An Algorithmic Framework for the Automated Synchronization of Multi-Domain BIM Representations via Canonical Clustering

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Abstract

Conventional synchronization between physical and structural BIM representations typically relies on merging adjacent nodes by altering element locations, which causes challenges for bidirectional interoperability. This discrepancy arises from the fundamental domain difference between high-fidelity physical representations and frame-based analytical models, often necessitating labor-intensive manual corrections. To address this challenge, this study proposes an automated computational method based on canonical clusters—an abstraction comprising a master node, slave nodes, and rigid linkage elements. Unlike conventional node merging approaches that alter building geometry, canonical clustering automates the synchronization between physical and structural models while establishing the topological connectivity required for structural analysis. By decoupling the analytical topology from the physical geometry, the method preserves the data integrity required for downstream automated construction processes. Validation using a reinforced concrete frame structure with misaligned joints demonstrated a seamless bidirectional workflow: the forward-converted analytical model completed structural analysis without errors, and the automated backward conversion successfully transferred a newly added set of beams and columns to the BIM model with 100% accuracy. This research provides a robust framework for managing multi-representation BIM data and automating iterative design-to-analysis cycles. Future work includes extending the method to steel and timber joints and exploring nonlinear joint modeling within the canonical clusters.

Keywords –

BIM; Interoperability; Data Exchange; Interfacing Technology; Model Synchronization; Structural Model.

1 Introduction

BIM interoperability refers to the capability of project stakeholders to exchange, interpret, and reuse digital information throughout building design, construction, and asset operation. During the design phase, in which project execution is conducted predominantly within software environments, the ability to reliably transfer data between BIM authoring platforms and domain-specific applications is essential, and structural engineering is no exception. Although more advanced and flexible finite element modeling techniques exist, most structural analyses continue to rely on simplified stick-and-node representations, referred to as frame-based analytical models in this paper. In these models, structural members are idealized as one-dimensional elements whose connectivity must be defined explicitly at shared nodes to ensure a valid topological formulation. This modeling approach fundamentally differs from model representations by BIM authoring tools such as Revit [1], where elements are volumetric and connectivity can be expressed through surface contact rather than precise nodal coincidence (Figure 1).

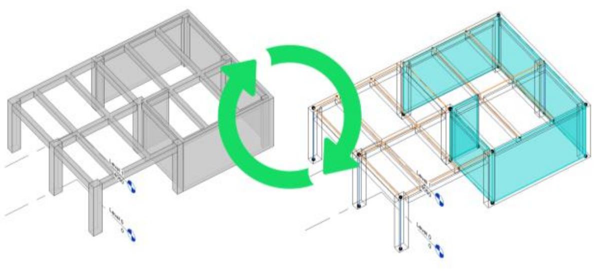

Figure 1. Volumetric BIM model (left) must be converted to frame-based analytical model (right) for structural analysis

This fundamental disparity in model definition principles introduces an inherent incompatibility between physical BIM models and frame-based analytical models. As a result, interoperability between BIM platforms and structural analysis environments cannot be achieved through direct model exchange alone. Instead, a model synchronization process is required, in which additional information must be generated, inferred, or reinterpreted to transform volumetric, object-based BIM representations into node-consistent analytical models suitable for structural analysis [2]. Such a requirement represents a persistent and nontrivial challenge in BIM-to-structural model interoperability.

An illustrative example of this model synchronization challenge arises in reinforced concrete (RC) building models. In practice, the centerlines of RC beams and columns are often offset from design grids to accommodate improved constructability or to create clearances for non-structural elements, resulting in slight misalignments at intersections. While such geometric configurations are valid in volumetric BIM element representations, converting such a BIM model into a frame-based analytical model introduces nodal inconsistencies (Figure 2).

