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Modelling Construction Accident Risk Dynamics in BIM–WBS Integrated Planning: A Qualitative System Dynamics Study Based on Indonesian Accident Data

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Abstract

Construction accidents in high-rise building projects continue to persist despite the growing adoption of Building Information Modelling (BIM) and structured planning approaches. In practice, safety risks and quality risks in construction activities are closely interconnected and often influence each other through two-way cause–effect relationships. However, existing studies tend to address safety and quality risks separately, with limited attention to their dynamic interactions within integrated planning environments. This study aims to model the dynamics of construction accident risks in BIM–Work Breakdown Structure (WBS) integrated planning using a qualitative system dynamics approach grounded in Indonesian construction accident data. Historical accident records were analyzed to extract recurring causal factors and mapped to construction activities and BIM functionalities to develop causal loop diagrams capturing bidirectional relationships between safety risk, quality risk, planning effectiveness, and control mechanisms. The results reveal reinforcing feedback loops in which quality failures increase safety risks and, conversely, safety incidents trigger quality degradation through rework, schedule pressure, and coordination breakdowns. Balancing loops demonstrate how BIM-enabled planning and risk control can mitigate both safety and quality risks simultaneously. The proposed qualitative system dynamics model addresses a critical research gap by explicitly capturing the two-way causal relationships between safety and quality risks, offering a holistic framework to support proactive, risk-informed planning in building construction projects.

Keywords: System Dynamics; Construction Accident Risk; Safety–Quality Interaction; Building Information modelling (BIM); Work Breakdown Structure (WBS)

INTRODUCTION

While existing studies acknowledge the benefits of integrating Work Breakdown Structure (WBS) and Building Information modelling (BIM) for improving construction safety and quality, most prior research implicitly assumes linear cause–effect relationships. Safety improvements are often discussed as direct outcomes of BIM adoption, while quality enhancements are treated as parallel benefits of improved coordination and information management. As a result, the dynamic interactions and feedback mechanisms through which WBS and BIM jointly shape safety and quality risks remain largely unexplored (Xu, 2025). In particular, the bidirectional causal relationship between safety risk and quality risk–where quality failures increase safety hazards and safety incidents, in turn, degrade quality performance through rework, schedule pressure, and workflow disruption has not been explicitly modelled in the current body of construction risk literature (Sarvari et al., 2024).

This limitation points to a critical research gap: the absence of a system-level representation that captures how WBS–driven task decomposition and BIM–enabled information flows interact to form reinforcing and balancing feedback loops influencing accident risk formation (Feng & Lu, 2017; Lee et al., 2018). Without such a representation, existing risk assessment frameworks are unable to explain why construction accidents persist even in projects that formally adopt BIM and structured planning practices. Addressing this gap requires an analytical approach capable of representing non–linear causality, feedback structures, and delays inherent in construction planning and execution processes (Collinge et al., 2022; Chong et al., 2025; Salzano et al., 2024; Lim & Latief, 2020; Ganbat et al., 2020; Deng et al., 2019).

To respond to this need, this paper employs a qualitative system dynamics approach and develops Causal Loop Diagrams (CLDs) to model the risk dynamics of BIM–WBS integrated planning in high-rise construction projects. The CLDs explicitly articulate how WBS quality, BIM utilization, safety risk, and quality risk are interconnected through feedback mechanisms that either amplify or mitigate accident risk over time. By grounding these causal relationships in historical construction accident data from Indonesia, the study moves beyond conceptual assertions and provides empirically informed insights into risk propagation mechanisms.

This study attempts to fill the gap in existing construction safety and risk management research in three fundamental ways. First, it explicitly models safety risk and quality risk as co-evolving system variables connected through reinforcing and balancing feedback loops, rather than treating them as parallel or independent project performance outcomes. Second, it operationalizes Swiss Cheese Theory within a system dynamics framework by extending static accident causation layers into a dynamic causal structure to explain how failures propagate, accumulate, and recur across project phases through learning and control feedback (Larouzee & Le Coze, 2020). Third, it embeds these dynamic safety–quality interactions within a BIM–WBS integrated planning environment, thereby directing the analytical focus of BIM-based safety research from static hazard identification toward explaining accident risk behaviour and persistence over time. Collectively, these contributions provide a holistic, feedback-based framework that supports proactive, risk-informed planning and offers a theoretical foundation for integrating safety and quality management in high-rise construction projects (Budi et al., 2022; Xu et al., 2021; Badran et al., 2023).

