructuring, though the reduction was not tracked against a quantified baseline and is reported here qualitatively. As a result of proper categorization, clashes were grouped more efficiently and the clash classification matrix goals were achieved as summarized in Table 5.

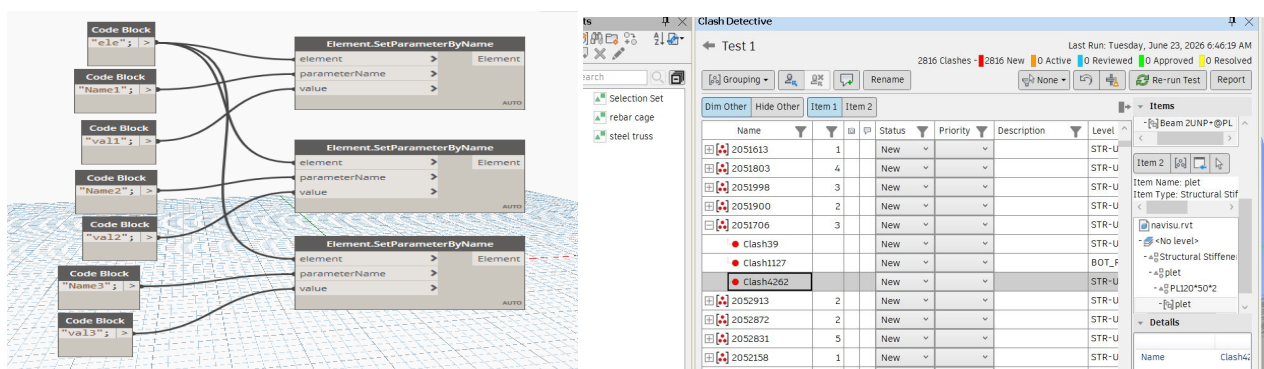


Figure 9. Parameter and set definition in Dynamo and clash count reduction.

Compared to recent research [12,29], the present case differs in that the semantic structuring was achieved not through a dedicated machine-learning filter but through a parametric workflow native to the Revit–Dynamo–Navisworks toolchain—suggesting that for projects of this scale, well-defined parameter taxonomies and visual programming logic

can deliver much of the practical benefit of automated filtering without requiring a separate machine-learning layer. Because the truss guard geometry is defined after the permanent structural layout, as noted in Section 3.3, the clash landscape is inherently reactive and prone to exactly the kind of volume explosion observed here, making upfront parameter definition a practical necessity rather than an optional refinement.

3.3. Plywood Formwork Cutting Plan Optimization

The formwork cutting optimization workflow (Section 2.6) used the floor-by-floor truss interaction geometry exported from Navisworks into Dynamo to generate optimized cut profiles for the plywood panels at each basement level. The unoptimized baseline of approximately 3350 square meters is a model-based estimate, not a contractor procurement record: it was calculated directly from the Revit model geometry and the project schedule, reflecting a typical floor area of approximately 1800 square meters per level under standard panel procurement without geometry-informed nesting. Following optimization, the required plywood area was reduced to approximately 2850 square meters; unlike the baseline, this optimized figure was validated against project delivery, it is the quantity the contractor subsequently procured and used to complete the formwork scope within the project timeline, confirming that the model-based optimization translated into an actual, realized material reduction rather than a theoretical saving only. Table 9. are the detailed parameters defined for the optimization layout.

Table 9. Detailed parameters defined for the optimization layout.

Parameter	Value	Description
Kerf	3 mm (0.003)	Added to both edges of every cut piece's width and height before sourcing stock
Edge/Trim Allowance	15 mm	Added on top of kerf, also to both edges—represents field-fit clearance against the irregular truss boundary.
Minimum/Reusable Offcut	0.25 m ² and ≥ 0.30 m in its shorter dimension	An offcut has to clear both thresholds to go back into inventory for reuse; anything smaller is written off as scrap immediately.

Due to the limitations of using Dynamo as the direct coding platform, it was best to draft the core optimization logic as a standalone Python 3.14 script, then wrap it into the .dyn JSON structure with correct node wiring in the visual environment. The code draws a polygon based on the plywood sheets overall layout and tries to minimize the overall area of the polygon under different arrangement and layout. Given the plywood sheets dimension (1.22 m $\times$ 2.44 m), the number of required sheets can be easily deduced. Figure 10 shows a schematic layout of plywood sheets for one story after deducting the openings (e.g., ramp, staircase and elevator opening). Optimization results are shown in Table 9.

