BIM-BASED DESIGN CHANGE FRAMEWORK FOR ASSESSING MEP SYSTEM STABILISATION

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Abstract

Design changes during construction remain a challenge, as late-stage modifications to complex MEP systems impact cost and schedule. While BIM enables documentation of design evolution through versioned IFC files, existing tools focus on retrospective change detection rather than forward-looking stability assessment. This study introduces two metrics, Change Intensity (CI) and Stability Index (SI), to track MEP design evolution across IFC versions. CI aggregates the proportion of elements changed, while SI applies a logistic function to translate CI into an interpretable stability score. Eleven IFCs from a real project demonstrate the framework's ability to identify disruption events and track design convergence.

Introduction

Design instability during the construction phase remains a critical challenge in construction project management. Studies have shown that site managers spend more time due to design modifications and rework. This extra time can result in up to 5 to 40% cost overrun (Aslam et al., 2019). Notably, changes made to MEP systems near the completion of the project can be costly, as often these systems must be rerouted around previously installed structural or architectural components.

Last-minute modifications, particularly in MEP design, are affected by numerous circumstances. The prevailing belief among contractors is that MEP design can be modified nearly up to the commencement of installation without substantial detriment to the installation process (Valkonen et al., 2025). The selected installation method significantly impacts this; the typically low level of prefabrication allows contractors to alter plans nearly up to the commencement of installation (Valkonen et al., 2025). The late involvement of the MEP contractor, often used in many countries for business and legal reasons, creates pressure to make changes after the MEP contract has been secured (Valkonen et al., 2025). One of the main causes for delayed design changes is the postponement in approval of changes to the architectural design and its subsequent effect on the MEP design, which follows later in the sequence (Tillmann, 2020).

Leveraging BIM now allows detailed documentation of the evolution of the design through versioned modelling files. Additionally, several commercial software packages can assist users in identifying the changes that occurred between model versions through comparison of either element property or geometry (Bockstael and Issa, 2016). These capabilities provide transparency into how a design has evolved over time.

However, for design managers, simply knowing the number of changes does not provide a reliable and actionable insight. The conventional method of tracking changes and reacting to them does not inherently yield enough reliable and useful insights (Juszczyk et al., 2016). There is a need to understand whether the design is converging toward stability or if there are more impactful changes still expected. Scholars have suggested that if the design change management practices are improved, including predicting or forecasting change impacts, it can enhance overall project performance, reduce negative impact on cost and schedule, and help in coordination decisions (Wang et al., 2022, Motawa et al., 2007).

Despite recent advances in BIM-based change management, a gap remains in that the existing BIM comparison tools detect what changed between model versions, but are limited in assessing design maturity or distinguishing meaningful design changes from metadata updates (Lin et al., 2019). Furthermore, only a limited number of metrics exist to quantify the rate at which a design approaches stability or when convergence will occur.

The current research addresses this gap by proposing two complementary metrics, which are Change Intensity (CI) and Stability Index (SI), to track MEP design evolution across consecutive IFC versions. CI measures the percentage of elements added, removed, or changed from each updated version of a design, and then uses that information to apply a logistic function and compute an interpretable stability score (SI). The resulting CI/SI framework, combined with smoothing and trend analysis techniques, allows the management to analyse the historical patterns of design evolution as well as make predictions about the future stability of designs going forward.

The objective of this study is to develop a simple framework that tracks MEP design evolution across IFC versions and provides interpretable metrics for assessing design stabilisation, enabling project teams to make informed decisions about coordination timing and construction readiness.

Literature review

The detection of design changes within BIM has evolved significantly over the past decade. Lee et al. (2011) developed foundational metrics to quantify the similarities and differences between IFC files. Their research proposed five key metrics, which are similarity rate, matching rate, globally unique identifier (GUID) preservation rate, missing rate, and addition rate. They performed the analysis on 88 IFC files and demonstrated the potential for automated comparison methods in tracking design evolution across project versions. Building upon this foundation, various commercial tools provided clash detection and model coordination mechanisms (Bockstael and Issa, 2016). However, the focus of these tools is primarily on identifying what changed between model versions, and they do not assess design progression or predict stabilisation patterns (Abdulfattah et al., 2023).