To guide this research, three research questions were developed through a step-by-step process to achieve the research objectives. First, the study seeks to examine how Work Breakdown Structure (WBS) and Building Information Modelling (BIM) interact in influencing quality risk and safety risk in high-rise building construction projects. Second, it investigates what feedback mechanisms and causal loop structures explain the bidirectional relationship between quality risk and safety risk within BIM–WBS integrated construction planning. Third, the research explores how qualitative system dynamics modelling can contribute to explaining the persistence of accident risk and identifying leverage points for improving safety and quality planning in high-rise construction projects.

Based on these questions, the objectives of this study are threefold. First, it aims to analyze the interaction between WBS and BIM in shaping quality risk and safety risk in high-rise building construction. Second, it seeks to identify and explain the feedback mechanisms and causal loop structures that characterize the bidirectional relationship between safety risk and quality risk. Third, it aims to develop a qualitative system dynamics model that explains accident risk persistence and highlights leverage points for more effective risk-informed planning and control. The benefits of this research are expected to be both theoretical and practical. Theoretically, this study contributes to the advancement of construction safety and risk management literature by integrating system dynamics, Swiss Cheese Theory, BIM, and WBS into a single conceptual framework that captures accident risk as a dynamic and systemic phenomenon. Practically, the study provides insights for project planners, safety managers, contractors, and policymakers by identifying how risk can escalate through planning deficiencies and how BIM–WBS integration can be strengthened to reduce both safety and quality risks simultaneously. In addition, the findings may serve as a reference for improving proactive planning strategies, enhancing digital risk management practices, and supporting safer and higher-quality execution of high-rise construction projects in Indonesia and similar construction contexts.

METHODS

Research Design

This study adopted a **qualitative system dynamics research design** to investigate the interaction between Work Breakdown Structure (WBS), Building Information Modelling (BIM), quality risk, and safety risk in high-rise construction projects. The research combines **document-based qualitative analysis**, **historical accident data**, and **system dynamics modelling** to develop causal loop diagrams (CLDs) that explain accident risk persistence and identify leverage points for risk mitigation

Materials

a) Data Sources

The materials used in this study consist of three main sources:

Construction Accident Data In Indonesia (2017-2024)

This study utilizes historical construction accident data in Indonesia covering the period from **2017 to 2024**, obtained from official records published by the **National Construction Safety Committee under the Ministry of Public Works**. The dataset consists of documented accident cases from building construction projects and was systematically filtered to ensure relevance to high-rise construction activities.

Each accident record includes a chronological description of the incident, identified root causes, and information on accident severity, including fatality data. The accident data were categorized based on accident type, contributing factors, and construction phase, as summarized in **Table 1.**

Detailed descriptions of individual incidents and root cause assessments are provided in the Appendix. Rather than being used for statistical inference, the accident data serve as empirical evidence to ground the identification of causal relationships and feedback mechanisms in the qualitative system dynamics model.

Table 1. Project type, project nature and estimated contract value

Project Type	No. Of Project	Contract Value (IDR)	Project Nature
Infrastructure			
Toll Road	14	100B-1T	New construction
Rail road	2	100B-1T	New construction
Utilities	1	100B	New construction
Bridge	3	100B-500B	New construction
Buildings			
Education	1	10B	Renovation

Commercial	1	35B	New construction
Office	1	45B	New construction
Residential	2	10-15B	New construction

Source: Processed by the author based on data on Indonesian construction accidents in 2017–2024 from the Construction Safety Committee, Ministry of Public Works of the Republic of Indonesia

b) Scientific Literature

To complement the accident data, this study conducts a qualitative document analysis based on a **structured** review of peer-reviewed scientific literature. Literature searches were performed using **Scopus** and **Web of Science** databases, focusing on research related to construction safety, quality risk, and digital planning approaches. The research topic was decomposed into key thematic search terms, including *"BIM–based safety management", "WBS–based planning and control", "construction quality risk",* and *"system dynamics in construction safety"*.

The literature search process employed a combination of **keyword-based queries and snowballing techniques,** allowing relevant references cited in key articles to be systematically explored. Searches were conducted between **November and December 2025**, with the final search completed on **28 December 2025.** The selected articles were subsequently analysed using descriptive and thematic coding to extract variables and causal relationships related to safety and quality risk dynamics. These variables were then synthesized to support the development and theoretical validation of the causal loop diagrams.

