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Research Article

# From Fragmented Site Information to Closed-Loop Coordination: Development of an Evidence-Traceable BIM Framework for Super High-Rise Construction in Xi'an, China

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## Abstract

Digitalisation has increased the volume of information available on construction sites, yet specialised models, monitoring systems, quality records, equipment platforms, and safety workflows frequently remain disconnected. This study develops an evidence-traceable Building Information Modelling (BIM)-driven smart construction-site management framework for super high-rise projects in Xi'an, China. A design-science-oriented procedure transformed the empirical outputs of 15 semi-structured interviews into a candidate management artefact. The antecedent dataset comprised approximately 87,000 Chinese characters of transcript material, a refined 118-code codebook, 15 role-domain stakeholder needs, and 28 functional requirements (22 Core and 6 Supporting). These inputs were triangulated with international and Chinese information-management standards, recent BIM-IoT and digital-twin literature, and contextual constraints of super high-rise construction. A nine-step development process established the design-input repository, mapped requirements to candidate elements, formed modules, compared layer arrangements, specified BIM-site data associations, designed process and state rules, defined interfaces and permissions, prepared representations, and completed internal checks. The resulting Framework V1.0 contains four technical layers and four configurable management modules connected by a BIM spatial/object index and a unified event-responsibility loop. Structural mapping located all 28 requirements within the framework. Walkthroughs of four representative scenarios produced continuous conceptual paths from data acquisition and spatial association to judgement, task assignment, action, reinspection, closure, and archiving. The contribution is not a new collection of isolated digital functions, but a requirements-driven coordination architecture

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that distinguishes authoritative data sources from the BIM index and makes responsibility and closure explicit. The reported 28/28 result demonstrates design coverage only; it does not establish software implementation, user acceptance, or field-performance improvement. Expert evaluation and subsequent field testing remain necessary.

**Keywords**

Building information modelling, Smart construction site, Super high-rise construction, Requirements engineering, Closed-loop management

## 1. Introduction

Super high-rise construction concentrates complex structural cycles, vertical logistics, temporary works, geotechnical risk, and safety-critical operations within a rapidly changing production environment. These conditions generate large volumes of model, schedule, monitoring, quality, equipment, personnel, and inspection data. Building Information Modelling (BIM), the Internet of Things (IoT), mobile applications, and smart-site platforms can improve visibility and information availability, but technology availability alone does not ensure that the information needed for management decisions is current, spatially located, responsibility-linked, or traceable to closure (Tang et al., 2019; Turk, 2020; Huang et al., 2023).

BIM research has long emphasised coordinated information and lifecycle value (Succar, 2009; Azhar, 2011), while more recent work has extended the discussion towards IoT integration, digital twins, and cyber-physical synchronisation (Deng et al., 2021; Opoku et al., 2021; Tuhaise et al., 2023; AlBalkhy et al., 2024). Nevertheless, a persistent implementation gap remains. A model may visualise a floor or element without representing the latest construction state; an equipment system may record load and operating status without receiving structured transport demand; a monitoring platform may issue a numerical alert without identifying the relevant excavation zone, support section, construction stage, and responsible organisation. In these cases, digital records exist, but the relationships required for timely and accountable action do not.

This distinction is particularly consequential in Xi'an. Super high-rise projects may combine deep foundation pits in collapsible-loess contexts (Li et al., 2024), repeated core-tube construction cycles, constrained vertical transportation, and continuously changing work-at-height hazard zones. The management problem is therefore not reducible to a single application or sensor. It concerns how heterogeneous evidence is linked to space, time, work activity, status, responsibility, and closure. Existing smart construction-site studies identify technology, organisation, standards, and data integration as critical development factors (Liu et al., 2021; Xiahou et al., 2022), but many proposed platforms remain technology-led or domain-specific. A requirements-driven management architecture is needed to show why each element exists, what it is responsible for, which data remain authoritative

elsewhere, and how a detected condition becomes a closed and auditable management event.

The empirical diagnosis preceding this study identified four management-problem domains in Xi'an super high-rise construction: disconnected foundation-pit monitoring and response; fragmented core-tube coordination and quality traceability; inefficient vertical transportation and equipment coordination; and discontinuous work-at-height safety management. A cross-cutting information-coordination failure connected the four domains. That diagnostic work intentionally stopped before designing a solution. The present paper addresses the next research objective: to transform the resulting stakeholder needs and functional requirements into an initial BIM-driven smart construction-site management framework.

Accordingly, the research question is: How can empirically derived management requirements be converted into an evidence-traceable BIM-driven smart construction-site framework that supports spatial association, cross-domain coordination, accountable action, and closure without overstating technological capability? The study makes three contributions. First, it provides a transparent transformation method from qualitative evidence to a design artefact. Second, it specifies an architecture in which BIM acts as a bounded spatial and object index across heterogeneous authoritative systems. Third, it operationalises closed-loop management through common event states, responsibility transitions, and reinspection rules while keeping project parameters configurable. Framework V1.0 is the design output of this stage; its relevance, feasibility, and contextual applicability require subsequent expert review, and its effectiveness requires later implementation and field evaluation.

## 2. Literature and Conceptual Foundation

### 2.1. From model-centric BIM to connected construction information

BIM provides structured digital representations that can support visualisation, coordination, simulation, and information retrieval. Early BIM frameworks established that value depends on processes and stakeholder responsibilities, not solely on software features (Succar, 2009; Eastman et al., 2011). Construction-stage studies likewise show that collaboration and timely information exchange influence whether BIM becomes a shared working environment or remains a specialist modelling activity (Ahuja et al., 2009; Xue et al., 2010; Love et al., 2014). This process perspective is important because super high-rise management decisions often require information generated outside the model authoring environment.

