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CDE Architecture Informed by Design Thinking for Rapid Design Change Propagation: A Socio-Technical Systems Approach to Cross-Border Construction

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ABSTRACT:

The Architecture, Engineering, and Construction (AEC) industry faces significant information latency in cross-border design change propagation, termed the "Latency Paradox". Employing Design Science Research (DSR) with a mixed-methods approach on a Vietnam-Australia project (X Group), this paper analyzes a critical 200mm reinforcement misalignment caused by reliance on asynchronous tools (email, PDF) and a prevalent "fear of error" culture. To address this, the study proposes a Common Data Environment (CDE) Reference Architecture integrating Design Thinking and Socio-Technical Systems theory. This architecture transforms the CDE into a "Living Model" with real-time Mobile-to-Model synchronization and a "blame-free" governance mechanism. Quantitative testing of 50 intervention events against a historical baseline, utilizing a novel T1-T4 scale, demonstrated significant improvements: Site-to-Design latency (T1 to T2: reporting receipt) reduced from a baseline median of 21.6 hours to 0.7 hours via mobile synchronization, while the resolution/instruction loop (T2-T3-T4: analysis and feedback) decreased from a baseline median of 44.2 hours to 5.5 hours, achieving a 98% propagation completion rate. The core contribution of this paper is providing a practical framework that effectively eliminates rework, while theoretically demonstrating the socio-technical operationalization of psychological safety within a digital environment to achieve cognitive alignment in global construction projects.

1. Introduction

1.1. The globalization of construction and the Latency Paradox

The modern construction project is characterized as a "complex adaptive system" that increasingly transcends national borders [1]. The globalization of the AEC supply chain has shifted the industry toward a model where design, engineering, and assembly occur in "disparate geographic locations separated by time zones" [1]. While this disaggregation offers economic efficiencies, it introduces profound risks. In their study of "design collaboration processes in remote architectural practice", researchers identify a persistent "latency in the digital era" that

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separates information generation from its execution [2].

A paradox has emerged: while geometric precision has reached the millimeter scale, the communication of changes often operates on a timescale of days, utilizing archaic mechanisms. This "Information Latency" creates a window of uncertainty where site teams proceed based on obsolete data, inevitably leading to rework and structural defects.

1.2. Problem statement: Information asymmetry and the "Latency Paradox"

This research focuses on design change propagation, defined as the mechanism by which modifications in one domain must be synchronized across related disciplines [3]. Despite the rapid digitalization of the AEC industry, the dynamic reality of on-site execution and field adaptations frequently outpaces the formal synchronization of digital design models [2]. This temporal disconnect creates what this study defines as the "Latency Paradox".

Empirical evidence from the cross-border "X Group" project illuminates the severity of this issue. When an on-site decision to adopt a precast split-wall system failed to reach the remote Vietnamese design team synchronously, the Australian site workforce faced a critical discrepancy. Operating under intense schedule pressure and a psychological "fear of error," the workers exhibited an operational regression: they defensively adhered to obsolete drawings to avoid personal liability, resulting in a 200mm misalignment of starter bars. This incident exemplifies Information Asymmetry, where the "truth" of the project was fractured between the physical reality on-site and the theoretical design intent.

While frequently attributed to legacy tools (e.g., emails, PDFs), framing this problem as a simple binary between "old tools" and "modern technology" is inadequate. The AEC industry already utilizes advanced cloud platforms [1], yet upgrading to these systems does not automatically eliminate latency. The X Group failure illustrates that Information Asymmetry persists due to a profound socio-technical failure rather than a mere technological deficit. When a fear of negative consequences prevents workers from reporting discrepancies [4], the resulting latency renders even the most sophisticated systems ineffective. Resolving this asymmetry necessitates a paradigm shift from purely technological implementation to human-centered governance [5].

1.3. Research gap and motivation

Building on the socio-technical friction identified in the X Group case, it is evident that while the literature on Building Information Modelling (BIM) is extensive, the current discourse on Common Data Environments (CDEs) predominantly centers on technical compliance and data structuring, such as the ISO 19650 standards and BIM Collaboration Format (BCF) protocols [6]. Although modern commercial platforms-notably Autodesk Construction Cloud, Procore, and Dalux- possess advanced cloud and mobile issue-tracking capabilities [1], they are frequently implemented through top-down, compliance-driven approaches [7]. Consequently, many existing CDEs are perceived by site workers merely as passive systems of record [6] or tools of power and control [7], rather than active, supportive engagement platforms.

Technological advancements, such as the move "toward artificially intelligent cloud-based building information modelling" [8] and the use of "IFC-graph for facilitating building information access" [9], offer promising algorithmic linkages to bridge data gaps. However, these purely technical solutions inherently assume rational user compliance, often overlooking the socio-technical "human factor" that triggered the operational regression observed in X Group. Specifically, existing CDE architectures lack embedded governance mechanisms designed to overcome the hierarchical friction and "fear of error" prevalent on construction sites [5].

The critical research gap, therefore, lies not in a deficit of cloud technology-which is already mature in the market-but in the absence of a Reference Architecture that integrates socio-technical governance with real-time synchronization. There is an urgent need for "humanising complex projects through Design

Thinking" [5] to develop a framework that overcomes human inertia and psychological barriers. This research aims to fill this gap by proposing a design-thinking-informed architecture that transforms the CDE from a static repository into a dynamic, truth-synchronizing environment capable of mitigating the Latency Paradox.