3.1. Research Methodology

a) Data Categorization and Validation

The classification of accident causal type is organized into 5 categories as shown in Table 2 were relevant and conceptually consistent with the Swiss Cheese Theory. This categorization interpreted as a temporal and systemic unfolding of those layers, extending the Swiss Cheese model from accident causation into project-level consequences and future risk propagation (Fu et al., 2024).

a. *Initial Cause* refers to initial gap embedded in the system, such as poor planning, inadequate design of temporary works, unrealistic schedules, or insufficient safety culture. They often remain unnoticed until triggered by operational conditions.
b. *Intermediate Failure* refers to process or control breakdowns that allow initial issues to escalate. At these stages the "holes" in multiple defensive layers begin to enlarge or align.
c. *Safety Event* refers to an incident or accident resulting from accumulated failures when all defensive layers fail simultaneously (Zhang et al., 2022).
d. *Project Impact* capturing direct project-level impacts, such as work stoppages, schedule delays, cost overruns, legal consequences, and reputational damage (Zeng et al., 2022). This highlights that safety failures impact may spread beyond the immediate event.
e. *Effect on Future Task* would appear if corrective actions are not properly implemented or even ignored, new latent conditions are created, leading to recurring risks in subsequent project phases or future projects (Mohammadi & Tavakolan, 2020). Ineffective learning and corrective actions may generate new latent conditions, reinforcing future risk exposure, whereas effective learning strengthens system and mitigates recurrence (Heydari et al., 2024).

This categorization introduces a feedback loop, which is not explicitly modelled in classic Swiss Cheese theory but is critical in system dynamics thinking. By linking these five stages, Swiss Cheese Theory were operationalized into a dynamic causal chain. Dynamic between safety accidents and quality defect are depict as a system-based temporal safety model rather than static accident explanation. There are two main point from this feedback loop which is (a) poor learning reinforces future risk latent condition; and (b) effective learning from accident or quality defect would create balancing feedback and strengthening risk mitigation. Each causal variable was mapped to its interrelationships with other variables through a comprehensive literature review as shown in Table 4. The identified linkages evaluated by a panel of seven domain experts including academics, practitioners, consultants, and contractor each with a minimum of ten years of professional practice in construction safety or quality assurance for validation. The consistency of expert judgments was subsequently assessed with Krippendorff's Alpha reliability test using JASP software (version 0.95.4.0) with consistency reliability value targeted above 0.67 (Etemadinia & Tavakolan, 2018).

b) Causal Loop Diagram Development

Causal Loop Concept

Descriptions of construction failures and safety accidents documented in the accident reports were systematically analysed to identify recurring patterns of interaction between quality-related and safety-related risk factors. Based on this analysis, key causal variables representing quality and safety risks were extracted and classified according to their roles in accident development. These variables were subsequently organized into conceptual maps to represent preliminary cause–effect relationships.

The conceptual maps served as the foundation for developing causal loop diagrams (CLDs), as illustrated in **Figure 1**, which depict the causal pathways through which planning deficiencies, intermediate failures, and control weaknesses evolve into safety incidents or quality defects (Ghamarimajd et al., 2024).

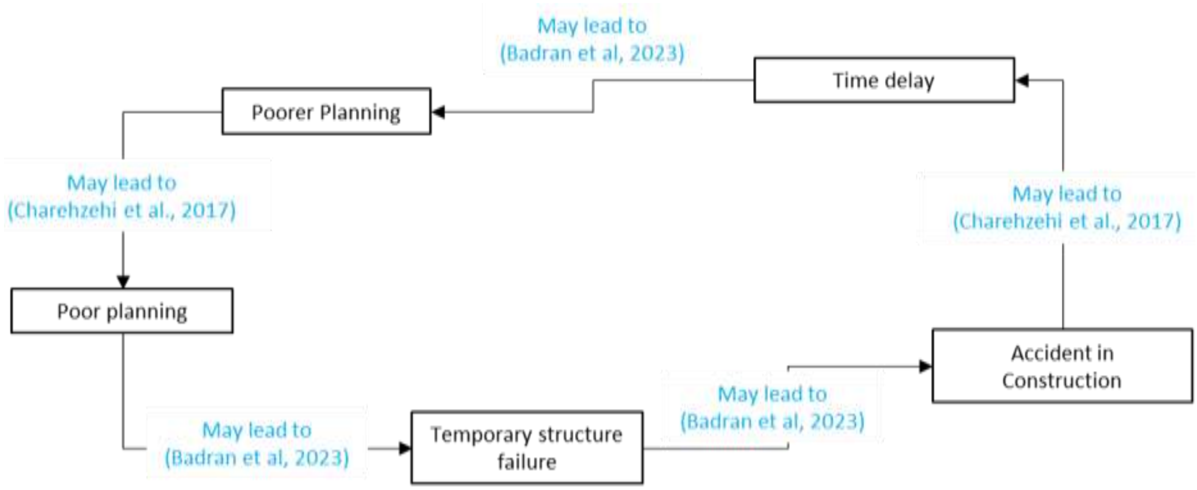


Figure 1. Causal Loop concept example

Source: Developed by the author based on the analysis of Indonesian construction accident data and the concept of qualitative system dynamics