The integration of BIM with IoT and field data has therefore become a major research direction. Tang et al. (2019) found recurring application patterns and persistent interoperability issues in BIM-IoT studies, consistent with persistent model-updating and interoperability concerns in the broader BIM literature (Volk et al., 2014). Huang et al. (2023) subsequently proposed a data-process perspective for BIM-IoT fusion, reinforcing the need to specify how data are acquired, processed, associated, and used.

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Digital-twin scholarship adds the expectation that physical and digital states are meaningfully connected rather than represented by a static model (Deng et al., 2021; Opoku et al., 2021; Sacks et al., 2020a). Yet digital-twin definitions and maturity levels remain diverse, and sophisticated synchronisation or predictive control should not be claimed without corresponding implementation evidence (Tuhaise et al., 2023; AlBalkhy et al., 2024).

For the present study, these findings support a deliberately bounded view of BIM. The model is valuable as a shared spatial and object index, but it need not become the master repository for every raw measurement, schedule transaction, equipment status, photograph, or audit record. Retaining authoritative sources while maintaining stable identifiers reduces duplication and preserves accountability. This position also responds to the broader interoperability argument that integration should enable purposeful exchange across specialised systems without erasing the division of labour that created those systems (Turk, 2020).

## 2.2. Smart construction sites as socio-technical management systems

Smart construction-site research encompasses sensing, communication, platforms, analytics, automation, mobile work, and visual management. Scientometric and factor-structure studies show that maturity depends on more than the adoption of devices; standards, organisational coordination, information integration, workforce capability, and process redesign are also influential (Liu et al., 2021; Xiahou et al., 2022). The practical implication is that a platform organised as a catalogue of technologies may not explain who confirms an anomaly, who accepts a task, which evidence permits closure, or how an event crosses organisational boundaries.

Lean and production-management research similarly stresses the value of shared status and reliable feedback. IoT standards can improve information flow, but managerial value emerges only when information supports coordinated decisions and action (Dave et al., 2016). Digital-twin roadmaps extend this reasoning towards synchronised construction management, while also revealing that many applications remain at monitoring or visualisation levels rather than automated control (Jiang et al., 2024). Reviews of artificial intelligence in construction likewise emphasise that analytical capability must be matched to appropriate data and management tasks (Pan & Zhang, 2021). A credible framework should therefore support automation where rules and data are sufficiently reliable, but retain professional judgement, statutory responsibility, and lower-technology fallbacks where they are not.

## 2.3. Information standards and open exchange

ISO 19650-1 and ISO 19650-2 establish concepts and processes for managing information across delivery activities, while ISO 19650-4 provides process and decision criteria for information exchange. ISO 12911:2023 provides a framework for specifying BIM implementation, and ISO 16739-1:2024 specifies the IFC data schema for open exchange. In China, GB/T 51212-2016 provides a unified basis

for BIM, GB/T 51235-2017 addresses BIM application during construction, and JGJ/T 434-2018 addresses construction-site supervision and management information systems. These standards do not prescribe the four modules developed in this study. Instead, they inform boundaries concerning information identification, exchange, versioning, responsibility, and traceability.

Standards alignment is treated here as design guidance rather than compliance certification. The framework identifies information owners, exchange points, minimum association keys, and audit records, but project-specific contracts, technical schemes, risk thresholds, data-retention rules, and government reporting requirements remain authoritative. This distinction prevents a conceptual framework from being presented as an approved implementation.

### 2.4. Requirements-driven design and the research gap

Design science is appropriate when research seeks to build and justify an artefact that addresses a relevant problem (Hevner et al., 2004; Peffers et al., 2007). Design knowledge should explain the problem context, the artefact, the design principles connecting them, and the limits of evaluation (Gregor & Hevner, 2013). Applied to construction management, this requires more than drawing an architecture: each layer, module, rule, role, and interface should remain traceable to empirical, normative, contextual, or literature evidence.

The reviewed literature provides substantial knowledge on individual technologies and use cases, but three gaps motivate this study. First, the transformation from practitioner evidence into framework components is often insufficiently documented. Second, architectures may assign BIM an unbounded integrative role without defining authoritative data ownership or minimum association granularity. Third, many frameworks describe monitoring and warning but leave action, reinspection, reopening, and closure under-specified. The present study responds with an evidence-traceable, role-aware, and closure-oriented design for four high-consequence super high-rise construction contexts.

## 3. Materials and Methods

### 3.1. Research design and unit of analysis

The study used a design-science-oriented, requirements-driven procedure to develop Framework V1.0. The unit of analysis was not an individual software product. It was the management relationship required to convert a relevant site condition into located information, an authorised judgement, an assigned action, verified completion, and an auditable record. Candidate framework elements were therefore specified in terms of management object, triggering condition, required information, responsible role, association key, state change, interface, and configurable parameter.

The scope was limited to construction-stage site management for super high-rise building projects in Xi’an. Design- and operation-stage information was included only when it provided a direct input or

interface. Software coding, API implementation, live device connection, detailed user-interface design, hardware selection, predictive-algorithm training, and government-system integration were excluded. These exclusions are necessary because the available evidence supports conceptual and process design, not a deployed information system.