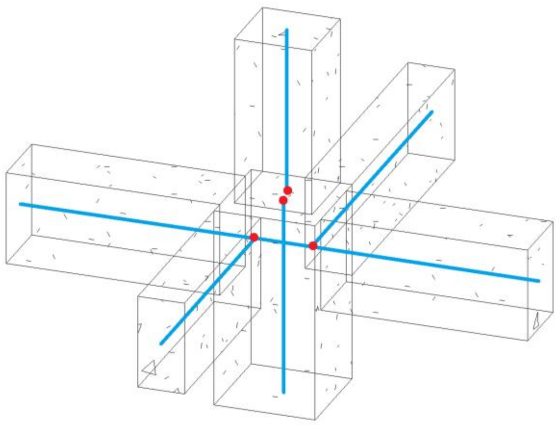

Figure 2. RC beams and columns deviating away from design grids result in nodal misalignment in frame-based analytical models

To resolve these nodal misalignments, BIM platforms and model interfacing software typically offer automated alignment functionalities where the element locations are adjusted in order to merge (or snap) the nodes that are within a certain proximity. Although this rule-based model adjustment method is simple to implement, robust, and computationally efficient, it comes with some crucial limitations. First, rule-based model adjustment can reduce model accuracy because the locations of elements are modified to enforce nodal alignment in the frame-based analytical model. These location adjustments alter the original geometric relationships defined in the BIM model, meaning that the resulting frame-based analytical model no longer accurately represents the actual building geometry. Second, converting the analytical model back to a BIM model becomes difficult once node alignment is achieved through snapping or merging operations. During this process, the precise location information of the original BIM elements is lost, and the frame-based analytical model no longer maintains a clear geometric correspondence with volumetric BIM representation. This issue is further exacerbated when new structural elements are introduced during structural analysis, since the locations of these new elements are defined relative to the adjusted analytical model rather than the original BIM geometry, making reliable reverse model synchronization increasingly problematic.

To overcome these limitations, this study proposes a bidirectional BIM-to-structural model synchronization method based on canonical clustering. In the proposed approach, instead of merging nodes at element intersections by adjusting element locations, nodes that are geometrically close are grouped and redefined as a canonical cluster. Within each cluster, the nodes are connected to one another to form a structurally bound network of nodes. This preserves the original element locations defined in the BIM model while enforcing the connectivity required for frame-based analytical models, thereby enabling consistent forward and reverse model synchronization.

2 Background

This section reviews existing approaches to BIM-to-structural model synchronization. First, current practices implemented in commercial software are examined to highlight the prevalence and limitations of node merging-based synchronization. Subsequently, related research literature is reviewed to clarify prevailing research directions and to identify gaps in addressing frame-based analytical model synchronization from physical BIM models.

2.1 Model Synchronization in Commercial Software

Existing BIM-to-structural model synchronization methods are largely based on the node merging approach. BIM authoring platforms such as Revit provide built-in functionality to generate frame-based analytical models directly from BIM geometry; however, this conversion process relies primarily on simple rules that merge nearby nodes by adjusting element locations to enforce nodal connectivity. While this approach is straightforward and efficient, it offers limited control over how geometric discrepancies are resolved. In addition, users are required to determine appropriate node merging rules and tolerance values for the target model through trial-and-error; ill-defined merging conditions can lead to model discontinuity and structural instability (Figure 3).

More advanced BIM data exchange platforms and structural analysis tools, such as Speckle [3] and SOFiSTiK [4], provide additional options for handling model exchange and analytical model preparation, including conditional tolerance and alignment settings. Nevertheless, the underlying principle remains the same, as these methods still resolve connectivity by merging nodes rather than preserving original element locations. As a result, the fundamental limitations associated with node merging persist, particularly with respect to bidirectional model synchronization.

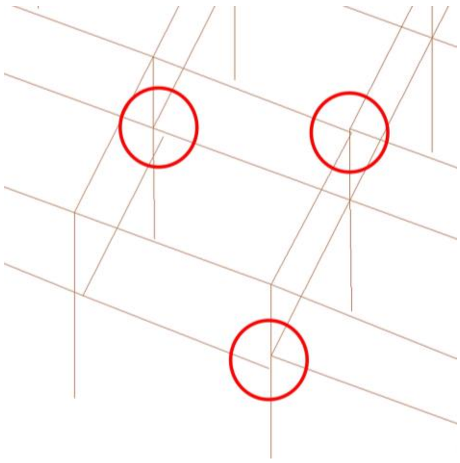

Figure 3. Ill-defined node merging settings can lead to incorrectly merged element intersections

2.2 Model Synchronization in Literature

A substantial portion of existing research has focused on converting BIM models into more detailed mesh-based finite element models (FEM) intended for high-fidelity structural simulation. For example, Ursini et al. present a scan-to-BIM workflow that focuses on the generation of detailed finite element models of built heritage, relying on geometric reconstruction and mesh-based modeling [5]. Recent work by Rudenko and Petryna targets BIM-driven generation of finite element models with elements of varying dimensionality and complexity, highlighting IFC-based enrichment strategies to support solid, shell, and beam elements within FEM environments [6].