Quality–Risk Causal Loop Diagram

The causal structures linking **initial causes, intermediate technical or quality failures, safety events, project** impacts, and **feedback effects on planning and control** were synthesized from the conceptual maps and formalized into causal loop diagrams. The CLDs, presented in **Figures 2,** were developed using **Vensim DSS version 10.4**, a system dynamics modelling software widely applied for qualitative feedback analysis (Kim et al., 2024). Each diagram represents reinforcing and balancing feedback loops that capture the dynamic interactions between quality risk and safety risk within BIM–WBS integrated construction planning.

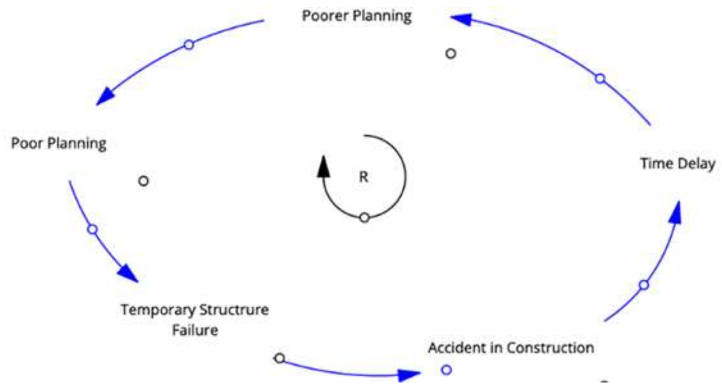


Figure 2. Causal Loop Diagram (CLD) Diagram example

Source: Compiled by the author using Vensim DSS version 10.4 based on the results of conceptual analysis

a) Quality–Safety Risk Causal Relationship Analysis

The causal relationships represented in the CLDs were further analysed through interpretive qualitative analysis and triangulated with findings from relevant scientific literature. This step aimed to ensure theoretical consistency and to validate the plausibility of the identified feedback mechanisms.

Bidirectional interactions between quality risk and safety risk are the key focus at this step., such as the reinforcing effects of quality failures on accident occurrence and the subsequent impact of safety incidents on rework, schedule pressure, and further quality degradation. The analysis provides a systemic explanation of accident risk persistence and supports the identification of leverage points for improving safety and quality planning in high-rise construction projects.

RESULTS AND DISCUSSION

Interaction between WBS, BIM, Quality Risk and Safety Risk

The analysis as shown in Table 2 reveals that Work Breakdown Structure (WBS) and Building Information Modelling (BIM) interact as interdependent planning mechanisms that jointly influence the formation and escalation of quality and safety risks in high-rise construction projects (Manzoor et al., 2025). WBS functions as the structural framework that defines task decomposition, sequencing, and work package boundaries, while BIM provides the information platform that visualizes, coordinates, and verifies these tasks throughout the project lifecycle (Lu et al., 2021). Deficiencies in WBS definition—such as unclear task scope, inadequate consideration of temporary works, or improper sequencing—were consistently associated with increased quality deviations, including construction errors, rework, and non-conformance to specifications (Fargnoli & Lombardi, 2020). These quality failures, in turn, created unsafe working conditions that elevated safety risk exposure.

Table 2. Causal stages analysis based on Swiss-Cheese Theory

Code	Initial Cause (Planning/Control)	Intermediate Failure (Quality)	Safety Event (Accident/Incident)	Direct Impact to Project	Effect on Future Task
A	Poor WBS definition and planning	Temporary structure inadequately designed or installed	Temporary structure failure causing injury or near-miss	Schedule delay due to investigation and rework	Increased time pressure reduces planning quality
B	Incomplete BIM-based hazard planning	Unidentified clash or constructability issue	Unsafe corrective work leading to accident	Schedule delay and cost overrun	Reduced time for safety and quality planning
C	Weak project control and monitoring	Quality defects remain undetected	Defective work causes unsafe conditions	Work stoppage and rescheduling	Lower effectiveness of control systems
D	Insufficient coordination between WBS and BIM	Incorrect sequencing of high-risk activities	Collision or fall accident during execution	Delay in critical path activities	Rushed resequencing increases planning errors
E	Inadequate safety planning at task level	Lack of temporary protection or access control	equipment-related incident	Schedule delay and productivity loss	Shortcut behaviors to recover schedule