Concurrently, the concept of digital twins has advanced from physical asset monitoring to evolve design process management. Boje et al. (2020) proposed directions for the semantic construction of digital twins that emphasises on the real-time data integration throughout the building lifecycle. To complement the design-based data integration, Dai et al. (2024) proposed digital twin modelling methods, which are based on IFC standards. In addition, the integration of BIM with lean principles has further demonstrated benefits, including waste reduction and enhanced visualisation (Sacks et al., 2010). However, these approaches typically address process management rather than quantitative design stability assessment.

Despite these advances, a critical gap persists in the literature. The existing methods focus on retrospective change identification rather than forward-looking stability assessment. For example, Abdulfattah et al. (2023) concluded that no established framework exists for quantifying design maturity progression across multiple model versions. Furthermore, the current comparison methods do not adequately distinguish between meaningful design changes, as indicated by Lee et al. (2011) who acknowledged that automated identification of modified versus newly generated information remains an unsolved challenge. Moreover, the methods for predicting design stabilisation timing are notably absent. While Saoud et al. (2017) proposed Design Structure Matrix approaches for change propagation prediction and subsequently, Chen and Whyte (2022) developed digital-twin-driven DSM methods; these approaches address change impact propagation rather than overall design convergence assessment.

More recently, researchers have explored approaches to managing time-evolving BIM data at the object level. Esser et al. (2022) proposed a graph-based version control method that represents IFC object networks as formal property graphs and describes model changes through graph transformations, enabling object-level synchronization rather than whole-file comparison. Their subsequent work extended this to event-driven collaboration environments for asynchronous BIM workflows (Esser et al., 2023). While these contributions advance the technical infrastructure for detecting granular changes between model versions, they focus on the mechanics of change detection rather than interpreting change patterns in terms of design stability. The present study complements this work by providing interpretable metrics that translate detected changes into actionable stability assessments.

Recent studies emphasize that artificial intelligence applications in construction should support practical decision-making (Pan and Zhang, 2021), yet current implementations prioritise technical sophistication over accessibility. This gap indicates an opportunity for frameworks that could convert the complex change data into actionable metrics for design managers and project stakeholders.

To address these gaps, this study introduces a framework comprising two complementary metrics, which are CI and SI. These metrics are designed to track MEP design evolution across consecutive IFC versions. The following section details the methodology for calculating these metrics and their application in assessing design maturity progression.

Methodology

The research was conducted using the Design Science Research Methodology as proposed by Peffers et al. (2007). The research process is structured into six sequential activities: problem identification, definition of objectives, artefact development, demonstration, evaluation, and communication, as shown in Figure 1.

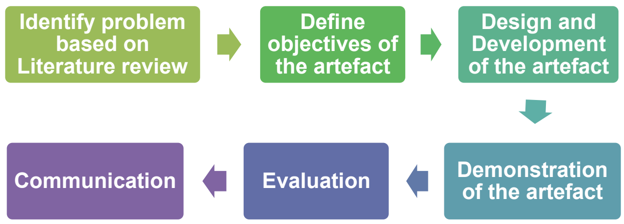

Figure 1. Research Method

The research addresses the problem that the existing BIM model comparison tools detect changes but do not assess whether the design is stabilising over time or not. To address this gap, a BIM-based analytical artefact was developed to quantify design change behaviour and assess stabilisation trends across model versions.

The artefact was iteratively developed and refined using a case study consisting of eleven consecutive IFC versions of a sprinkler system spanning approximately five months of design development. The sprinkler system was chosen because the changes made by architects and clients to the suspended ceiling and interior finishes cause design alterations in sprinkler systems, which make them one of the critical systems in MEP systems. This system is suitable for the demonstration of the problem. The Iterative refinement was guided by sensitivity analysis and empirical behaviour observed in the case study, consistent with DSR principles of relevance, rigor, and utility.

A positive side of this research approach is that it does not require extensive data sets like complex machine learning approaches, which need extensive training data, the CI and SI metrics. The current approach offers immediate interpretability with simple computation. The logistic transformation used in SI calculation provides an intuitive scale that facilitates communication among project stakeholders and supports decision-making in construction management.

Change Intensity (CI)

Design changes between consecutive IFC files are quantified using a CI metric, which captures the proportion of elements affected by different types of changes. CI is defined as (1):

$$CI = A + R + G + P \quad (1)$$

Where:

A = Percentage of added elements

R = Percentage of removed elements

G = Percentage of elements with geometric changes

P = Percentage of elements with property changes

The formulation provides a normalised measure of design activity between versions. CI reflects how much the model has changed without yet interpreting whether those changes indicate convergence or instability.