1.4. Research objectives and scope

The primary objective is to develop and evaluate a Design-thinking-informed CDE Reference Architecture that minimizes information latency. The study addresses the following Research Questions:

- RQ1: What are the specific socio-technical pain points governing design change propagation in cross-border projects?
- RQ2: How can Design Thinking principles be translated into a CDE Reference Architecture to optimize propagation speed and cognitive alignment?
- RQ3: Does the implementation of this architecture empirically reduce information latency, and what are the underlying mechanisms?

2. Theoretical framework

To address the multifaceted nature of the problem, this research synthesizes four distinct theoretical perspectives: the Information Processing View, Socio-Technical Systems Theory, the concept of Boundary Objects, and Design Thinking.

2.1. The information processing view of construction organizations

Galbraith’s Information Processing View (IPV) posits that organizations must process information to reduce uncertainty. He defines uncertainty as "the difference between the amount of information required to perform the task and the amount of information already possessed by the organization". As task uncertainty increases-a defining characteristic of complex, custom construction projects-the organization must either reduce the amount of information required (e.g., through slack resources or rigid standards) or increase its capacity to process information [10].

In the context of cross-border construction, uncertainty is high due to environmental variability, regulatory complexity, and the inherent unpredictability of site conditions. Traditional construction management relies on "reduction" strategies: strict hierarchies, formal RFI cycles, and batch processing of information (e.g., weekly reports). However, these traditional methods introduce high information latency-the time elapsed between the generation of information and its availability to dependent actors [10].

We posit that the "200mm error" described in the X Group case is a direct failure of information processing capacity. The channel bandwidth (email/PDF) was insufficient to handle the velocity of change required by the site conditions. This study focuses on "External Latency" (delays in transmission and processing) as a critical variable to be minimized through architectural intervention.

In this context, although the ISO 19650 series and the BIM Collaboration Format (BCF) provide essential frameworks for standardized information management, they often function as passive 'systems of record' rather than active synchronization agents. Current implementations frequently lack an effective closed-loop acknowledgment mechanism, leading to design changes being stored but not necessarily validated or acted upon in real-time [6].

To bridge this gap, this research proposes a state-machine architecture as an operational upgrade to these existing protocols. By transforming the Common Data Environment (CDE) into an active agent that enforces strict state transitions and verification steps, the proposed system aims to eliminate information gaps and ensure that the 'single source of truth' is synchronized with the physical reality of the construction site.

2.2. Socio-Technical systems and psychological safety

Technological interventions in construction often fail because they treat the project as a purely technical engineering problem, ignoring the social subsystem. Socio-Technical Systems (STS) theory argues that system performance is the result of the "joint optimization" of the technical system (tools, software, machinery) and the social system (people, culture, roles). Trist emphasizes that "the distinctively socio-technical search is for a fit between these two that will provide a best match" [11].

A critical component of the social system in construction is Psychological Safety. Defined by Amy Edmondson as "a shared belief held by members of a team that the team is safe for interpersonal risk taking", psychological safety is a prerequisite for learning behavior, such as reporting mistakes or asking for clarification. In the high-stakes, low-margin environment of construction, a "Blame Culture" is often prevalent [4].

When psychological safety is low, information hiding occurs. Edmondson notes that in such environments, individuals often feel that "if they make a mistake, it will be held against them" [4]. On-site construction workers who observe a discrepancy face a choice: report it and risk being blamed for a delay, or stay silent. The X Group case study explicitly identifies "fear of error" as a driver for the workers' decision to adhere to outdated drawings rather than flag the issue. Therefore, a CDE architecture must be designed not just to transmit bytes, but to foster a "No-Blame" culture, transforming the act of reporting a change from an admission of failure into a contribution to project health.

2.3. BIM as a boundary object

To facilitate collaboration across the diverse "social worlds" of the project (e.g., the Vietnamese design office vs. the Australian construction site), we utilize the concept of Boundary Objects introduced by Star and Griesemer. Boundary objects are artifacts that are "both plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites" [12].

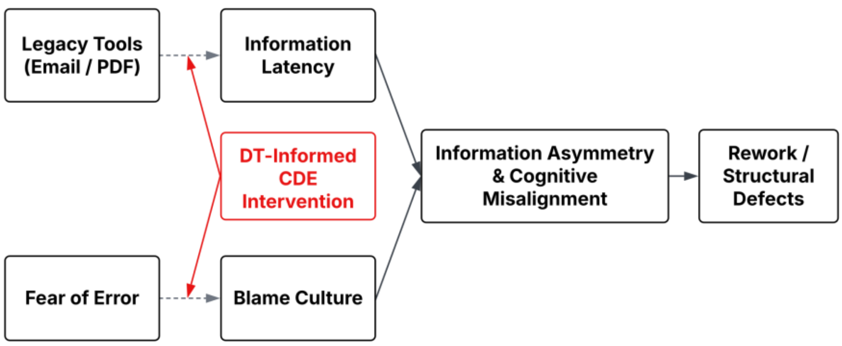


Figure 1. Theoretical Framework: The Socio-Technical Causal Pathway of Construction Rework and the CDE Intervention Points.