Although node merging in frame-based analytical modeling is occasionally acknowledged in recent studies as a necessary preprocessing step for establishing frame-based analytical models, it is typically treated as an auxiliary operation rather than a subject of methodological innovation [7], [8], [9]. Across these works, node merging is described primarily as a practical necessity for enabling data transfer, without proposing alternative representations or mechanisms that could mitigate its known limitations.

3 Proposed Method

3.1 Canonical Clustering and Linkage Elements

The first step in defining the components that constitute a canonical cluster is to define where each joining element ends. A commonly accepted approach in structural modeling is to use the locations where each element's cross-section changes shape as the termination point for that element [10]. For a common RC joint, this leaves a block in the middle of the joining elements (Figure 4 - left). In this proposed method, this block is replaced by a canonical cluster (Figure 4 - right). The same approach can be applied to a steel joint where panel zones are replaced by canonical clusters.

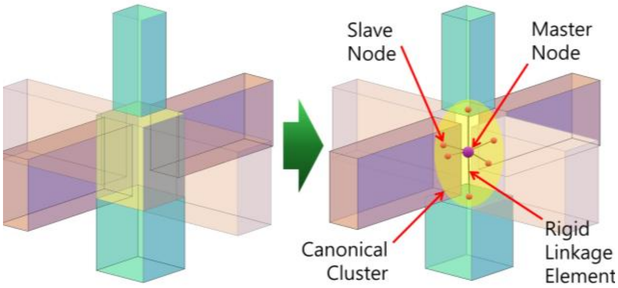

Figure 4. For an RC joint, the joint block (left) is replaced by a canonical cluster (right) defined by a master node, a set of slave nodes, and linkage elements

More formally, a canonical cluster can be defined as a tuple:

$$C = (m, S, E, \phi) \tag{1}$$

where,

- $m \in \mathbb{R}^3$ is the master node,
- $S = \{x_1, \ldots, x_n\} \subset \mathbb{R}^3$ is a finite set of slave nodes, corresponding to locations where structural element cross-sections change,
- $E = \{(m, x) | x \in S\}$ is the set of linkage elements,
- $\phi: E \to K$ assigns each linkage element a constraint type, where K is the space of admissible mechanical relations.

The master node is defined as the Euclidean centroid of the slave nodes:

$$m = \frac{1}{|S|} \sum_{x \in S} x \tag{2}$$

By representing joints using canonical clusters, the proposed method eliminates the need for element relocation during model synchronization. The combination of a master node and internal linkage elements forms an assembly that explicitly accommodates geometric separations between joining members while still enforcing the topological connectivity required for frame-based analytical models. An additional advantage of this representation is the flexibility it provides in tailoring joint behavior to different analysis objectives. For linear elastic analysis, the linkage elements within a canonical cluster can be defined as rigid elements with fixed connectivity, allowing the cluster to behave as a rigid joint block. For nonlinear analysis where joint deformation is expected, the proposed method allows plastic hinges, springs, or other nonlinear components to be introduced within the cluster, enabling the explicit modeling of joint deformation, stiffness degradation, and hysteretic behavior [10]. As a result, the canonical cluster serves not only as a geometric reconciliation mechanism but also as a versatile analytical abstraction that supports multiple levels of structural idealization within a unified synchronization method consistent with common structural joint modeling practices.

3.2 Implementation of Model Synchronization Using Canonical Clustering

The proposed bidirectional synchronization method was implemented as a Python-based application utilizing the IfcOpenShell library for IFC file manipulation and geometry extraction. The implementation consists of two primary synchronization pathways: a forward path that transforms BIM geometry (Revit model [1]) into frame-based analytical models (Midas GEN [11]), and a reverse path that propagates analytical modifications back to the original BIM representation (Figure 5).