## 3.2. Design inputs and empirical provenance

The principal empirical input was the completed first-stage qualitative study. Between March and June 2026, 15 practitioners were interviewed using purposive maximum-variation sampling. Participants represented project/construction management (n = 3), BIM/digital construction (n = 3), safety/environmental management (n = 3), quality/technical management (n = 3), equipment/MEP management (n = 2), and regulatory inspection (n = 1). They averaged 9.7 years of relevant experience and had worked on projects 200-350 m in height. Interviews lasted 30-42 minutes and generated approximately 87,000 Chinese characters of anonymised transcript material. Saturation was judged after Interview P12, with P13-P15 serving confirmatory purposes. The refined codebook contained 118 codes; 20% of transcripts were independently coded and Cohen's kappa was 0.81.

That earlier analysis produced four problem domains, one cross-cutting meta-problem, stakeholder needs for 15 role-domain combinations, and 28 functional requirements. The present study did not recode the interviews or generate new requirements. Instead, it preserved each requirement identifier and attached design attributes including the applicable context, management object, trigger, principal user, BIM association key, expected status output, responsible role, priority, and source. This separation protects the boundary between empirical findings and researcher-generated design choices.

**Table 1**

*Evidence sources and their design roles*

| Source type | Material used | Role in framework development |
|---|---|---|
| Empirical | 15 interviews; problem themes; stakeholder needs; 28 requirements; traceability matrix | Defines management problems, users, required functions, and applicability conditions |
| Normative | ISO 19650-1/-2/-4; ISO 16739-1; GB/T 51212; GB/T 51235; JGJ/T 434 | Constrains information organisation, exchange, versioning, responsibility, and open association |
| Contextual | Super high-rise production cycles; Xi'an geotechnical context; site connectivity and system variation | Defines high-consequence scenarios, configurable parameters, and fallback arrangements |
| Literature | BIM collaboration, BIM-IoT integration, smart sites, digital twins, design science | Supports architecture choices and positions the contribution |

| | | |
|---|---|---|
| Design record | Candidate structures, mapping decisions, internal-check forms, revision log, V1.0 freeze record | Distinguishes evidence from researcher synthesis and supports reproducibility |

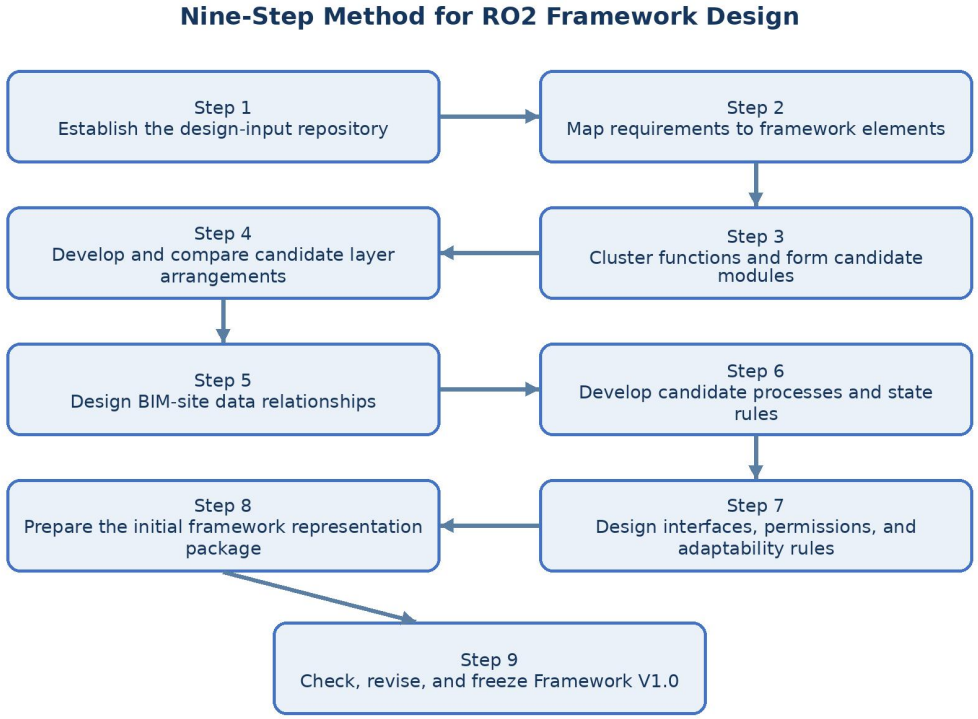
*Note.* The framework is supported by multiple evidence types; researcher-generated clustering and representation remain design choices rather than empirical findings.

## 3.3. Nine-step framework-development procedure

The development procedure comprised nine documented steps (Figure 1). Step 1 established a design-input repository and labelled every input as empirical, normative, contextual, literature-based, or researcher-generated. Step 2 mapped each functional requirement to candidate elements. Step 3 clustered functions and tested whether groups had a single management objective, identifiable inputs and outputs, responsible roles, limited duplication, and the ability to be independently configured. Step 4 developed and compared alternative technical-layer arrangements. Step 5 specified relationships between BIM objects and heterogeneous site data, including minimum association keys. Step 6 designed process chains, event states, transition rules, escalation, reinspection, and reopening. Step 7 defined interfaces, permissions, authoritative sources, and adaptability rules. Step 8 prepared diagrams, tables, scenario descriptions, and the evaluation package. Step 9 completed internal coverage, consistency, traceability, standards-alignment, and boundary checks before freezing V1.0.