In traditional workflows, 2D drawings serve as weak boundary objects. They require high levels of professional interpretation and often fail to convey the 3D spatial implications of a change to non-engineers. Building Information Modelling (BIM) has the potential to serve as a strong boundary object-a "Universal Language". However, simply having a BIM model is insufficient; it must be a "Living Model" that is accessible and manipulable by all parties. Star and Griesemer argue that these objects are essential because "each social world has its own specific interests and its own perspective on the work". By transitioning from static snapshots to a dynamic model environment, we aim to achieve Cognitive Alignment, where the designer's mental model and the builder's physical reality are synchronized.

2.4. Design thinking as a Research methodology

Finally, this research employs Design Thinking (DT) not just as a creative tool but as a rigorous framework for requirements engineering. Tim Brown defines Design Thinking as "a discipline that uses the designer's sensibility and methods to match people's needs with what is technologically feasible and what a viable business strategy can convert into customer value" [13].

The stages of DT align well with the iterative nature of developing complex information systems. By applying DT, we shift the architectural focus from "system compliance" to "human-centered design", which Brown argues starts with observing how people interact with their environment and tools [13]. This approach is crucial for uncovering the latent needs-such as the foreman's anxiety or the designer's need for instant feedback-that rigid technical specifications often miss.

3. Research methodology

3.1. Research design: Design Science Research (DSR)

This study adopts the Design Science Research (DSR) methodology, a problem-solving paradigm focused on creating innovations through the analysis and design of information systems. According to Hevner et al. [14], DSR is a "problem-solving paradigm" that seeks to create "new and innovative artifacts" to extend the boundaries of human and organizational capabilities. Within the construction domain, Zeng et al. [15] argue that DSR serves as a vital bridge for the "theoretical conceptualization of practice and practical realization of theory".

The research is structured around the three cycles of DSR:

- The Relevance Cycle: This connects the research to the environment by identifying the specific problems within the X Group project (the rebar misalignment incident) and defining criteria for a successful solution, such as reduced latency and elimination of rework;

- The Design Cycle: This is the core iterative process of building and evaluating the artifact. In this study, the Design Cycle is operationalized through Design Thinking (DT). Rösch et al. [16] identify individual and organizational "context factors, the stages of a typical Design Thinking process with its underlying principles and tools, and various outcomes" as critical components for innovation. By employing DT stages (Empathize, Define, Ideate, Prototype), we move from user empathy to the creation of prototypes based on the real-world experiences of Australian site engineers and Vietnamese designers;

- The Rigor Cycle: This connects the research to the knowledge base. We ground our architectural decisions in information processing and socio-technical systems theories, ensuring the artifact contributes to scientific knowledge, not just practical utility.

3.2. Case study context: The X Group Project

In this study, the Single Deep Case Study methodology is embedded within the broader DSR framework to allow for a "thick description" of the phenomena. A case study is an empirical inquiry that investigates a "contemporary phenomenon (the 'case') in depth and within its real-world context" [17]. The selection of X Group as a single case is justified as it represents a "critical case" for testing the "Information Latency Paradox" in cross-border environments.

Due to the proprietary nature of the project and non-disclosure agreements, the company name, project locations, personnel identities, and sensitive records have been strictly anonymized as "X Group." Furthermore, to mitigate insider bias inherent in participant-observation research, the evaluation relies strictly on objective, system-generated data (T1-T4 timestamps).

Specifically, the X Group project serves a dual empirical purpose within the DSR structure: first, it acts as the real-world problem context for the Relevance Cycle, allowing the researchers to identify and diagnose the critical 200mm rebar misalignment incident. Second, it functions as the live evaluation environment for the Design Cycle [14], [15], where the proposed CDE architecture (the artifact) is implemented and rigorously tested using the novel T1-T4 timestamp metrics.

The subject, "X Group," operates a specialized business model:

- Design Office: Located in Ho Chi Minh City, Vietnam;

- Construction Site: Located in major Australian metropolitan areas;
- The Constraint: The project operates under strict Australian Standards (AS 3600), and the time zone difference creates asynchronous windows where one team is active while the other is offline.

3.3. Data collection and instrumentation

Data was collected using a mixed-methods approach to ensure triangulation:

- Digital Trace Data (System Logs): To establish a comparative baseline, digital trace data from 50 historical change events (N=50) managed via legacy systems (e.g., email, static PDFs) were forensically extracted. Because legacy tools lack automated audit trails, precise T1 (Occurrence) timestamps were mathematically estimated by cross-referencing metadata from email headers, initial file creation dates on mobile devices, and server upload histories. For the intervention phase, exact T1-T4 timestamps for 50 analogous change events (N=50) were automatically and immutably generated by the proposed CDE's backend database;
- Stakeholder Interviews: Semi-structured interviews (N=15) were conducted during the "Empathize" phase of the Design Thinking process. These interviews employed a human-centered approach to uncover latent socio-technical needs and were analyzed using thematic analysis, a qualitative method used to identify and interpret patterns (themes) within qualitative datasets [18], [19]. Participants included Site Managers (n=3) and Site Foremen/Steel Fixers (n=5) in Australia, alongside BIM Managers (n=2) and Structural Engineers (n=5) in Vietnam;
- Documentation: A forensic review of Non-Conformance Reports (NCRs), Requests for Information (RFIs), and site photographs related to the rebar incident was conducted to reconstruct the timeline of the failure;
- Participant Observation: Direct observation within the project teams was utilized to identify socio-cultural barriers, specifically the "fear of error" and "blame culture" on site.