Stability Index (SI)

To interpret CI in terms of design stabilisation, SI was introduced. The SI transforms CI values into an interpretable stability signal using a two-step process:

Step 1: Raw Stability Index (Logistic Mapping)

A logistic function is used to map CI values to a bounded stability scale [0, 100], shown as (2):

$$SI_{raw} = \frac{100}{1+e^{\frac{CI-\theta}{s}}} \quad (2)$$

Where:

θ is the stability threshold,

S controls the steepness of the transition around the threshold

The logistic function was selected because design stabilisation is non-linear, i.e., small increases in CI near the threshold can significantly reduce confidence, while very low CI values rapidly increase perceived stability. Earlier studies have used logistic growth models as part of forecasting model comparisons to evaluate trend-based cost predictions (Narbaev and De Marco, 2014a).

Step 2: Smoothed Stability Index (Moving Average)

Single version stability measurements may be sensitive to isolated events such as bulk geometry updates or metadata changes. To reduce this sensitivity and reveal underlying stabilisation trends, a moving average is applied to the raw SI values, shown in (3):

$$SI_{smoothed} = \frac{1}{n}\sum_{j=i-n+1}^{i} S\,I_{raw,j} \quad (3)$$

where n is the window size.

In this study, n-3, meaning that stability is evaluated based on the three most recent versions. The moving average smooths short-term fluctuations and supports the interpretation of sustained convergence behaviour, which is more relevant for design management decisions than single version stability. Multiple practical descriptions show moving averages are widely applied in fields like finance, forecasting, business, and economics (smoothing trends, forecasting) (Hansun, 2013, Hyndman, 2025).

Trend-Based Prediction Logic

Rather than predicting absolute future design stability, the artefact supports trend-based anticipation of stability behaviour. A simple first-order extrapolation (2) is used to estimate near-term change intensity:

$$CI_{predicted} = CI_i + (CI_i - CI_{i-1}) \quad (4)$$

The predicted CI is then transformed using the same logistic mapping to obtain a predicted raw stability value. Final anticipated stability is expressed as a moving average combining recent and predicted values, shown in (5):

$$SI_{predicted} = moving\ average\ of\ (SI_{raw,recent} + SI_{raw,predicted}) \quad (5)$$

This mechanism does not claim deterministic forecasting but provides early warning signals indicating whether the design process is converging, persisting, or diverging.

Artefact Iteration

The artefact parameters were iteratively calibrated through sensitivity analysis:

- For Threshold and Steepness, twelve parameter combinations were tested (θ = 5-20%, s = 2-5). The final values θ = 10% and s = 3 were selected as they provided the most interpretable separation between stable and unstable design phases
- For the moving average window, sizes of n = 2, 3, 4, 5 were evaluated. A three-version window was selected as it balanced responsiveness with robustness against isolated spikes.

These iterations ensured that the artefact remains sensitive to meaningful design changes while avoiding overreaction to short-term anomalies.

Demonstration

The artefact was demonstrated on a real-world case study involving a sprinkler system from a Finnish under-construction sports arena project. The gross area of the building was 15000 sqm with eight storeys. The dataset consisted of eleven consecutive IFC versions spanning approximately five months of design development. The initial version of the dataset contained approximately

15,800 MEP elements, enabling analysis of stabilisation over time.

Evaluation

To assess the extent to which the artefact met its intended purpose, an evaluation process was carried out. Evaluation focused on the ability to identify convergence and divergence trends against updated design changes, and the interpretability of CI and SI metrics for design management decisions. This paper details the evaluation results along with the final design of the artefact and how those results were used to provide a practical BIM-based tool for evaluating the stabilisation of the MEP design phase/preliminary designs using open IFC data.

While the by Peffers et al. (2007) framework guided the sequential process of this research, from problem identification through communication, Hevner et al. (2008) provide a complementary set of guidelines for evaluating the rigour and relevance of design science outputs. Table 1 maps these guidelines to the current study to demonstrate that the developed artefact satisfies established quality criteria for design science research.