Source: The results of the author's categorization and analysis are based on Indonesian construction accident data in 2017–2024 and the Swiss Cheese Theory framework

BIM utilization was found to moderate these effects by enabling clash detection, constructability review, and 4D simulation aligned with WBS activities. When BIM and WBS were poorly integrated, risk visibility was reduced, allowing quality defects and safety hazards to remain undetected until construction execution. Conversely, effective BIM–WBS integration supported early identification of both quality and safety risks at the task level, reducing the likelihood of downstream accidents (Rodrigues et al., 2021). These findings indicate that quality risk and safety risk do not arise independently but are co-produced through planning structures embedded in WBS–BIM interaction. The interaction between WBS-BIM-quality risk-safety risk is illustrated in Table 2 as a reference basis for the next stage.

From the five dominant causal loop path, a 5 stages cause–effect model developed earlier in which each stage was assigned a Code (e.g., Code A = loop A as shown in Table 2. Each loop code is confirmed by experts for validation and tested using intervariable reliability analysis.

The results of the inter-variable reliability analysis as shown in Table 5. indicates a consistency value of 0.843. Therefore, based on the Kripendorf Alpha criteria, all feedback provided by the experts can be declared consistent and acceptable.

Table 3. Reliability Test

			95% CI	
Method	Krippendorff's alpha	SE	Lower	Upper
Ordinal	0.843	0.069	0.525	0.793
***Note.* 5 subjects/items and 7 raters/measurements.**				

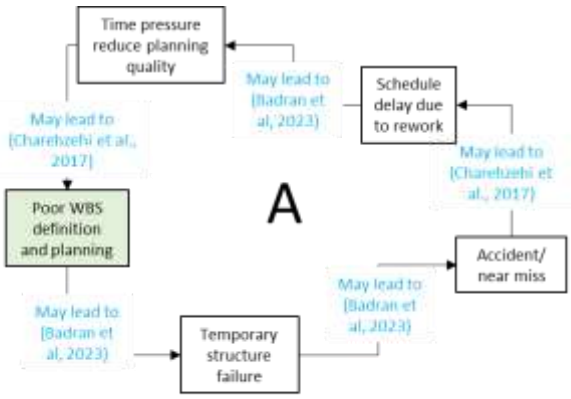
Source: The results of the author's data processing using JASP software version 0.95.4.0 based on the assessment of seven experts

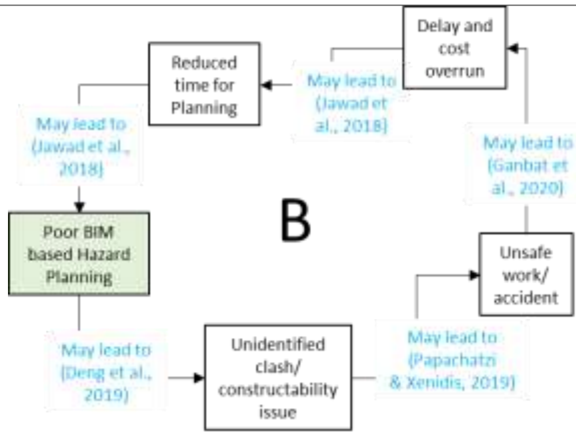
Feedback Mechanism and Causal Loop Structures

The causal loop concept developed in this study obtained by examined accident data together through consultation with experts from the Indonesian national construction safety committee, who then selected the five most frequently occurring causal loops from all of the root cause analysis data studied that shown in Figure 3 A to E. It reveals feedback mechanisms that explain the bidirectional relationship between quality risk and safety risk within BIM–WBS integrated planning. The causal loop, illustrating how deficiencies in planning and control can amplify accident risk over time.