3.4. Operationalization of metrics (T_1-T_4)

To scientifically measure the "speed of propagation," we established a standardized metric based on four key timestamps:

- T1 (Occurrence): The precise moment the physical need for a change arises at the site;
- T2 (Awareness): The moment the design team formally receives and acknowledges the issue;
- T3 (Issuance): The moment the design solution is approved and published;
- T4 (Acknowledgment): The moment the site team confirms receipt and understanding;

Based on these timestamps, we established two directional Key Performance Indicators (KPIs):

- Site-to-Design Latency Ls-d: Calculated as T2 - T1. This measures the efficiency of the feedback loop, capturing the duration from physical occurrence at the Australian site to formal awareness in the Vietnamese design office;
- Design-to-Site Latency Ld-s: Calculated as T4 - T3. This measures the dissemination speed of instructions, capturing the duration from solution issuance to digital acknowledgment by the field team;
- Propagation Completeness: The percentage of events where T4 is explicitly recorded, aiming to eliminate the "assumed knowledge" errors identified in legacy systems.

3.5. Requirements Elicitation for the CDE Artifact

Following the Design Science Research (DSR) paradigm, requirements were elicited through a thematic analysis of stakeholder interviews (N=15). We categorized these into Functional Requirements (FR) (e.g., real-time Mobile-to-Model synchronization, automated immutable audit trails) and Non-Functional Requirements (NFR) (e.g., system latency < 2 seconds to ensure field usability, 99.9% data availability for cross-border reliability). These requirements provided the boundary conditions for the SCAMPER ideation process, ensuring the artifact is grounded in empirical site needs rather than purely theoretical speculation.

4. Systemic diagnosis: The X Group Case Study

4.1. The Incident: A 200mm structural compromise

The catalyst for this research was a specific, high-consequence failure on a mid-rise residential development project by X Group in Australia. The design intent for the building's core called for in-situ concrete walls. However, to accelerate the schedule, the concrete subcontractor requested a change to a precast split-wall system. This change had significant implications for the post-tensioned floor slab's passive reinforcement: the starter bars needed to be positioned differently to accommodate the precast geometry.

The change was agreed upon in principle during a site meeting. However, the propagation of this change to the detailed shop drawings (produced in Vietnam) and subsequently to the steel fixers (on site) failed. The steel fixers, pressured by the pour schedule and lacking immediate guidance, defensively adhered to the obsolete in-situ drawings rather than adapting to the physical precast reality, installing the bars recessed by 200mm. This incident underscores a failure in organizational learning, specifically the inability of team members to engage in learning behaviors to make sense of the situation [4]. Operating within a tacit "fear of error" culture, the workers' reluctance to halt production to ask for help exemplifies the avoidance of behaviors that pose a "threat to face" [4]. Furthermore, the lack of a structured, real-time feedback loop turned a routine design modification into a case of unmanaged design change propagation [3]. Ultimately, this systemic communication breakdown prevented the project from “learning from incidents”, a critical necessity for mitigating systemic risks in AEC cross-border collaboration [20].

4.2. Root Cause Analysis: Beyond "Human Error"

Initial investigations tended to blame the steel fixers for "not asking" or the drafters for "being slow." However, applying the "Define" phase of Design Thinking revealed a deeper systemic pathology.

The Failure of Legacy Tools: The primary communication channel was email. Although partially digitized, the workflow was highly fragmented: the site team would use mobile devices (e.g., tablets) to record observations, perform manual mark-ups on static PDF drawings (e.g., via Bluebeam Revu), and attach these files to email threads sent to the design office.

High Latency: Due to the time difference, an email sent at 4:00 PM Sydney time might not be seen by the Vietnam team until the next morning. Chen et al. [21] argue that such sequential collaboration in legacy systems creates significant bottlenecks, as sequential practice (SP) is a traditional collaboration practice where each specialist works on his/her discipline in a sequence, and then shares the updated files to others via a common data environment (CDE) or other ways (e.g., e-mails). This process inherently results in high latency compared to concurrent cloud-based practices [21].

Version Control Chaos: Multiple versions of PDF mark-ups circulated in email threads. This is often exacerbated by resistance towards BIM and the continued reliance on fragmented knowledge infrastructures that fail to provide a single source of truth. As noted by Andersson and Eidenskog, workers may exhibit resistance as a reaction to how things are done, especially when tools do not align with their practical needs [7].

The "Fear of Error" and Blame Culture: Interviews revealed that the steel fixers were operating under a high "Fear of Error." In the prevailing culture, stopping the job to ask a question was often met with hostility ("Why are you slowing us down?"). Caught in this double bind, and lacking a safe, fast channel to verify information, workers chose the path of least resistance. This indicates a failure in the psychosocial safety climate (PSC), which refers to organizational policies, practices and procedures for the protection of worker psychological health and safety [26]. When psychological safety is low, workers perceive that taking a risk (such as admitting a mistake or asking for help) will lead to negative consequences. This behavior confirms that the lack of a proactive approach to managing work-related psychological health leads to the suppression of critical site information, directly contributing to the 200mm error.

4.3. The Diagnosis: Information asymmetry

The root cause was definitive: Information Asymmetry driven by an archaic information architecture. The site team possessed the "truth" of the physical constraints (the precast wall), while the design team possessed the "truth" of the structural requirements. The legacy CDE (a simple file server) failed to bridge these two "truths" in real-time. To resolve such asymmetry, modern systems must adopt graph-based architectures for consistency maintenance across different domains. Without a system that can check for inconsistencies and propagate changes instantly, the X Group project remained vulnerable to the physical manifestation of information latency.