Table 1. Mapping of DSR guidelines to the study

DSR Guideline	Application in this study
Guideline 1: Design as an Artifact	The CI/SI framework is a purposeful artifact developed to quantify and track BIM design stability.
Guideline 2: Problem Relevance	Addresses the critical gap where existing BIM tools lack stability assessment for project management.
Guideline 3: Design Evaluation	The framework was demonstrated and evaluated on 11 real-world IFC versions to ensure empirical validity.
Guideline 4: Research Contribution	Provides novel interpretable metrics (CI and SI) that offer a new way to measure and visualize design stabilization.
Guideline 5: Research Rigor	Rigor is maintained through sensitivity analysis and the iterative calibration of threshold and steepness parameters.
Guideline 6: Design as a Search Process	The "search" involved testing 12 parameter combinations and evaluating various moving average window sizes to find the optimal configuration.
Guideline 7: Communication of Research	Findings are presented to both technical and management audiences through the detailed documentation in this paper.

Results

Change Intensity across IFC versions

Change Intensity was calculated for ten consecutive version transitions from 1 March □ 8 March to 15 July □ 26 July by aggregating added, removed, geometry-changed, and property-changed elements as shown in Figure 2.

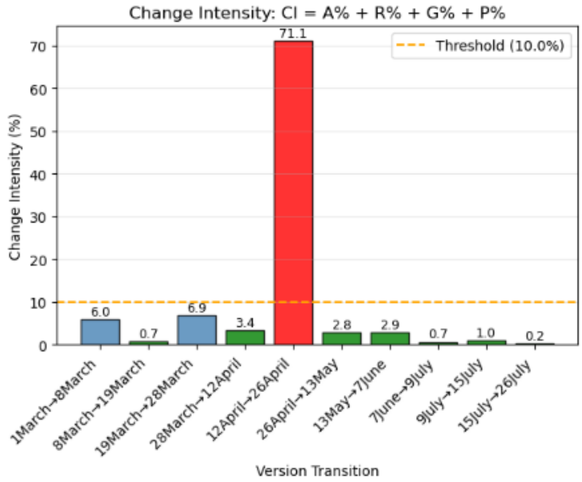

Figure 2. Change Intensity over revisions

A clear exception occurred during the 12 April → 26 April transition, where CI spiked sharply to approximately 71%. This spike was primarily driven by many elements undergoing property changes, indicating a bulk update event rather than gradual design development. Such behaviour reflects a disruptive intervention in the design process, for example, late requirement changes, system reconfiguration, or data restructuring. After this event of instability, CI values dropped rapidly and consistently, reaching near-zero levels by 15 July → 26 July, signalling a return to stable and controlled design changes.

Stability Index Behaviour

The raw SI, computed using the logistic function, responded sensitively to CI fluctuations as shown in Figure 3.

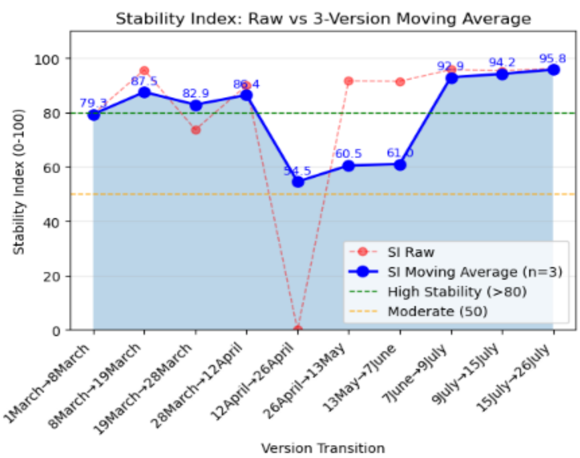

Figure 3. Stability Index

During early revisions, raw SI values remained mostly in the high-stability range (>80), reflecting low change intensity and increasing design stability. On 12 April □ 26 April, the extreme CI spike caused the raw SI to collapse to near zero, demonstrating the model's ability to correctly penalise disruptive design behaviour. However, this sharp drop also illustrates the volatility of raw SI when isolated bulk changes occur.

To address this, a 3-versions moving average was applied. The smoothened SI successfully dampened abrupt fluctuations while preserving the overall trend. Following the disturbance on 12 April → 26 April, the smoothed SI gradually recovered, crossing back into the high-stability zone and reaching 95.8 on 15 July → 26 July. This progression reflects a transition from unstable redesign back to controlled convergence.

Stability Trend Prediction and Evaluation

As described earlier, there were eleven versions of IFCs that were used in the demonstration. Nine versions were used to calculate the stability trends, and the last two were used for the prediction of the stability index. Figure 4 indicates the trend analysis, which shows a positive SI trend (+1.6) combined with a negative CI trend (−0.7%) in the most recent versions. Based on linear extrapolation of CI and the smoothed SI trajectory, the predicted next version indicates continued stability.