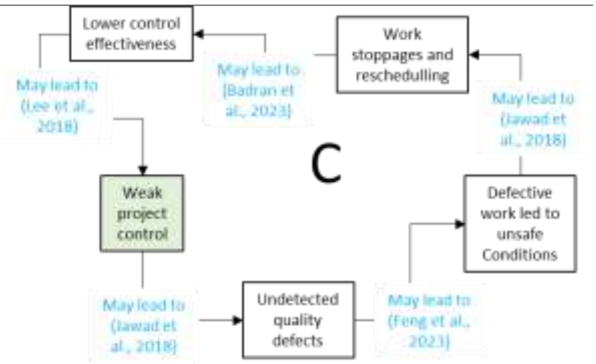
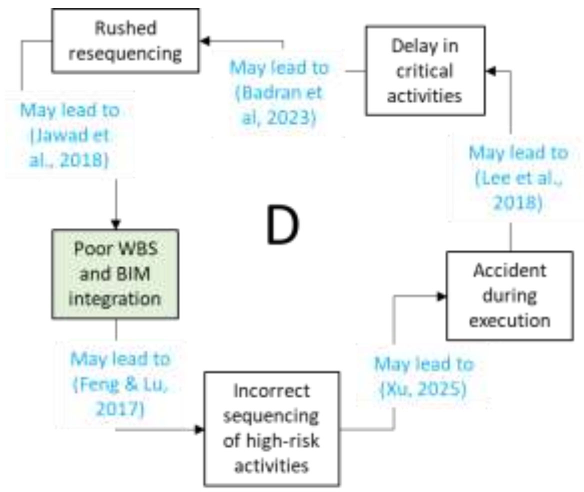
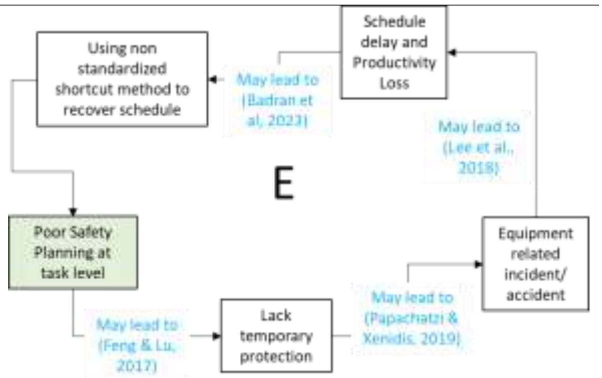
The following is a description of each causal loop map from the analysis of accident data compared with the related reference.

Table 3. Causal Loop Concept Map

<table>
<tr><th>Loop (Ref)</th><th>Loop Description</th><th>Loop Concept Map</th></tr>
<tr><td>A
[19]
[20]</td><td>Poor WBS definition and limited BIM verification lead to quality failures, such as defective temporary structures or incorrect installations. These failures increase the probability of safety incidents. If accident happened, subsequently trigger rework and may cause schedule disruption that may lead to increased time pressure. Elevated time pressure further degrades planning quality and weakens safety controls, reinforcing the original risk conditions.</td><td>


</td></tr>
<tr><td>B
[21]
[22]
[23]
[24]</td><td>Inadequate WBS definition and limited BIM-based hazard identification may lead to undetected constructability and safety issues during the planning stage, which subsequently manifest as quality failures during execution. These quality failures create unsafe working conditions and increase exposure to hazards, thereby elevating the likelihood of safety incidents and near-miss events. Safety incidents, in turn, disrupt workflow continuity, trigger rework, and intensify schedule pressure, which further degrades planning effectiveness and coordination quality. This degradation reduces</td><td>


</td></tr>
</table>

<table>
<tr><td></td><td>the effectiveness of subsequent BIM–WBS planning and control activities, allowing latent risks to persist or re-emerge in later tasks</td><td></td></tr>
<tr><td>C
[19]
[24]
[25]
[26]</td><td>Improper control during construction execution may allow defects to remain undetected, resulting in work that fails to comply with required standards. Such nonconforming work may generate unsafe conditions that increase the likelihood of incidents or accidents. When accidents occur, they often disrupt construction activities through delays or temporary work stoppages, necessitating adjustments to work sequencing and schedules. These delays, in turn, intensify time pressure and can undermine the effectiveness of supervision and control during subsequent stages of implementation.</td><td>
</td></tr>
<tr><td>D
[19]
[24]
[25]
[26]
[27]</td><td>Task preparation that is not supported by WBS-based BIM integration may result in inadequate preparation and sequencing of construction activities, particularly for critical tasks. Such deficiencies increase the likelihood of accidents during execution. When accidents occur, they often disrupt critical activities and lead to project delays, ultimately affecting overall project duration. In response, management may adopt accelerated or rushed rescheduling strategies, which can further compromise the quality of subsequent planning and introduce additional risks in later construction stages.</td><td>
</td></tr>
<tr><td>E
[19]
[22]
[25]
[26]</td><td>Safety planning that is not structured using Work Breakdown Structure (WBS) may lead to inappropriate safety protection measures allocation for high-risk activities. Such inadequacies can increase the likelihood of worker accidents or equipment-related incidents during construction execution. The occurrence of these incidents often results in project delays, which subsequently generate pressure to accelerate ongoing work. Under such conditions, management may resort to shortcut practices to recover lost time, thereby further elevating safety and operational risks in subsequent stages.</td><td>
</td></tr>
</table>

Source: The results of the author's synthesis and development based on Indonesian construction accident data, literature review, and expert validation

Causal Loop Diagram Development

The qualitative system dynamics approach employed in this study provides a systemic explanation for accident risk persistence that cannot be captured by linear or static risk assessment methods. By explicitly modeling feedback structures, the causal loop diagrams illustrate how accidents persist even in projects that formally adopt BIM and structured planning, due to reinforcing interactions among planning deficiencies, quality failures, safety incidents, and schedule pressure. This modeling approach shifts the analytical focus from isolated risk factors to dynamic risk behavior emerging from system interactions.