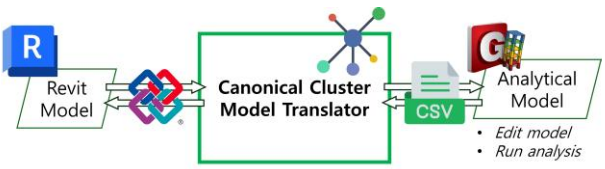

Figure 5. Bidirectional model synchronization using canonical cluster model translator

3.2.1 Forward Synchronization: BIM Model to Structural Model

The forward synchronization process begins with parsing the IFC file exported from Revit to extract structural elements classified as IfcColumn and IfcBeam entities. For each element, the geometric representation is processed using world coordinate transformation to obtain the mesh vertices in a consistent global reference frame. The element endpoints are computed by first identifying the element's primary axis as the coordinate direction exhibiting the largest variance among its vertices. Vertices located near the minimum and maximum extents along this axis are then grouped, and the centroid of each group is taken as an endpoint. This approach ensures that the analytical node positions correspond to the geometric centers of the element end faces rather than arbitrary mesh vertices, providing a robust method for endpoint extraction regardless of mesh density or element orientation. Cross-sectional dimensions are extracted by measuring the extent of vertices perpendicular to the primary axis, enabling automatic matching to predefined section profiles in the structural analysis software's section library. Then, for each identified cluster containing multiple nodes, a master node is created at the Euclidean centroid of the element end nodes or slave nodes. Rigid linkage elements are then generated connecting each slave node to the master node. These linkage elements are assigned a rigid material that distinguishes them from structural members in the analysis model. The master-slave relationships are recorded in a separate mapping file that documents the constraint type and node groupings. This explicit documentation of cluster topology is essential for the reverse synchronization process, as it provides the information necessary to distinguish between original structural nodes and nodes introduced during the clustering procedure.

3.2.2 Reverse Synchronization: Structural Model to BIM Model

The reverse synchronization pathway enables modifications made in the frame-based analytical model to be reflected in the original BIM model. This process operates by comparing the modified CSV files against the original synchronization outputs to identify changes in nodal coordinates and element connectivity. The implementation maintains traceability between IFC entity identifiers and the corresponding CSV node and element records, allowing geometric transformations to be mapped back to specific BIM elements. When nodal coordinates are modified in the frame-based analytical model, the reverse converter calculates the displacement vectors and applies corresponding transformations to the associated IFC elements. For elements connected to nodes within a canonical cluster, the transformation considers only the slave node positions, as the master node and linkage elements exist solely within the analytical abstraction and have no corresponding BIM representation. The modified IFC file preserves all non-geometric attributes of the original elements, including material assignments, property sets, and spatial containment relationships, ensuring that the round-trip synchronization maintains the semantic richness of the BIM model.

4 Validation

4.1 Validation Model Description

The proposed bidirectional synchronization method was validated using a reinforced concrete frame structure modeled in Autodesk Revit 2025 [1]. The test model consists of a two-story building, featuring a grid layout of 5 bays in the X-direction and 7 bays in the Y-direction. The building has plan dimensions of approximately 19 meters by 28 meters, with story heights of 4.0 meters for the first floor and 2.5 meters from the second floor to roof. The structure comprises 96 columns and 164 beams, totaling 260 structural elements. To evaluate the robustness of the canonical clustering method under realistic modeling conditions, beams and columns were intentionally shifted away from the design grid intersections to induce geometric misalignments at joints (Figure 6 and Table 1).

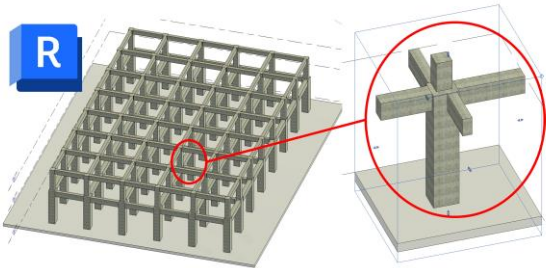

Figure 6. Reinforced concrete frame structure used as the validation model, created in Revit 2025

Table 1. Number of grid-aligned and shifted elements and their minimum and maximum shift distances