**Figure 1**

*Nine-step method for RO2 framework design*



*Note.* Source: Developed by the authors from the documented RO2 design procedure.

### 3.4. Module-formation and architecture criteria

A provisional requirement group became a business module only when it met five criteria: a clearly defined primary management objective; identifiable inputs and outputs; identifiable responsible roles; no unnecessary duplication of master data maintained elsewhere; and independent activation or adjustment as the construction stage changed. Capabilities used by more than one context, including BIM navigation, spatial coding, master data, event states, permissions, interfaces, and dashboards, were treated as shared services rather than duplicated across modules.

Alternative layer arrangements were compared against separation of concerns, support for heterogeneous site systems, traceability, project adaptability, and the risk of assigning decisions to technical devices. The selected four-layer arrangement separates data generation, transmission, integration/service, and management application. This separation makes it explicit that a sensor or imported file supplies data, a transmission channel delivers it, integration services align identities and status, and authorised roles make and close management decisions.

### 3.5. Internal evaluation and claim boundaries

Internal evaluation had two components. First, a structural coverage check asked whether every requirement had at least one primary location in V1.0. Requirements could depend on several elements, but one primary location was recorded to avoid double counting. Second, four scenario walkthroughs followed representative events across inputs, spatial association, judgement, notification, assignment, action, reinspection, closure, and archival. Checks also examined layer clarity, module boundaries, authoritative-source preservation, traceability, configuration, and claim discipline.

The internal evaluation is deliberately limited. A mapped requirement indicates that the conceptual design contains an identifiable element; it does not indicate that the function has been programmed, is usable, is accepted by experts, or improves safety, quality, time, or cost. The four walkthroughs test logical continuity, not actual data latency or organisational compliance. These boundaries were applied during drafting and are repeated in the Results and Limitations sections.

## 4. Results

### 4.1. Transformation of requirements into modules and shared capabilities

The 28 requirements comprised 22 Core and 6 Supporting requirements. Core requirements directly addressed recurrent, high-consequence management problems and the common event loop. Supporting requirements provided trend views, weather context, audit reports, post-shift review, maintenance coordination, and complete event histories. No Extended requirements were advanced into V1.0.

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**Table 2**

*Requirement distribution and design transformation*

| Requirement group | Identifiers | Core | Supporting | Design outcome |
|---|---|---|---|---|
| Foundation-pit/foundation risk | FR-1.1-FR-1.6 | 4 | 2 | Module 1 |
| Core-tube coordination and quality traceability | FR-2.1-FR-2.6 | 5 | 1 | Module 2 |
| Vertical transportation/equipment coordination | FR-3.1-FR-3.6 | 4 | 2 | Module 3 |
| Work-at-height safety | FR-4.1-FR-4.6 | 5 | 1 | Module 4 |
| Cross-module closed-loop management | FR-CL.1-FR-CL.4 | 4 | 0 | Shared workflow, dashboard, access control, and traceability governance |
| Total | 28 requirements | 22 | 6 | All mapped into V1.0 |

*Note.* Counts refer to first-level requirements retained from RO1; compound actions were decomposed only for internal mapping.

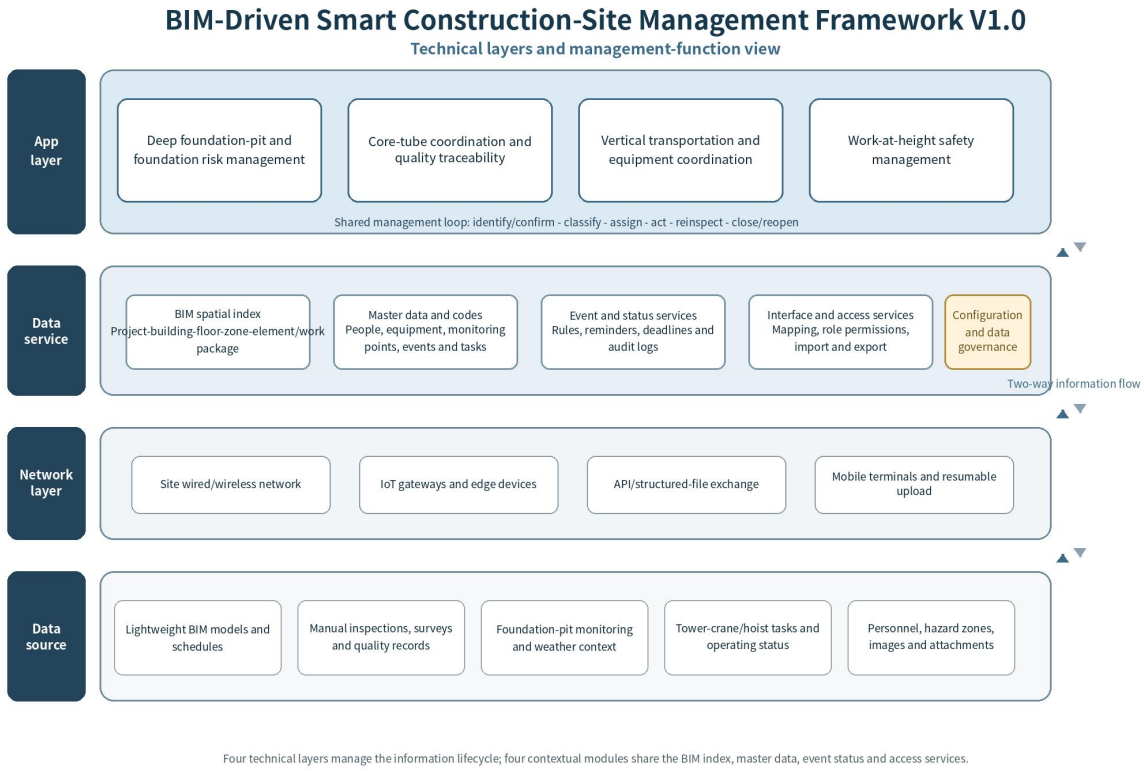
## 4.2. Overall structure of Framework V1.0