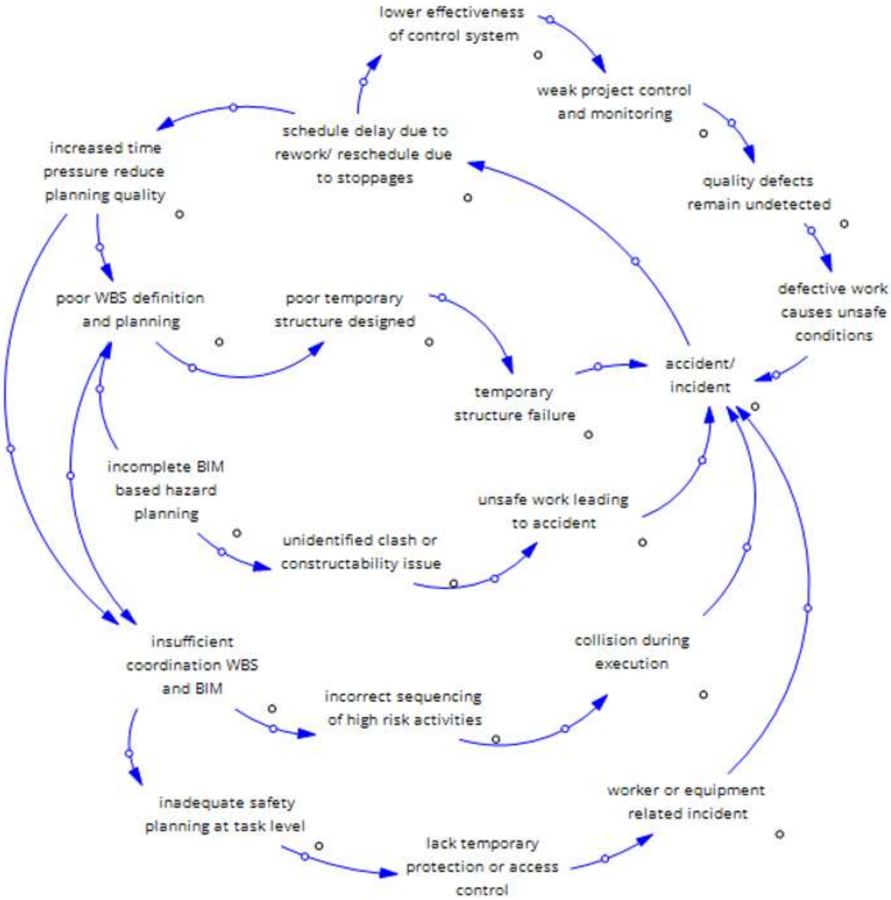


Figure 3. Causal Loop Diagram (CLD) map

Source: The author's modeling results are based on data on Indonesian construction accidents in 2017–2024, literature review, and expert validation.

The CLD analysis further enables the identification of leverage points for improving safety and quality planning in high-rise construction projects. Key leverage points were identified at the planning and control stages, including improvements in WBS task definition, enhanced BIM-based verification of temporary works, and tighter integration of safety and quality controls within 4D planning workflows. Interventions at these points were shown to weaken reinforcing risk loops and strengthen balancing loops that mitigate accident risk. These results demonstrate that qualitative system dynamics modelling not only explains accident persistence but also supports more proactive and risk-informed decision-making by highlighting where targeted planning interventions can produce system-wide safety and quality improvements

Interpretation of Quality–Safety Risk Dynamics in BIM–WBS Integrated Planning

The findings of this study indicate that quality risk and safety risk in high-rise construction projects are not independent phenomena, but dynamically interconnected outcomes shaped by planning structures embedded in Work Breakdown Structure (WBS) and Building Information Modelling (BIM). The causal loop diagrams reveal that deficiencies in WBS definition and BIM utilization tend to generate quality-related issues, such as design inconsistencies, improper sequencing and rework, which subsequently create unsafe working conditions. These unsafe conditions increase the likelihood of safety incidents, thereby reinforcing the initial quality problems through workflow disruption and corrective actions. This interpretation supports the view that accident risk formation is a systemic process rather than a linear chain of isolated failures.