Element Type	Aligned to Grid	Shifted from Grid	Min. Shift (mm)	Max. Shift (mm)
Beam	110	54	100	250
Column	84	12	100	100

4.2 Forward Synchronization Validation

The forward synchronization process was executed to transform the Revit model into a frame-based analytical model compatible with structural analysis software Midas GEN [11]. The IFC file exported from Revit was processed through the canonical cluster translator, which extracted structural elements and generated master nodes based on the discretized endpoint coordinates. The canonical clustering method identified clusters corresponding to the joint locations where multiple elements converge. The resulting frame-based analytical model was imported into Midas GEN and subjected to a linear elastic structural analysis to verify the structural integrity of the converted model. The successful completion of the analysis without numerical errors or warnings related to structural instability confirmed that all joints were properly represented through the canonical cluster abstraction.

4.3 Backward Synchronization Validation

The backward synchronization pathway was validated by introducing modifications to the frame-based analytical model and propagating these changes back to the BIM representation. A set of new structural elements, consisting of additional beams and columns, was added to the frame-based analytical model in Midas GEN to simulate a design revision scenario. The modified CSV files were processed through the reverse synchronization algorithm where the newly added beams and columns were translated into IFC entities with appropriate geometric representations and property assignments. The converted IFC file was imported back into Revit 2025 to assess the fidelity of the roundtrip synchronization.

5 Results and Discussion

5.1 Forward Synchronization Results

The forward synchronization successfully transformed the Revit model into a frame-based analytical model (Figure 7). The initial geometry extraction from the IFC file produced 484 nodes and 260 structural elements.

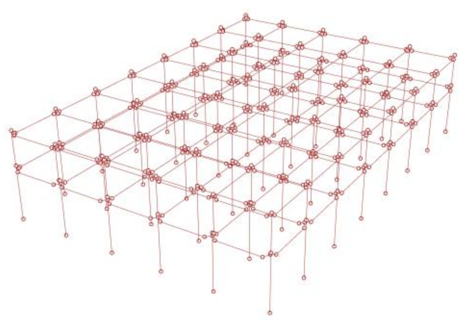

Figure 7. Frame-based analytical model generated by canonical clustering method

Figure 8 and Figure 9 compare the outcomes of the node merging method and the proposed canonical clustering method. The node merging method consolidated the 484 original nodes into 144 nodes by relocating element endpoints to common coordinates within the specified tolerance. While this approach reduced model complexity, it fundamentally altered the geometric representation of the structural elements by modifying their endpoint positions. In contrast, the canonical clustering method preserved all 484 original nodes and introduced 96 master nodes positioned at the Euclidean centroid of each identified cluster. An additional 36 slave nodes were also introduced, as initially node-aligned elements required splitting to accommodate the linkage elements and the master nodes. A total of 472 linkage elements were generated to connect the slave nodes to their respective master nodes, increasing the total element count from 260 to 732. This approach maintained the original geometry of the structure while establishing the topological connectivity required for structural analysis. When subjected to gravity and lateral loads, the converted model successfully completed static structural analysis without errors.

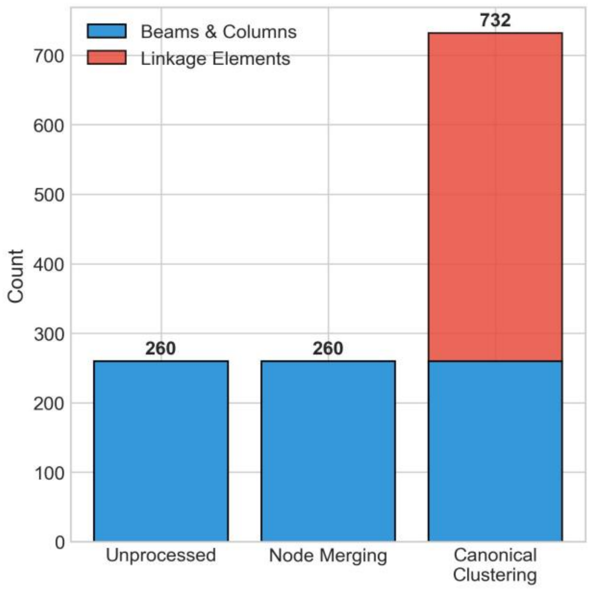

Figure 8. Element count comparison between unprocessed, node merging, and canonical clustering model synchronization