Framework V1.0 consists of four technical layers and four configurable management modules (Figure 2). The data-source and acquisition layer obtains raw information. The communication and transmission layer moves information under permitted conditions and records transmission status. The data integration and service layer aligns identifiers, time, location, event state, permissions, and interface mappings while preserving authoritative sources. The management application layer supports role-based query, judgement, coordination, assignment, action processing, reinspection, and audit. The four business modules occupy the application layer but share the BIM index, master-data dictionary, rule services, event/task service, permissions, audit log, and reporting services.

**Figure 2**

*Overall structure of the BIM-driven smart construction-site management framework V1.0*

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*Note.* Source: Developed by the authors. V1.0 denotes version status, not expert validation or field implementation.

**Table 3**

*Responsibilities and boundaries of the four technical layers*

| Layer | Primary responsibility | Main content | Boundary and output |
|---|---|---|---|
| Data source and acquisition | Generate or obtain raw information for management judgement | BIM models, schedules, manual inspections, survey/quality records, foundation-pit monitoring, weather, equipment tasks/status, personnel information, images | Outputs source, time, object/location ID, and validity status; does not approve actions or close events |
| Communication and transmission | Deliver data from different sources to specified services | Wired/wireless networks, gateways, mobile terminals, APIs, structured-file import, resumable upload | Outputs transmission status and receipt; does not alter business meaning or confirm professional validity |
| Data integration and service | Unify identities, locations, statuses, interfaces, and logs | Master data, spatial coding, BIM index, cleaning, time alignment, event/task states, rule services, permissions, interface mapping | Provides queryable services; retains authoritative sources and avoids duplicating equipment master status |

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| | | | |
|---|---|---|---|
| Management application | Support query, judgement, coordination, action, reinspection, and audit | Four modules, cross-module dashboards, mobile action processing, reports | Produces decisions, tasks, evidence, and closure records; automated outputs do not replace statutory/professional sign-off |

## 4.3. BIM as a spatial and object index

A central design decision was not to store all project information inside the BIM model. BIM provides a stable navigation and association structure organised as project-building-floor-zone-workface/work package-element. Mobile and cross-spatial objects use separate identifiers for personnel, equipment, monitoring points, and events. Data granularity follows the management task: a quality record may require an element or pour-batch link, whereas a safety photograph may require only a floor, hazard zone, and event ID. This avoids forcing every record to element level while preserving a route from summary status to its source evidence.

The association design also distinguishes an identifier from an authoritative value. The BIM index may point to a tower crane and its service range, but the equipment system remains authoritative for operational status. It may point to a monitoring location, while the monitoring organisation remains responsible for the raw measurement. It may locate a quality event, while authorised survey and quality roles confirm conformance. This separation supports interoperability and accountability simultaneously.

**Table 4**

*Minimum BIM-site association keys*

| Business object | Minimum association key | Key business data | Requirement source |
|---|---|---|---|
| Foundation-pit monitoring record | Monitoring-point ID + excavation zone + support section + construction stage | Value, threshold, trend, weather context, responsible organisation | FR-1.1-FR-1.6 |
| Core-tube quality record | Floor + element ID/pour batch + work package | Climbing-form position, pouring, curing, verticality, acceptance, sign-off | FR-2.1-FR-2.6 |
| Vertical transportation task | Equipment ID + service floor + time window + work package | Demand, material, capacity, task status, maintenance window | FR-3.1-FR-3.6 |
| Work-at-height risk | Floor + hazard zone + event ID | Risk level, photo, responsibility, deadline, action, reinspection | FR-4.1-FR-4.6 |
| Cross-module event/task | Event ID + object/location ID + responsible role | Unified state, timestamp, attachment, change log, permission | FR-CL.1-FR-CL.4 |

## 4.4. Four contextual management modules

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#### 4.4.1. Deep foundation-pit and foundation risk management

Module 1 links monitoring points, excavation zones, support sections, construction stages, thresholds, weather context, and responsible organisations. Its process begins with data-validity confirmation and spatial association. Configured threshold or trend rules generate a prompt, but authorised safety or technical personnel confirm the risk classification and decide whether work suspension, support adjustment, or another measure is necessary. Action and continued monitoring are recorded against the event. The practical test is whether an anomaly record can answer where and when the condition occurred, which stage and structure were affected, who was responsible, what action was taken, and whether an authorised person confirmed closure.

#### 4.4.2. Core-tube coordination and quality traceability

Module 2 organises changing core-tube status by floor, element, pour batch, work package, and climbing-form cycle. It links model/version checks, embedded items, formwork position, pour records, curing, verticality, inspection evidence, nonconformance actions, and sign-off. The integrated floor status is not a manually selected colour; it is derived from required evidence and unresolved-event states. An unsigned or failed inspection therefore prevents a completed status from concealing an outstanding issue. The module supports next-cycle decisions and retrospective quality traceability without treating the BIM model as the authoritative source for all laboratory, survey, or inspection records.