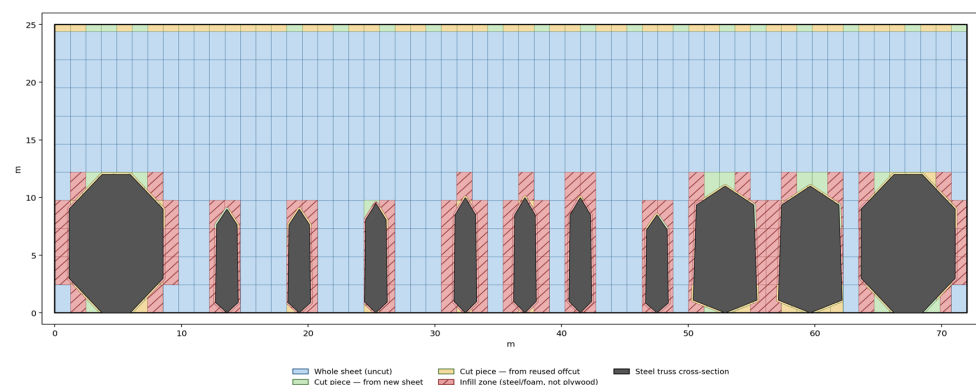


Figure 10. Schematic layout of plywood sheets.

Applying this nesting logic across all five basement levels produced the level-by-level and total plywood savings summarized in Table 10.

Table 10. Summary of applying the nesting logic across all five basement levels produced the level-by-level and total plywood savings Results.

Schedule:		Formwork (Plywood Panels)—Material Takeoff					
Phase:		Basement Excavation—Truss Guard Shoring (Phases 1–5)					
Discipline:		Structural—Temporary Works					
Source		Revit (Federated) + Dynamo Nesting Script					
Sheet Size:		1.22 m × 2.44 m (standard market stock)					
Level	Truss Guard Profile Zone	Floor Plan Area (m ²)	Baseline Panel Req. (m ²) (Unoptimized)	Optimized Panel Req. (m ²) (Dynamo Nested)	Area Saved (m ²)	Reduction (%)	Std. Sheets Req. (EA)
B1	Upper Basement—Wide Bay	1800	690	590	100	14.5%	199
B2	Transition Zone—Tapered Truss	1800	680	575	105	15.4%	194
B3	Mid Basement—Standard Bay	1800	660	560	100	15.2%	189
B4	Lower Transition—Brace Zone	1800	660	565	95	14.4%	190
B5	Base Slab—Narrow Bay	1800	660	560	100	15.2%	189
TOTAL		9000	3350	2850	500	14.9%	961
OPTIMIZATION SUMMARY (Dynamo Nesting vs. Unoptimized Baseline)							
Baseline Plywood Requirement (Unoptimized) (m ²)						3350	
Optimized Plywood Requirement (Dynamo Nested) (m ²)						2850	
Total Area Saved (m ²)						500	
Percentage Reduction (%)						14.9%	
Standard Sheets Required (1.22 m × 2.44 m)						961	

Applying the >80% cutoff substitution rule described in Section 2.6, which reassigned panels requiring extensive truss-profile cutting to steel formwork or infill, reduced the total plywood requirement to approximately 2850 square meters, a reduction of roughly 500 square meters, or approximately 15% of the baseline estimate. The resulting material balance for the retained plywood scope—2860.8 m² of stock area purchased against 2850.0 m² of net part area—yields 10.8 m² of combined offcut and scrap, approximately 0.4% of stock area. The subsequent panel-by-panel nesting of the retained plywood scope achieved near-total material utilization (approximately 99.6%), since the substitution rule had already removed the panels that would otherwise have generated the greatest cutting waste. This reduction translates directly into procurement and cost savings, since fewer standard sheets need to be purchased to cover the same formwork scope, while also reducing the volume of site-generated offcut that would otherwise result from manual, on-site trimming of standard panels to fit the truss profile at each level. Because the truss guard's cross-section changes at every story, a static or manually derived cutting plan would have required re-deriving the formwork boundary by hand at each of the five basement levels, whereas the automated export of federated clash and interaction-zone geometry allowed the optimization to be applied consistently and rapidly across the full basement scope without re-modeling effort at each level.