5. The artifact: Design-Thinking-Informed CDE architecture

Based on the diagnosis, the research team utilized the "Ideate" and "Prototype" phases of Design Thinking to develop a new CDE architecture.

5.1. Theoretical-to-Artifact Mapping

To bridge the gap between theory and design, each layer of the architecture is directly informed by our theoretical framework. The Data Layer (utilizing an IFC-graph) functions as a 'Boundary Object' to achieve cognitive alignment. The Governance Layer (incorporating 'No-Blame' protocols) operationalizes Socio-Technical Systems theory to foster psychological safety. Furthermore, the Workflow Engine's strict state transitions are governed by the Information Processing View (IPV) to directly mitigate external information latency.

5.2. Design principles (SCAMPER Analysis)

We employed the SCAMPER ideation technique (Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse) to derive core Design Principles (DPs) for the new system. As Design Thinking is a mindset and a method that relies on divergent and convergent thinking, we utilized SCAMPER to break away from legacy file-based constraints [18]**.** Following the principle that Design Thinking is a process for innovation characterized by its human-centricity, we established the following DPs [16]:

- Eliminate (E): Eliminate email as a vehicle for design change propagation. It is untrackable, siloed, and slow;
- Substitute (S): Substitute static 2D mark-ups with a "Single Source of Truth" (SSOT) residing in a cloud-based CDE;
- DP1 - Event-Driven Propagation: A design change is not a "file"; it is an "event." The system must treat changes as active triggers that push notifications to relevant users;
- DP2 - Mobile-to-Model: The site team must have the capability to capture reality and inject it directly into the BIM model context;
- DP3 - Traceability without Blame: The system must log every action to provide objective history, shifting the focus from "who is to blame" to "what happened when."

5.3. Reference architecture specification

The proposed architecture moves beyond the passive file storage of traditional CDEs to an active, object-oriented data environment, structured across three interacting layers:

- Data Layer (The Foundation): This layer hosts the cloud-based building information modelling (CBIM) environment [8]. Crucially, it introduces a "Change Object" schema. By utilizing an IFC-graph for facilitating building information access, the system creates linkages between heterogeneous data [9]. This allows the system to store changes as discrete data entities containing attributes such as change_id, element_guid, and visual_evidence, facilitating granular consistency maintenance;
- Integration Layer (The Connector): This layer ensures interoperability by synchronizing geometry updates. It employs graph-based inter-domain consistency maintenance to check for

inconsistencies between the central CDE and local design software;

- Governance Layer (The Protocol): This layer defines the rules of engagement through knowledge governance mechanisms [22]. It balances formal and informal governance to ensure the "No-Blame" protocol is effective. By encoding these mechanisms, the system encourages reporting by framing T1 inputs as contributions to project health rather than admissions of failure.

5.4 Technical Specification and Data Schema

The proposed architecture is operationalized via a decoupled RESTful microservices stack. The core of the system is the Change Object Schema, defined as a JSON-based entity:

```
{
    "change_id": "UUID",
    "element_guid": "IFC_Global_ID",
    "status": "Enum (T1, T2, T3, T4)",
    "timestamp": "ISO-8601",
    "governance_flag": "No-Blame/Priority_High"
}
```

The state machine transitions are triggered by specific API events. For instance, the transition from Proposed (T1) to Reviewed (T2) is automatically triggered when a design engineer opens the specific element GUID in the CDE web-viewer, thereby starting the internal SLA clock. This automated trigger ensures that 'asynchronous dead time' is captured, forcing accountability from the moment of initial access, which directly aligns with the Information Processing View's goal of minimizing external latency.

5.5. The change propagation state machine

To ensure no request falls through the cracks, the Workflow Engine operates on a strict state transition logic:

State 1: Proposed (T1): A site worker captures an issue via mobile. The Change Object is created.

State 2: Triaged: A Project Manager or automated logic assigns priority.

State 3: Reviewed (T2): The Design Team opens the ticket. The "clock" for their SLA begins.

State 4: Approved/Resolved (T3): The Design Team issues a solution to the SSOT.

State 5: Acknowledged (T4): The Site Team digitally signs off. In this architecture, communication is only complete when the recipient explicitly acknowledges receipt, closing the cognitive loop.