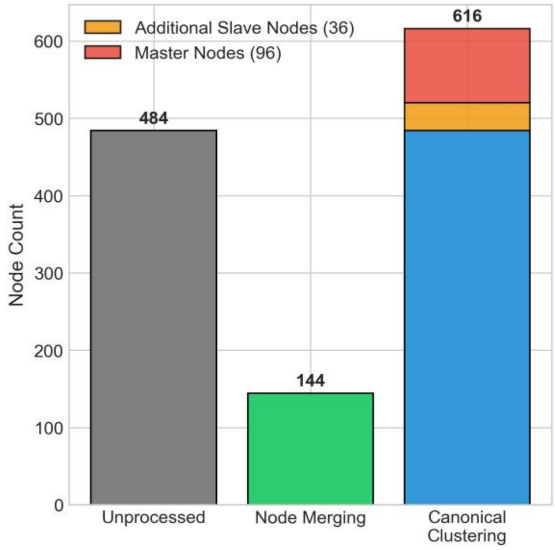

Figure 9. Node count comparison between unprocessed, node merging, and canonical clustering model synchronization

5.2 Backward Synchronization Results

The backward synchronization successfully propagated modifications from the frame-based analytical model back to the BIM representation. An additional frame assembly spanning the structure comprising six columns and five beams (i.e., five bays in the horizontal direction) was added to the analytical model in Midas GEN to simulate a design revision for added lateral strength (Figure 10). Under conventional node merging–based synchronization, such a design revision cannot be reliably propagated back to a BIM model. Since node merging resolves connectivity by modifying existing element locations, the geometry of newly added elements is implicitly determined by these altered attachment points. As a result, backward translation would require geometric modification of the added elements in the BIM model, thereby violating the analytical consistency of the revised structural model and rendering the analysis results invalid.

The reverse synchronization module correctly identified and removed the additional six master nodes and 40 rigid linkage elements from the added frame assembly, preventing these analytical abstractions from being erroneously represented in the output IFC file. The converted IFC file was imported into Revit 2025, where the newly added elements were verified for geometric accuracy and property assignments. All six columns and five beams were correctly positioned according to the nodal coordinates specified in the modified analytical model. The material assignments and cross-sectional dimensions of the new elements matched the corresponding definitions in the CSV data files, demonstrating that the reverse synchronization pathway accurately translates analytical model modifications into valid BIM representations.

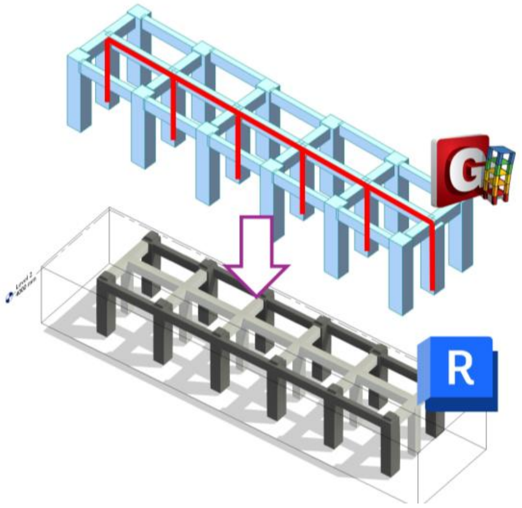

Figure 10. New elements (top) were introduced to the analytical model which were successfully converted to Revit elements (bottom)

5.3 Computational Cost

Compared to the node merging method, the proposed canonical clustering method introduces significantly more nodes and elements to the frame-based analytical model. Since the size of the global stiffness matrix increases quadratically with the number of degrees of freedom, this increase will lead to higher computational cost. Therefore, the practical implications of the proposed method should be carefully evaluated. For this purpose, in addition to canonical clustering with rigid linkage—where linkage deformation does not need to be computed—canonical clustering with non-rigid linkage (e.g., elastic linkage) should also be considered to assess the additional computational cost associated with evaluating the deformation of each linkage element. Figure 11 compares the mean execution time and mean peak random-access memory (RAM) usage over 100 analysis runs between each method. For each analysis run, lateral point loads were applied in the x- and y-directions on the windward side, and the structure was analyzed under linear elastic conditions using OpenSeesPy [12].