3.4. Rebar Consumption Optimization in the Truss-Rebar Interaction Zone

The designers' initial bar bending schedule, prepared from the early structural drawings prior to BIM-based coordination with the truss guard system, estimated a total rebar consumption of approximately 1100 tons of steel for the project. Against the building's total built area of approximately 15,000 square meters, this corresponds to a unit consumption of approximately 73 kg/m², a figure already on the higher side of the typical reinforcement intensity range for a commercial building of this type. When the structural drawings were subsequently developed into fabrication-level shop drawings, the bar bending schedule increased to a total of 1203 tons—a 9% increase over the original estimate. This escalation was traced largely to the rebar–truss interaction zone (Section 2.5), where the as-built geometry of the truss guard system, the required clearances, and the resulting bar repositioning and supplementary reinforcement at clash locations added substantial steel weight that the early, pre-coordination schedule had not anticipated.

With the objective of recovering part of this increase, the rebar and truss guard models were integrated within the federated Revit–Navisworks environment and the categorized clash-detection workflow described in Section 2.5 was applied specifically to the rebar–truss interaction zone. Using the Dynamo-generated selection sets to isolate and group the Category 1 clashes (Table 5), the structural team was able to systematically review bar positions, hook orientations, and lap splice locations against the truss geometry, identifying instances of conservative or redundant reinforcement that had been added in the shop-drawing stage to resolve clashes generically rather than through targeted repositioning. The elements affected were concentrated in the wall and column reinforcement cages within the truss guard interaction envelope across the five basement levels, where the shop-drawing stage had generically added supplementary bars and closer spacing at every detected clash location rather than repositioning bars around the truss geometry on a case-by-case basis. Once the design team reviewed the grouped clashes and issued revised bar-placement directions, the affected elements were remodeled in Revit and new shop drawings were produced reflecting the targeted revisions. Figure 11 shows the Revit-generated bar schedule for a representative wall reinforcement group before and after this remodeling: the bar count for this group is unchanged (147 bars), but the total reinforcement weight is reduced from 16,297 kgf to 15,894 kgf (a reduction of approximately 403 kgf, or 0.4 tons, at this single-element scale) as redundant bars were removed and remaining bars repositioned around the as-built truss geometry rather than duplicated at each clash point. A full element-by-element accounting of all affected walls and columns across the entire interaction zone is beyond the scope of this paper; the example in Figure 11 is presented as illustrative of the mechanism underlying the aggregate 51-ton reduction rather than as a complete quantity takeoff. ACI 318 was the design code targeted throughout the project, and the revised reinforcement arrangements were checked by the structural design team against its applicable strength and detailing provisions before being incorporated into the updated shop drawings; this review was conducted and documented internally by the project's design team, but did not include a separate, formal sign-off by an external engineer of record or third-party peer reviewer. Following this review and the associated bar repositioning and substitution, the total rebar consumption was reduced to approximately 1152 tons—recovering roughly 51 tons of the 103-ton increase, or approximately 49.5% of the escalation introduced at the shop-drawing stage, while still containing the net increase relative to the original 1100-ton estimate.

(a) Before clash-driven review

Ø16	Rebar Bar: Ø16	8	12000 mm	8	1.58 kgf/m	152 kgf
Ø10	Rebar Bar: Ø10	20	13200 mm	20	0.60 kgf/m	158 kgf
Ø16	Rebar Bar: Ø16	43	2400 mm	43	1.58 kgf/m	328 kgf
Ø16	Rebar Bar: Ø16	45	2400 mm	45	1.58 kgf/m	172 kgf
Ø10	Rebar Bar: Ø10	33	9000 mm	33	0.60 kgf/m	178 kgf
Ø16	Rebar Bar: Ø16	47	2400 mm	47	1.58 kgf/m	179 kgf
Ø10	Rebar Bar: Ø10	25	12000 mm	25	0.60 kgf/m	180 kgf
Ø16	Rebar Bar: Ø16	13	10000 mm	13	1.58 kgf/m	206 kgf
Ø10	Rebar Bar: Ø10	29	12000 mm	29	0.60 kgf/m	208 kgf
Ø16	Rebar Bar: Ø16	44	3000 mm	44	1.58 kgf/m	210 kgf
Ø10	Rebar Bar: Ø10	40	12000 mm	40	0.60 kgf/m	288 kgf
Ø10	Rebar Bar: Ø10	41	12000 mm	41	0.60 kgf/m	295 kgf
Ø16	Rebar Bar: Ø16	104	2400 mm	104	1.58 kgf/m	397 kgf
Ø16	Rebar Bar: Ø16	238	2400 mm	238	1.58 kgf/m	908 kgf
Grand total: 147						16297 kgf