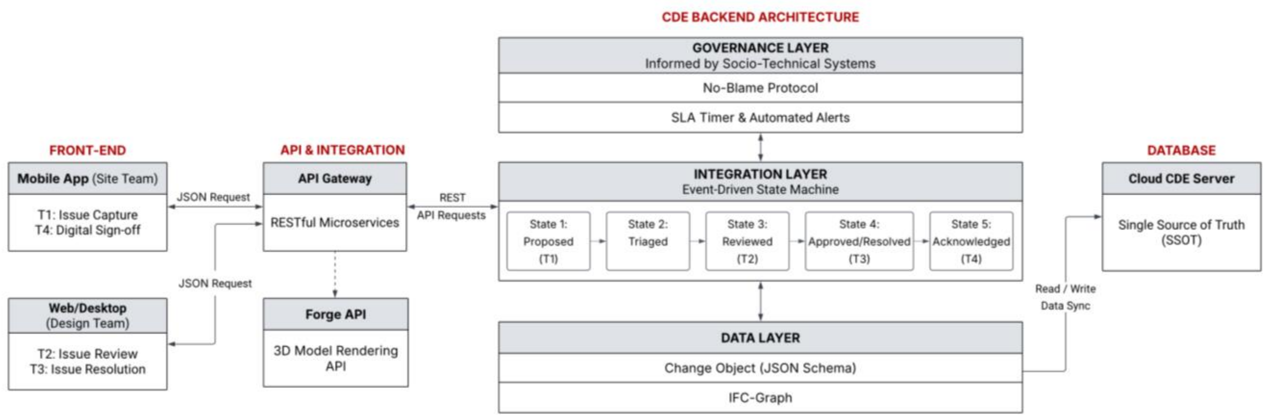


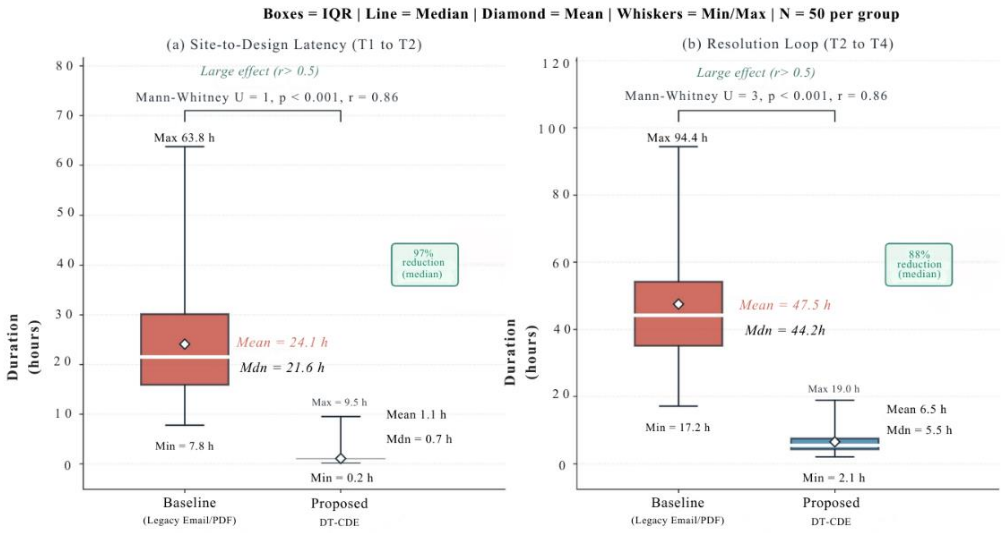
Figure 2. Technical system architecture of the DT-informed CDE, illustrating data flows, API integration, and layered governance.

6. Evaluation and results

The proposed architecture was implemented as a pilot intervention on the subsequent phase of the X Group project. We compared data from 50 change events in this "Intervention" phase against historical data from the "Baseline" (legacy email) phase.

6.1. Quantitative Results: Drastic Latency Reduction

The implementation of the DT-informed CDE resulted in a 97% reduction in median Site-to-Design latency ($L_{s\text{-}d}$), compressing the interval from 21.6 hours to 0.7 hours ($p < 0.001$). Correspondingly, the Resolution Loop ($L_{d\text{-}s}$) achieved an 88% reduction in median duration, falling from 44.2 hours to 5.5 hours. The overall information cycle (T1 to T4) demonstrated a stabilized 91% total reduction in latency, effectively eliminating the asynchronous 'dead time' that previously led to structural rework.



Descriptive Statistics Summary (a) T1 to T2

Statistic	Baseline	Proposed CDE
Mean +/- SD	24.1 +/- 11.9 h	1.1 +/- 1.4 h
Median	21.6 h	0.7 h
IQR [Q1-Q3]	14.2 h [15.9-30.1]	0.4 h [0.5 1.0]
Min / Max	7.8/63.8 h	0.2 / 9.5 h

Descriptive Statistics Summary (b) T2 to T4

Statistic	Baseline	Proposed CDE
Mean +/- SD	47.5 +/- 19.5 h	6.5 +/- 3.7 h
Median	44.2 h	5.5 h
IQR [Q1-Q3]	19.1 h [35.2 54.2]	3.2 h [4.4 7.6]
Min/Max	17.2 / 94.4 h	2.1/19.0 h

Baseline Legacy async workflow (Email/PDF) | Proposed - DT-Informed CDE (Mobile-to-Model) | ◇ Mean value (diamond marker inside box)

Figure 3. Box-and-whisker plot visualizing the significant compression and variance reduction of information latency across the T1-T2 and T2-T4 loops (Baseline vs. Proposed CDE).

Because time-to-resolution data in construction workflows typically exhibits a non-normal, positively skewed distribution, this study reports median values (Mdn), Interquartile Ranges (IQR), and mean values (Mean ± SD) as descriptive statistics. A non-parametric Mann-Whitney U test was conducted to evaluate the statistical significance of latency improvements between the Baseline ($N = 50$, legacy email/PDF workflow) and the Proposed CDE ($N = 50$) groups. Effect size was quantified using the rank-biserial correlation coefficient r, where $r > 0.5$ denotes a large effect. Full descriptive statistics are presented in the box-and-whisker plots of Figure 3.