Evaluating the trends based on the results shown in Table 2, it was noticed that the predicted stability points align with the raw/actual stability value of the last two versions, i.e., 9 Jul → 15 Jul difference is 1.1, and 15 Jul → 26 Jul difference is 0.5. The predicted SI for the last two versions remains within the high-stability regime, corresponding to an estimated ~80% stability confidence.

The results show different phases of design evolution that validate the framework's effectiveness. During initial revisions from 1 March to 12 April, CI values remained between 0.73% and 6.92% with raw SI exceeding 73%, which indicates controlled incremental development consistent. The versions from 12 April to 26 April represented a significant disruption event, with CI spiking to 71.06% and raw SI collapsing to zero, which was caused by bulk property updates or late requirement changes rather than gradual evolution. The 3-version moving average effectively reduced this instability, dropping gradually to 54.5 while maintaining trend visibility. After this abrupt disturbance, the design showed gradual stabilisation. CI decreased constantly from 2.84% to 0.23%, while smooth SI recovered from 60.5 to 95.8 by the final alteration. The positive SI trend (+1.6) combined with the negative CI trend (−0.7%) in recent versions demonstrates the framework's capacity to differentiate between normal iteration, disruptive interventions, and stabilisation patterns.

Table 2. Results of Raw and Predicted Stability Index

Version	CI (%)	SI_raw	SI_avg	Window
1 Mar → 8 Mar	5.96	79.3	79.3	[1..1]
8 Mar → 19 Mar	0.73	95.6	87.5	[1..2]
19 Mar → 28 Mar	6.92	73.6	82.9	[1..3]
28 Mar → 12 Apr	3.43	89.9	86.4	[2..4]
12 Apr → 26 Apr	71.06	0.0	54.5	[3..5]
26 Apr → 13 May	2.84	91.6	60.5	[4..6]
13 May → 7 Jun	2.88	91.5	61.0	[5..7]
7 Jun → 9 Jul	0.66	95.8	92.9	[6..8]
9 Jul → 15 Jul	0.96	95.3	94.2	[7..9]
15 Jul → 26 Jul	0.23	96.3	95.8	[8..10]

Discussion

The proposed research framework builds upon existing literature in the collaboration and coordination of BIM-based projects by integrating temporal analysis of multiple sequential versions of an IFC, rather than a single-instance comparison. While the commercial tools used to identify conflicts and clashes between elements of a built project are well known (e.g., Hasannejad et al. (2023)), the question of whether the design is stabilising or not has not been addressed within the academic literature. This distinction could influence decisions made by design managers regarding project coordination, timeliness of projects, and construction readiness. To

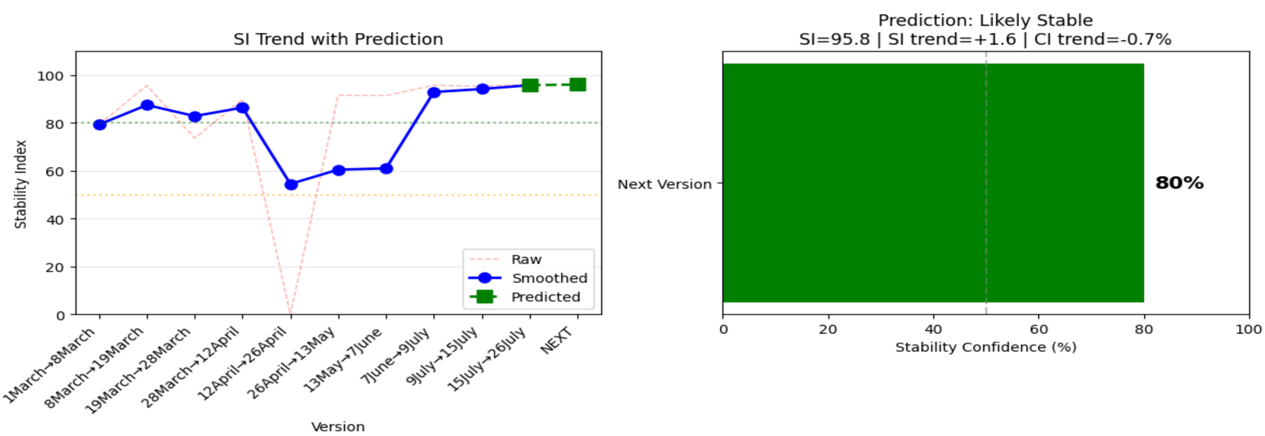

Figure 4. Stability Index trend with prediction

address this gap in the building and construction industry, 2 interpretable project metrics, CI and SI, are proposed with a demonstration of the framework.