The analysis further suggests that BIM does not function as a stand-alone safety solution; its effectiveness depends on how well it is operationalized through WBS-based planning. When BIM models are weakly linked to task-level work packages, the potential of BIM for early hazard identification and quality verification remains underutilized. Conversely, clearer WBS structures appear to enable more meaningful BIM-based visualization and coordination, allowing quality and safety concerns to be addressed earlier in the planning process. This finding helps explain why construction accidents continue to occur even in projects that formally adopt BIM, as technological adoption alone does not automatically translate into risk reduction without appropriate planning integration.

The reinforcing loops identified in the causal loop diagrams illustrate how quality failures and safety incidents mutually intensify one another over time. For example, quality deficiencies often necessitate rework, which introduces schedule pressure and increases work intensity. These conditions weaken safety controls and heighten exposure to hazards, leading to additional safety incidents. The resulting accidents further disrupt construction processes, creating new quality issues and perpetuating the cycle of risk escalation.

This feedback-based interpretation extends prior construction safety research that predominantly focuses on direct cause–effect relationships. While earlier studies have acknowledged links between accidents, rework, and delays, they rarely conceptualize these relationships as reinforcing loops embedded within planning and control systems. By explicitly modelling these dynamics, the present study demonstrates that accident risk persistence is not merely the result of repeated human error or technical failure, but a consequence of systemic interactions among planning quality, safety management, and project control mechanisms. This perspective aligns with system accident theories, which emphasize the role of organizational and structural factors in shaping risk behaviour (Charehzehi et al., 2017; Jawad et al., 2018).

Role of BIM–WBS Integration as a Risk Moderation Mechanism

In addition to reinforcing loops, the analysis identifies balancing mechanisms through which BIM–WBS integration can moderate the escalation of quality and safety risks (Papachatzi & Xenidis, 2019). These balancing loops are associated with planning interventions such as improved task definition, BIM-based constructability review, 4D sequencing, and integrated safety–quality controls at the work package level. When such mechanisms are present, emerging quality issues are more likely to be detected before execution, reducing the likelihood of unsafe corrective actions and limiting downstream accident risk.

The presence of these balancing loops suggests that BIM–WBS integration can serve as a structural leverage point for risk mitigation. Rather than responding reactively to accidents, planners and managers can intervene earlier by strengthening the alignment between WBS and BIM functionalities. This finding contributes to the ongoing discussion in BIM and safety literature regarding the need for more integrated and process-oriented approaches to digital construction management. It also reinforces arguments that risk mitigation strategies should focus on upstream planning decisions rather than solely on downstream safety enforcement.

5.1.Implications for Construction Risk Research and Practice

From a research perspective, this study advances construction risk literature by explicitly modelling the bidirectional relationship between quality risk and safety risk within a system dynamics framework. Previous studies have often treated quality and safety as parallel dimensions of project performance, whereas the present analysis demonstrates that they co-evolve through feedback-driven processes. This integrated perspective provides a more comprehensive explanation of accident risk behavior in complex construction environments, particularly in high-rise projects where interdependencies among activities are pronounced.

From a practical standpoint, the findings suggest that improving safety outcomes requires more than isolated safety measures or technological adoption. Effective risk mitigation depends on the integration of planning structures, digital tools, and control mechanisms. Strengthening WBS definition, enhancing BIM-based verification, and embedding safety and quality considerations into task-level planning may help weaken reinforcing risk loops and strengthen balancing mechanisms. These insights support a shift toward more proactive, risk-informed planning practices that address the root causes of accident risk rather than its symptoms.

CONCLUSION

While this study advances the integration of quality and safety through a causal factor perspective grounded in system dynamics, its findings are subject to limitations related to data availability. The relatively small number of analysed accident and quality failure cases may have restricted the identification of certain causal factors and feedback structures within the safety–quality system. As a result, some causal pathways and interactions may remain unexplored. Future research should employ larger datasets and advanced network-based modelling techniques, such as Bayesian networks, to quantify causal strengths and simulate dynamic feedback scenarios. In addition, adopting a risk-based approach that integrates systematic risk identification, analysis, response, and control can further strengthen the development of integrated quality and safety management systems, providing a foundation for proactive planning and resource allocation in construction projects. The authors gratefully acknowledge the support provided by the National Construction Safety Committee from Ministry of Public Work Indonesia for facilitating access to construction quality failures and accident cases data. Also, for the experts that participated in this study, their practical insights and professional judgement made a substantial contribution to the development of this research.

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