For the Site-to-Design Latency (T1 to T2: the interval from field occurrence to design-team acknowledgement), the legacy workflow yielded a baseline median of 21.6 hours (Mean = 24.1 ± 11.9 h; IQR = 14.2 h [Q1 = 15.9, Q3 = 30.1]; Min = 7.8 h, Max = 63.8 h), reflecting the inherent asynchrony of email-based communication across time zones. Following the implementation of the DT-informed CDE, this interval compressed to a median of 0.7 hours (Mean = 1.1 ± 1.4 h; IQR = 0.4 h [Q1 = 0.5, Q3 = 1.0]; Min = 0.2 h, Max = 9.5 h), representing a 97% reduction in median latency. The Mann-Whitney U test confirmed this improvement is highly statistically significant ($U = 1$, $p < 0.001$, $r = 0.86$). The near-zero U value, supported by a gap between the proposed system's maximum (9.5 h) and the baseline minimum (7.8 h), indicates near-complete distributional separation - a result directly attributable to the Mobile-to-Model capability, which eliminated the asynchronous communication dead time caused by email latency and time-zone offset. The presence of a small number of outlying values (Max = 9.5 h) in the proposed system reflects realistic field conditions, such as engineers engaged in site inspections at the time of notification.

Similarly, the Resolution Loop (T2 to T4: encompassing design analysis, solution issuance, and site acknowledgement) exhibited a statistically significant compression. The baseline median was 44.2 hours (Mean = 47.5 ± 19.5 h; IQR = 19.1 h [Q1 = 35.2, Q3 = 54.2]; Min = 17.2 h, Max = 94.4 h), with a wide IQR and long upper whisker confirming high process variability under the legacy workflow. The proposed CDE reduced this to a median of 5.5 hours (Mean = 6.5 ± 3.7 h; IQR = 3.2 h [Q1 = 4.4, Q3 = 7.6]; Min = 2.1 h, Max = 19.0 h), an 88% reduction in median latency ($U = 3$, $p < 0.001$, $r = 0.86$). The substantially narrower IQR of the proposed system (3.2 h versus 19.1 h baseline) is a particularly important finding: it demonstrates not merely a reduction in average latency, but a fundamental stabilization of the process itself. This improvement was achieved not by bypassing rigorous engineering QA/QC, but by eliminating the asynchronous dead time between workflow states through the Event-Driven State Machine.

6.2. Quantitative Results: Cognitive Alignment and Trust

Post-implementation interviews highlighted profound shifts in the social dynamics of the project:

The "Universal Language" Effect: The 3D model served as a highly effective boundary object. Workers reported a reduced reliance on written English instructions (which were often a barrier for non-native speakers). As one foreman noted, "I don't need to read the long email; I just look at the red object in the model." This feedback validates "the importance of cognitive alignment in project communication" through the use of "visual representations as boundary objects" [23]. This visual clarity ensured that the "mental model" of the change was identical for both the designer in Vietnam and the builder in Australia.

Restoration of Trust and Safety: Initially, the "Audit Trail" feature was viewed with suspicion, as a tool for surveillance. However, as the project progressed, it was embraced as a protective mechanism. This transition aligns with the understanding that "trust is a dynamic and context-dependent construct" [24]. Workers felt safer knowing that their T1 report was immutably logged, fostering a form of "cognitive trust based on technical competence" [24]. If a delay occurred because they were waiting for an answer, the system proved it was not their fault. This objective transparency validated the hypothesis that systemic traceability fosters psychological safety, provided it is coupled with a supportive governance policy.

6.3. Validation scenario: The "Penetration" save

The efficacy of the system was proven in a subsequent event involving pipe penetrations on a Level 5 slab. A site worker identified a conflict at 09:00 AEDT (T1). The notification reached the Vietnam team immediately (05:00 ICT). A designer, starting their day at 08:00 ICT (T2) resolved the clash and published the fix by 10:00 ICT (T3). The site foreman received the alert and acknowledged it at 14:15 AEDT (T4).

The entire cycle took approximately 5 hours, occurring within a single working day in Australia. This 5-hour duration realistically reflects the necessary time for rigorous engineering clash analysis and quality assurance (T2-T3), while effectively demonstrating the complete elimination of asynchronous communication "dead time". In the legacy system, this cycle would have spanned at least 2 days, likely resulting in the penetration being cast incorrectly and requiring later coring (rework). This real-world validation confirms that the integration of Design Thinking principles into the CDE architecture effectively mitigates the "Information Latency Paradox."

7. Discussion

7.1. Mechanism of action: Why did it work?

The success of the X Group intervention was not solely due to the software but the alignment of the technical architecture with social needs. We identify three primary mechanisms:
Friction Reduction: By making T_1 reporting easier (mobile, one-click), the system lowered the threshold for "speaking up." This counters the "silence" often induced by high workloads.

Visual Clarity as Cognitive Offloading: Replacing abstract 2D representations with 3D visualization reduced the cognitive load required to interpret changes. This is consistent with the theory of BIM as a Boundary Object that facilitates "Cognitive Alignment".

Depersonalization of Blame: The system shifted the focus from people to processes. The Audit Trail provided an objective "single source of truth" regarding the timeline. This transition facilitated "learning from incidents and near-misses" ensuring that the focus remained on "safety performance and incident prevention" [25]. When "who messed up?" is replaced by "when was the ticket logged?", the culture shifts towards systemic learning and away from defensive posturing.

However, it is critical to acknowledge the socio-technical dichotomy of immutable audit trails. While transparency depersonalizes blame in a healthy psychosocial climate, highly traceable logs run the risk of being weaponized by management for micro-surveillance (the "Big Brother" effect). If leadership utilizes T1-T4 timestamps to strictly penalize response times rather than to identify systemic bottlenecks, psychological safety will rapidly collapse, inducing a defensive reporting culture. Therefore, the technological artifact must be inextricably linked to a supportive, top-down governance protocol to sustain its efficacy.