#### 4.4.3. Vertical transportation and equipment coordination

Module 3 creates a transparent queue linking trade and material demand to service floor, work package, time window, equipment capacity, operational status, and maintenance windows. Rule services can identify overlapping assignments, unavailable equipment, or capacity conflicts, but dispatch authority remains with the equipment manager. Operators report execution times, and deviations or conflicts feed post-shift review and schedule adjustment. This design responds to the management gap between equipment telemetry and production demand: either source alone is insufficient for coordination.

#### 4.4.4. Work-at-height safety management

Module 4 links floors, changing hazard zones, photographs, personnel or work-team information, risk grades, responsible parties, deadlines, action evidence, and authorised reinspection. Proximity between personnel data and hazard zones is treated as a risk prompt, not a substitute for barriers, permits, supervision, or personal protective measures. Where lawful and reliable personnel-location data are unavailable, the association can begin with work permits, team assignments, or zone check-ins. High-risk events cannot be closed by the party responsible for rectification without authorised reinspection; overdue, rejected, or recurrent events are escalated or reopened.

**Table 5**

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*Operating specification of the four management modules*

| Module | Primary objects | Required inputs | Primary outputs | Critical boundary |
|---|---|---|---|---|
| Foundation pit/foundation | Monitoring point, zone, support section, stage, risk event | Monitoring, thresholds, progress, weather, responsible organisation | Located warning, task, trend, reinspection, compliance export | Risk thresholds; professional confirmation; acquisition frequency |
| Core tube/quality | Floor, element, pour batch, cycle, inspection event | Model version, form position, pour/curing, survey, acceptance, programme | Integrated floor status, outstanding issue, next-cycle prompt, quality history | Sign-off roles; model/version control; batch and checklist rules |
| Vertical transportation/ equipment | Equipment, service floor, request, time window, work package | Demand, capacity, equipment status, programme priority, maintenance | Queue, conflict prompt, dispatch record, actual execution, shift review | Dispatch authority; capacity rule; request lead time; maintenance window |
| Work-at-height safety | Floor, hazard zone, person/team, event, task | Stage, hazard evidence, risk grade, responsibility, deadline, reinspection | Hazard map/card, rectification task, escalation, closure/reopening history | Privacy/lawful data use; reinspection role; evidence and retention rules |

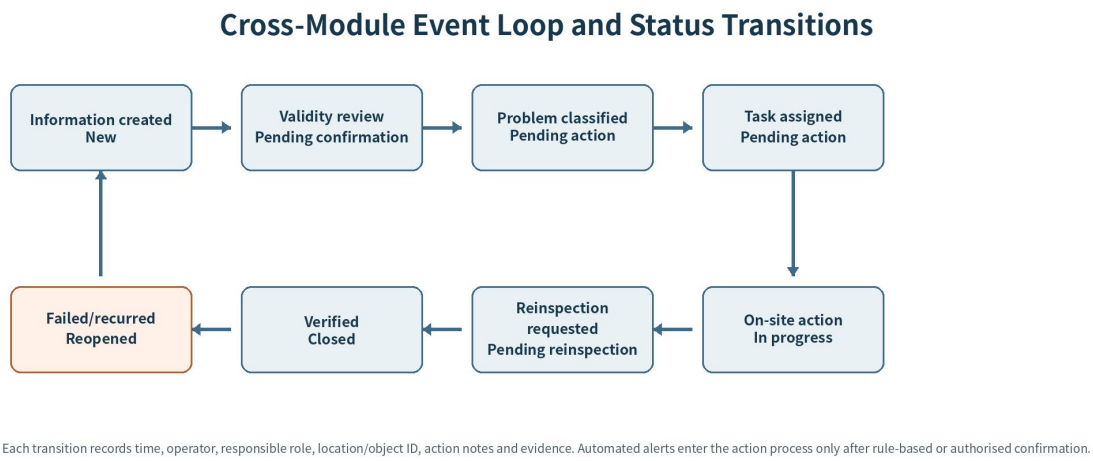
## 4.5. Unified event-responsibility loop

The four modules share a common event logic (Figure 3): information generation, validity confirmation, problem judgement and registration, graded notification, task assignment, action, reinspection, closure, and archiving. Each transition records the operator, time, reason, object or location, and relevant attachments. The loop separates rectification from closure, supports escalation when deadlines or risk grades require it, and creates a linked reopening record when reinspection fails or a condition recurs. This distinction is central to the framework because a warning without responsibility and closure is only a notification, not a management loop.

**Figure 3**

*Cross-module event loop and status transitions*

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*Note.* Source: Developed by the authors. Projects may add approval steps but should retain responsibility, deadline, reinspection, and closure evidence.

**Table 6**

*Common event states and transition responsibilities*

| State | Meaning | Primary responsibility | Permitted transition |
|---|---|---|---|
| New | Source and basic identifiers recorded | Acquisition system or submitter | Proceed to validity confirmation; retain return reason for invalid data |
| Pending confirmation | Awaiting rule check or authorised confirmation | Data owner/professional role | Retain as status if no issue; register event if confirmed |
| Pending action | Classified event awaits acceptance/action | Professional manager and responsible organisation | Set responsibility and deadline; begin action |
| In progress | Responsible party acts and submits evidence | Responsible team/subcontractor | Request reinspection when measures are complete |
| Pending reinspection | Awaiting authorised verification | Authorised reinspector | Close if accepted; reject or reopen if not |
| Closed | Closure conditions satisfied and archived | Authorised closer | Maintain read-only history; link any recurrence |
| Reopened | Failed reinspection, recurrence, or new invalidating evidence | Original responsibility chain and escalation role | Reclassify, reassign, act, and reinspect |

## 4.6. Requirement coverage and scenario walkthroughs

The structural coverage check assigned every requirement a primary location. The result was 28/28: all 22 Core and 6 Supporting requirements were represented. FR-CL.4 is implemented as a requirement-

to-framework traceability matrix and design-change log rather than a user-interface menu item. The coverage result means that the framework contains a structural response to each requirement; it does not indicate implementation or effectiveness.