The CI and SI metrics have been developed to be easily understood by project managers without requiring a statistical background to understand how the results are represented. For example, if a project manager sees a CI value of 15%, they know 15% of elements have changed; or if they see an SI value of 85%, they know that all project elements are in a stable condition. This transparency is not merely convenient, but it is essential for adoption in practice, where stakeholders need to trust and understand the basis for recommendations. The proposed metrics also do not rely on complex machine learning algorithms (Abdulfattah et al., 2023, Pan and Zhang, 2021) to determine how an element will behave in the future based on its previous history; therefore, no statistical expertise is required to understand the CI and SI metrics.

The study supports the existing research by extending element-based two-version IFCs comparison to an analysis of a series of consecutive IFC versions. Most of the change detection studies only catalogue differences between two versions (Moayeri et al., 2015), which provides valuable data and information, but provides limited information to reveal patterns of design evolution over time. This research demonstrates through tracking CI and SI over 11 versions of IFCs that the design process follows recognisable patterns of design. These patterns include controlled incremental refinement during initial phases, possible disruption events that produce temporary instability, and eventual convergence towards stability as a design develops.

This finding of this research aligns with the established understanding of iterative design processes in BIM-enabled projects, where coordination activities gradually resolve conflicts until the design reaches a sufficient level of maturity for execution (Ahmad et al., 2017). In complex project management, coordination noise is experienced during an iterative information flow. To address this noise, moving average filters are utilised. This approach is complemented by logistic growth models, which have been validated in previous literature for forecasting the progression of design stability (Largani et al., 2026, Narbaev and De Marco, 2014b). This prediction mechanism provides a potential solution for the challenges in construction readiness due to design changes, mentioned in recent researches (Radzi et al., 2025).

Limitations and Future Research

This study is based on one project only and focuses on fire sprinkler systems, which limits the generalizability of the results. The selected thresholds and weighting factors, while suitable and effective in this case, may require calibration for different project types and levels of model granularity. Additionally, the current CI formulation treats all geometric changes and all property changes as equally weighted. In practice, repositioning an element carries different design implications than modifying a pipe cross-section, yet both are captured identically as geometric changes. Similarly, updating a critical performance parameter such as a flow rate differs in significance from a metadata update such as a naming convention change.

To address these limitations, future studies can investigate weighted sub-categorisation of change types based on their functional relevance to the design intent. Furthermore, future research can apply the framework across multiple projects and building systems to validate its robustness and explore adaptive or learning-based threshold selection

Practical Implications

The framework provides a practical way for design managers to optimise coordination, timing, and resource allocation. A construction site with complete situation awareness of upcoming design changes can perform better than traditional sites in terms of rework reduction and cost overrun. The 10% CI threshold provides a simple decision rule, which is that if the transitions exceed this threshold warrant investigation into root causes and potential downstream impacts. This alertness helps the site manager to stay aware of the design change situation. The smoothed SI trend enables actionable scheduling of design reviews, and positive trends suggest approaching stability. While negative trends indicate continued volatility, requiring additional coordination meetings to stabilise the design. For this case project, the framework would have flagged the April disruption event in real-time and enabled the managers to inspect the cause and assess the impact before implementation. This approach aligns with research demonstrating that early conflict identification through BIM reduces costly on-site modifications (Khanzode et al., 2008). The prediction capability mentioned in the results of the case study estimates 80% stability confidence for subsequent versions. This stability confidence has the potential to support decisions regarding construction release timing and trade coordination scheduling.

Conclusions

This study presented a BIM-based framework for tracking MEP design development leveraging CI and SI metrics. CI quantifies element-level modifications across consecutive IFC versions, while SI applies a logistic transformation to produce a bounded stability score from 0 to 100%. The demonstration of eleven IFC versions from a real project demonstrated that the framework successfully identifies disruption events, tracks design convergence, and supports trend-based prediction of stabilisation. The approach addresses a critical gap in existing tools, which focus on retrospective clash detection rather than forward-looking stability assessment, providing project managers with interpretable metrics for coordination timing and construction readiness decisions. Proposed future work can extend validation across multiple projects and building systems, integrate with scheduling tools, and explore adaptive thresholds for different project contexts.

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