(b) After remodeling and bar repositioning

Ø16	Rebar Bar: Ø16	8	12000 mm	8	1.58 kgf/m	152 kgf
Ø10	Rebar Bar: Ø10	20	13200 mm	20	0.60 kgf/m	158 kgf
Ø16	Rebar Bar: Ø16	43	2400 mm	43	1.58 kgf/m	328 kgf
Ø16	Rebar Bar: Ø16	45	2400 mm	45	1.58 kgf/m	172 kgf
Ø10	Rebar Bar: Ø10	33	9000 mm	33	0.60 kgf/m	178 kgf
Ø16	Rebar Bar: Ø16	47	2400 mm	47	1.58 kgf/m	179 kgf
Ø10	Rebar Bar: Ø10	25	12000 mm	25	0.60 kgf/m	180 kgf
Ø16	Rebar Bar: Ø16	13	10000 mm	13	1.58 kgf/m	206 kgf
Ø10	Rebar Bar: Ø10	29	12000 mm	29	0.60 kgf/m	208 kgf
Ø16	Rebar Bar: Ø16	44	3000 mm	44	1.58 kgf/m	210 kgf
Ø10	Rebar Bar: Ø10	41	12000 mm	41	0.60 kgf/m	295 kgf
Ø16	Rebar Bar: Ø16	104	2400 mm	104	1.58 kgf/m	397 kgf
Ø16	Rebar Bar: Ø16	238	2400 mm	238	1.58 kgf/m	908 kgf
Grand total: 147						15894 kgf

Figure 11. Revit-generated bar schedule for a representative wall reinforcement group in the truss-rebar interaction zone, before (a) and after (b) clash-driven review and remodeling. Bar count is unchanged (147 bars); total weight is reduced from 16,297 kgf to 15,894 kgf.

The 51-ton project-wide reduction is not attributable solely to the truss-rebar interaction-zone review described in Section 2.5. Table 11 disaggregates the reduction by zone: within the five basement levels and the foundation; the scope directly covered by the federated clash detection and Dynamo-based selection-set review; rebar consumption was reduced by 32.8 tons, from 661.8 to 629.0 tons.

Table 11. Aggregate changes before and after optimizing consumption.

Level	Before Optimization (Tons)	After Optimization (Tons)	Reduction (Tons)
B1	92.6	85	7.6
B2	85.4	83.3	2.1
B3	83.2	79.1	4.1
B4	81.5	73	8.5
B5	73.7	68.6	5.1
Foundation	245.4	240	5.4
Basement + Foundation	661.8	629	32.8
Above-Ground Stories (Independent shop drawing review)	541.2	523	18.2
Project Total	1203	1152	51.0

The remaining 18.2 tons of the total reduction occurred in the fourteen above-grade stories, which fall outside the truss guard's interaction zone and were therefore not subject to the clash-driven review process; this portion of the saving instead resulted from an independent shop-drawing optimization review conducted separately for the above-grade structural frame. The basement and foundation reduction of 32.8 tons is therefore the figure directly attributable to the BIM-federated, clash-driven workflow that is the focus of this study, while the above-grade reduction of 18.2 tons reflects a parallel, conventional design-review process outside the present study's coordination methodology.