**Table 7**

*Structural coverage of the 28 requirements*

| Range | Primary location in V1.0 | Coverage content | Result |
|---|---|---|---|
| FR-1.1-1.4 | Module 1; BIM index; event service; loop | Monitoring-point/zone association, threshold judgement, warning, response record | Core 4/4 |
| FR-1.5-1.6 | Module 1; query/export; contextual-data interface | Trend query, regulatory export, weather context | Supporting 2/2 |
| FR-2.1-2.5 | Module 2; BIM index; quality/status services | Form position, verticality, pouring, acceptance, floor status | Core 5/5 |
| FR-2.6 | Module 2; audit/export services | Traceability report and sign-off chain | Supporting 1/1 |
| FR-3.1-3.4 | Module 3; equipment/programme interfaces; rules | Equipment status, demand, coordination view, conflict prompt | Core 4/4 |
| FR-3.5-3.6 | Module 3; task log; maintenance interface | Execution review and maintenance-window coordination | Supporting 2/2 |
| FR-4.1-4.5 | Module 4; BIM zone index; event/reminder services | Hazard zones, personnel association, chain, escalation, photo location | Core 5/5 |
| FR-4.6 | Module 4; audit log | Complete safety-event history | Supporting 1/1 |
| FR-CL.1-CL.3 | Shared loop; dashboard; access control | Cross-module logic, spatial visualisation, role access | Core 3/3 |
| FR-CL.4 | Traceability matrix and design-change log | Link evidence, framework element, and later evaluation item | Core 1/1 |

**Table 8**

*Internal walkthrough of representative scenarios*

| Scenario | Required input | Process chain | Responsibility chain | Walkthrough finding |
|---|---|---|---|---|
| Foundation-pit anomaly | Value + point/zone + stage + threshold + responsible organisation | Validity -> classification -> notification -> action -> monitoring/reinspection | Safety/technical judgement; construction action; authorised closure | Located event with continuous record |
| Core-tube pre-pour | Floor/element + model version + | Register -> coordinate -> rectify | Construction, technical, survey, | Unsigned issue cannot |

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| | | | | |
|---|---|---|---|---|
| conflict/quality deviation | embedded items/survey/acceptance + programme | -> review/sign-off -> update status | quality, BIM roles | be hidden by completed status |
| Tower-crane/hoist conflict | Equipment status + service floor + demand + time window + capacity/maintenance | Prompt -> dispatch judgement -> adjustment -> feedback -> review | Equipment dispatch; trade confirmation; operator feedback | Prompt is traceable but does not replace dispatch authority |
| Work-at-height hazard | Hazard zone + photo + risk level + responsible party + deadline | Locate -> classify -> assign -> rectify -> reinspect -> close/reopen | Safety classification/reinspection; subcontractor action; escalation | Rectifier cannot self-close; recurrence can reopen |

All four walkthroughs produced a continuous conceptual path from data, location, and judgement to responsibility, action, reinspection, and closure. They also exposed three matters that require external expert judgement: appropriate update frequencies for different risk and management tasks; the practical availability of personnel-location and equipment-interface data; and the allocation of reinspection and escalation authority under different project organisations. These questions were retained for the next evaluation stage rather than resolved by researcher assumption.

## 5. Discussion

### 5.1. The contribution is integration through management relationships

The framework does not claim that foundation-pit monitoring, quality inspection, equipment scheduling, or safety reporting are individually novel. Existing systems already provide parts of these functions. The contribution lies in defining how four contexts share a BIM index, common identifiers, event states, permissions, and a responsibility loop while retaining module-specific data and professional roles. This responds directly to the empirical meta-problem: information was plentiful, but location, time, work activity, status, responsibility, and closure were not maintained as a common relationship.

This finding extends the interoperability literature. Turk (2020) argues that interoperability should support specialised work rather than eliminate specialisation. V1.0 applies that principle operationally: monitoring organisations, equipment systems, schedules, survey records, and quality systems retain authoritative responsibilities, while the integration/service layer creates the references needed for coordinated management. The architecture therefore avoids both extremes of isolated applications and an unrealistic single repository.

### 5.2. A bounded role for BIM

Treating BIM as a spatial/object index is a deliberate theoretical and practical choice. Model-centric

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approaches sometimes imply that more information should be embedded in the model. In a live construction environment, however, raw monitoring streams, equipment telemetry, approvals, photographs, and task histories have different owners, frequencies, security conditions, and evidentiary requirements. Attempting to make the BIM file authoritative for all of them can create duplication and stale information. Stable associations allow the model to support spatial reasoning and navigation while specialist systems continue to manage domain records.

This design is compatible with ISO 19650 information-management principles and open exchange through IFC, but it goes beyond file exchange by specifying minimum business keys. An IFC-compatible object is not automatically a useful management reference unless the system can also identify the relevant floor or zone, current work package, event, responsible role, and state. The proposed keys translate interoperability into decision-relevant relationships. They also permit lower granularity when element-level association is unnecessary or infeasible.