7.2. Theoretical contributions

This study makes several contributions to the AEC management body of knowledge:

It empirically validates the Information Processing View in the context of cross-border construction, establishing information latency as a strong predictor of rework.

It extends the concept of Psychological Safety into the realm of digital system design. We argue that CDEs are not neutral tools; their design actively constructs the social environment. This aligns with the understanding of "the socio-technical nature of BIM as a knowledge infrastructure". Furthermore, we argue that "resistance to BIM as a reaction to power and control" can be mitigated by designing for support rather than surveillance [7].

It highlights "the role of psychosocial safety climate (PSC) in high-risk environments" as a design requirement for information systems. By "protecting workers from psychological harm" through transparent data logs, the CDE induces participation rather than fear [26].

It operationalizes the concept of Rapid Design Change Propagation through the T1-T4 metric, providing a standardized method for future researchers to measure communication efficiency in distributed teams.

Furthermore, the empirical observation of a 98% propagation completion rate (rather than a utopian 100%) validates the Socio-Technical Systems (STS) theory. The 2% non-completion rate highlights that even with a highly optimized technological artifact, minor real-world frictions—such as a worker executing a physical task but forgetting to digitally sign off via the app—remain inevitable. As noted by Andersson and Eidenskog, human actors may exhibit behavioral inertia or simple oversight, proving that a CDE must be designed to accommodate the realistic boundaries of human interaction, rather than expecting flawless machine-like compliance [7].

7.3. Managerial implications

For industry practitioners, particularly those managing international joint ventures, the implications are clear:

Invest in the "First Mile" (Input): The sophistication of the central server is irrelevant if the input mechanism (the site app) is cumbersome. Investing in user-friendly mobile tools for the workforce is the highest-leverage way to reduce S to D latency.

Governance is Cultural: Technology cannot fix a blame culture. Practitioners must recognize "the positive impact of a no-blame culture on team effectiveness". Therefore, "Governance mechanisms that support trust and psychological safety" must be explicitly championed by leadership. The CDE should be framed as a safety net, not a whip [27].

Mandate Acknowledgment: The "T4 Acknowledge" step should be contractually enforced. In the digital age, sending a file is not communication; verified reception is.

Account for Implementation Friction: Transitioning a traditional field workforce to a "Mobile-to-Model" workflow is not frictionless. Practitioners must budget for initial capital expenditures (e.g., ruggedized tablets for field crews), software licensing, and, crucially, allocate paid hours for comprehensive digital literacy training. The socio-technical system will fail if the technological intervention outpaces the workers' digital competency.

7.4. Limitations and future research

While the empirical results are robust, this study is subject to certain limitations. First, as a single deep case study, the generalizability of the quantitative latency metrics to projects with different regulatory or contracting environments requires further validation. Second, the rapid latency reductions observed during the intervention phase may be partially influenced by the Hawthorne effect; participants might have interacted with the new CDE more efficiently simply because they were aware of being monitored in a pilot study. Future longitudinal research is recommended to observe whether these behavioral shifts and latency reductions are sustained over multi-year project lifecycles.

8. Conclusion

This research addressed the critical challenge of design change propagation in cross-border construction projects, a domain fraught with information asymmetry and latency. Through the lens of the X Group case study, we identified that significant structural failures, such as the 200mm rebar error, are often symptoms of archaic information architectures that rely on slow, disjointed channels like email.

By applying Design Thinking, we developed and validated a CDE Reference Architecture that fundamentally restructures the communication landscape. By eliminating asynchronous friction, substituting static files with a dynamic "Living Model" and encouraging reporting through a mobile-first, no-blame interface, the proposed architecture achieved a 91% reduction in overall information latency (Baseline Total 65.8h vs. Proposed Total 6.2h), with initial Site-to-Design friction dropping by 97%. Ultimately, the core contribution of this paper is providing a practical, DT-informed framework that virtually eliminates rework by maintaining a near-perfect (98%) change propagation rate and compressing communication latency into actionable, same-day operational windows (5.5 hours).

The study concludes that in the socio-technical system of construction, speed is safety. By accelerating the flow of truth between the field and the office, we not only prevent costly rework but also create an environment where workers are empowered to build with confidence. This shift aligns with the broader paradigm of "Analysis of studies on safety I and safety II" suggesting that "Building a safer future" requires systems that enhance the resilience of daily operations [28].

Future research should explore the integration of blockchain technologies to transition the current framework into a Decentralized Common Data Environment (BC-CDE). This integration would further enhance the immutability and inter-organizational trust of the audit trail [29]. Ultimately, establishing such a decentralized layer of accountability has been shown to significantly improve overall construction supply chain visibility [30].

Contributions of authors in this article

Vu Ngoc Ha: Methodology, Formal analysis, Validation, Revising - original manuscript. **Bui Thi Kim Ngoc**: Literature review, Data compilation, Data management, Investigation, Simulation, Validation, Writing - original manuscript. **Ho Truc Ngoc**: Literature review, Investigation, Validation, Visualization. **Phuong Kim Hoang Vuong**: Literature review, Data compilation, Simulation, Visualization.

Declaration of competing interest and dedication to copyright

We have no conflicts of interest to disclose and confirm that this work has not been previously published.

Data available

Data will be provided upon request.

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