4. Conclusions

Across all four optimization streams, the results demonstrate that the value of the BIM-based workflow lay less in any single software tool and more in the data continuity

established across the toolchain. For example, geometry generated in Tekla informed steel nesting in Plus 2D. Additionally, rebar and truss geometry modeled in Revit, structured through Dynamo, and federated in Navisworks made a 6000-clash dataset tractable. The same Navisworks–Dynamo workflow that resolved Category 2 clashes was reused to optimize plywood-cutting. Furthermore, the Category 1 clash groups generated by that pathway were subsequently mined to recover 51 tons of over-specified reinforcement from the shop-drawing bar-bending schedule. This pattern directly addresses the research gap identified in Section 1.5. Instead of treating clash detection, quantity takeoff, and resource optimization as separate functions applied independently to the permanent structure, the present workflow used the outputs of one stage as the structured input to the next. This is done within a single federated model encompassing both the temporary truss guard system and the permanent reinforced concrete frame. Taken together, the results for steel, rebar, and plywood indicate that the principal benefit of integrating temporary and permanent systems into a single federated model extends beyond clash avoidance. However, it translates directly into measurable reductions in the quantities of materials procured for both systems. This reuse is the central empirical finding of the present study and forms the basis for the discussion that follows.

Key Achievements at a Glance:

- Steel waste cut to below 3%: down from a 4.5% baseline across ~18 tons of steel, with offcut waste eliminated entirely and scrap contained to ~500 kg.
- Over 6000 clashes made tractable: a parameter-driven, Dynamo-generated selection-set methodology converted an unmanageable single-story clash count into a structured, resolvable dataset.
- Plywood demand reduced by ~15%: from 3350 m² to 2850 m², via Dynamo-based nesting of panel cut-outs against the truss guard's floor-by-floor profile.
- In total, 51 tons of over-specified rebar recovered: clawing back 49.5% of the 103-ton shop-drawing escalation through targeted review of the truss-rebar interaction zone.
- One clash dataset, three optimization streams: the categorized clash data generated for coordination purposes was reused, without re-modeling, to drive both the plywood and rebar optimization results above—the central finding of this study.

5. Limitation and Future Work

The data-reuse pattern identified here suggests several directions for further work. First, future studies could test whether the categorized clash dataset generated for a truss-rebar interaction zone can be reused for additional material streams beyond the three examined here (steel, plywood, rebar). This could include MEP routing or temporary bracing hardware to establish how many independent optimization tasks a single federated clash run can practically support. Second, because the rebar recovery in this study achieved only partial restitution of the shop-drawing escalation, future work could examine whether earlier—rather than retrospective—integration of the truss-rebar interaction zone into the bar bending schedule process would close more of that gap, and could quantify the coordination cost of doing so against the 51-ton saving achieved here.

The findings presented in this study are derived from a single case-study project—a fourteen-story building with a five-level basement, a truss-based guard shoring system, and a specific software toolchain (Tekla Structures, Revit, Navisworks, and Dynamo). As with any single-case methodology, the quantitative outcomes reported here, should be interpreted as evidence that the proposed workflow can generate these categories of savings, rather than as fixed benchmarks generalizable to all high-rise excavation projects. Moreover, the structural performance, deformation, stability, and staged removal checks are not presented in this study and remain out of the scope of this research. Several project-

specific factors are likely to influence the magnitude, and potentially the direction, of these outcomes if the workflow were applied elsewhere.

The workflow presented here also depends on the simultaneous use of five software platforms: Tekla Structures, Plus 2D, Autodesk Revit, Navisworks Manage, and Dynamo. Each of them requires its own license, training investment, and dedicated modeling or coordination expertise. For large contractors and projects of the scale examined in this study, this toolchain cost is readily absorbed within the broader project budget. However, for smaller firms or lower-value projects, the combined licensing and staffing overhead required to maintain proficiency across five platforms may pose a meaningful barrier to adoption, regardless of the workflow's technical benefits. Future work could examine whether a reduced toolchain or open-source, lower-cost alternatives to one or more of these platforms can reproduce a comparable share of the reported savings.

From a practical standpoint, the workflow is most directly transferable to contractors and BIM coordination teams already operating a Revit–Navisworks–Dynamo environment on high-rise projects with basement excavations of comparable scale, where the parameter-driven clash-grouping strategy can be implemented without new software procurement. For teams using a different authoring or coordination platform, the underlying principle—encoding phase, category, and interaction-zone attributes directly on model elements so that a visual-programming layer can generate structured clash groups—is platform-agnostic and could in principle be reproduced with equivalent scripting environments (e.g., Grasshopper for Rhino-based workflows, or the Navisworks API directly), although this transferability has not been tested here and would require separate validation. Projects where the temporary-works subcontractor delivers shoring drawings late, or in a non-BIM format, would need to establish this data exchange as a contractual requirement rather than a purely technical add-on.

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