The node merging method exhibited a significantly shorter mean execution time (0.018 seconds) compared to the canonical clustering methods with rigid and elastic links (0.051 seconds and 0.088 seconds, respectively). Although the absolute execution times are small, the proportional increase is notable. For more complex scenarios, in terms of model composition, loading conditions, and consideration of nonlinear behaviors, these differences may scale to practically significant levels and must be further investigated.

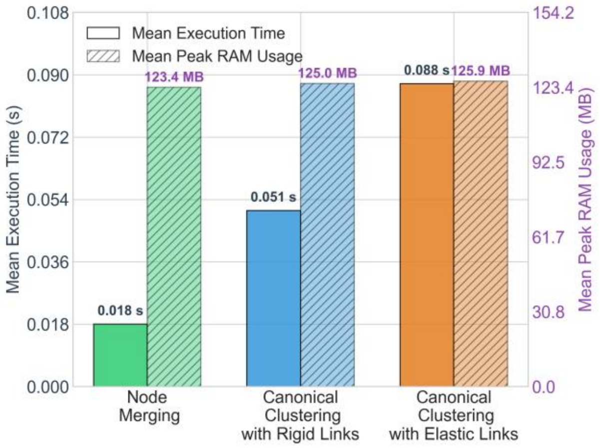

Figure 11. Mean execution time and mean peak RAM usage comparison for 100 analysis runs

Although differences in RAM usage were observed between the tested methods, the magnitude of these differences was not significant. This suggests that the general operational overhead is proportionally greater than the additional memory required to handle extra elements and nodes.

5.4 Limitations and Future Work

The current study was limited to reinforced concrete frame structures with standard beam-column joints. Steel and timber connections, which involve distinct geometric and mechanical characteristics, were not addressed and require further investigation. In addition, the validation process was conducted using only one reinforced concrete structure with a narrow model revision scope. Future work will extend the proposed method to a wider range of structural systems, covering diverse materials and connection typologies. Furthermore, the validation process will be expanded to include substantially larger models with more complex revision scopes, enabling evaluation of the method's robustness and scalability under more extensive design changes.

Additionally, the structural implications of the canonical clustering method for nonlinear analysis warrant deeper exploration. In particular, modeling nonlinear joint behavior requires appropriate parameterization of plastic hinges and spring elements within the canonical cluster, and further research is needed to establish systematic methods for determining these parameters to accurately represent joint deformation behavior.

From a computational perspective, the canonical clustering methods showed higher execution times than the node merging approach. Although all execution times were below 0.1 seconds, this increase may become significant for more complex models and nonlinear analyses, warranting further investigation into scalability and efficiency.

6 Conclusion

This paper presented a bidirectional model synchronization method that enables interoperability between BIM authoring tools and structural analysis software through the use of canonical clusters. The proposed method addresses geometric misalignment at structural joints by introducing a master-slave node abstraction connected by rigid linkage elements, preserving the original geometry of structural elements while establishing the topological connectivity required for frame analysis. Validation using a reinforced concrete frame structure with intentionally misaligned joints demonstrated the effectiveness of the proposed method. The forward synchronization successfully generated a frame-based analytical model that completed structural analysis without errors. The backward synchronization accurately propagated newly added structural elements from the analytical model to the BIM environment with correct geometric positioning and property assignments.

While the validation results demonstrate the feasibility of the proposed approach, this study was limited to reinforced concrete frame structures with standard beam–column joints and a narrow model revision scope. Future work will extend the method to a wider range of structural systems, materials, and connection typologies, and will evaluate its robustness and scalability under larger and more complex model revisions. In addition, the implications of canonical clustering for dynamic and nonlinear structural analysis warrant further investigation, particularly with respect to systematic parameterization of joint nonlinear behavior to accurately represent deformation mechanisms. From a computational perspective, the canonical clustering method showed higher execution times than the node merging approach; although the mean execution time remained below 0.1 second, this increase may become more significant in more complex analysis scenarios and should be further investigated.

7 Acknowledgements

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