## 5.3. Closed-loop coordination as a governance mechanism

The unified event loop is more than a workflow diagram. It defines governance conditions: data must be identifiable and valid; a problem must be confirmed and classified; responsibility and deadline must be explicit; action evidence must be separated from authorised reinspection; failed or recurrent conditions must be reopenable; and closure must be auditable. These rules address a frequent weakness in technology-led systems, where alerts and dashboards are treated as outcomes. From a management perspective, the meaningful outcome is a verified state change with retained responsibility and evidence.

The common state model also enables cross-module dashboards without reducing management to colour coding. A warning or critical label must be traceable to its source event, object or location, judgement, and responsibility chain. This is consistent with the movement from static BIM towards connected, data-centric, and digital-twin information systems (Sacks et al., 2020a; Sacks et al., 2020b; Jiang et al., 2024). However, V1.0 stops short of claiming a digital twin because bidirectional real-time synchronisation and automated control were not implemented or evaluated.

## 5.4. Implementability and staged adoption

The architecture supports staged adoption. Stage 1 can establish spatial codes, structured event records, task assignment, deadlines, mobile evidence, reinspection, and audit trails without demanding extensive sensor integration. Stage 2 can connect existing monitoring, quality, programme, and equipment systems through APIs or controlled structured-file exchange. Stage 3 can introduce more advanced rule services, conflict prompts, and cross-module dashboards after master-data quality, interface reliability, organisational roles, and update frequencies are stable. This sequence reflects the practical reality that information discipline and responsibility rules often determine whether later automation is trustworthy.

Fallback arrangements are equally important. Structured file import may be acceptable when a direct interface is unavailable, provided source, version, import time, and failure records are retained. Mobile applications in high-level work areas may require local storage and resumed upload. Personnel-location functions can fall back to permit, team, or check-in associations. These provisions do not lower the intended management standard; they separate the stable management logic from the technology available on a particular project.

## 5.5. Comparison with prior frameworks

Prior BIM-IoT and digital-twin frameworks commonly emphasise sensing, data fusion, platforms, simulation, and visualisation (Tang et al., 2019; Deng et al., 2021; Huang et al., 2023; Tuhaise et al., 2023). V1.0 shares the layered separation of acquisition, communication, service, and application, but adds three management-oriented specifications. First, it preserves an evidence chain from qualitative problem to functional requirement to framework element. Second, it defines authoritative-source and minimum-association rules rather than assuming that technical connectivity ensures semantic usefulness. Third, it provides a common responsibility and closure model across risk, quality, logistics, and safety contexts.

The design also differs from broad smart-site maturity models. Maturity studies identify influential capabilities and organisational factors (Liu et al., 2021; Xiahou et al., 2022), whereas the present framework specifies how a project could configure a management architecture for particular events. The approaches are complementary: maturity affects implementation feasibility, while V1.0 defines the management relationships and boundaries to be assessed.

## 5.6. Theoretical and practical implications

Theoretically, the study demonstrates a traceable route from qualitative construction-management evidence to a design artefact. The route preserves the distinction among empirical requirements, normative constraints, contextual conditions, literature principles, and researcher synthesis. This contributes to design-science transparency because the framework can be challenged at the level of an individual requirement, mapping decision, boundary, or transition rule rather than accepted as an indivisible diagram.

Practically, the framework can guide project information requirements, system procurement, interface planning, and expert review. Clients and contractors can use the layer boundaries to prevent duplicated data ownership; BIM teams can define spatial and object keys; specialist managers can define professional confirmation and closure authority; and technology suppliers can identify minimum inputs, outputs, and audit records. The framework should therefore be read as a configuration and integration blueprint, not a fixed software menu.

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## 6. Limitations and Future Research

Four limitations define the interpretation of the results. First, V1.0 was derived from 15 practitioners and normative/literature sources relevant to Xi'an super high-rise construction. Maximum variation and saturation support the adequacy of the qualitative design input, but they do not establish statistical representativeness or transferability to every region or project type. Second, the availability and quality of personnel-location data, equipment interfaces, monitoring frequencies, and model updates vary substantially among projects. Third, risk thresholds, approval permissions, data-retention periods, and regulatory outputs must be configured against applicable standards, contracts, approved technical schemes, and lawful data-use arrangements. Fourth, internal mapping and scenario walkthroughs can reveal structural omissions or discontinuities but cannot demonstrate reductions in accidents, rework, duration, or cost.

The next research stage should use a multidisciplinary modified Delphi process to assess relevance, completeness, clarity, feasibility, and contextual applicability. The three unresolved matters identified by the walkthroughs should receive targeted expert attention. Revisions should retain a change log that records the expert rationale, affected requirements, and effect on coverage. After expert refinement, implementation research should examine data-interface reliability, user interaction, response time, closure compliance, and outcome measures across actual projects. Comparative evaluation could then test whether the common event model transfers beyond Xi'an and whether module priorities change with project stage, contractual structure, or digital maturity.

## 7. Conclusions

This study developed Framework V1.0 for BIM-driven smart construction-site management in super high-rise projects in Xi'an. A nine-step, evidence-traceable design procedure transformed 28 empirically derived requirements into four technical layers, four contextual management modules, a bounded BIM spatial/object index, and a unified event-responsibility loop. The modules address foundation-pit and foundation risk, core-tube coordination and quality traceability, vertical transportation and equipment coordination, and work-at-height safety. Shared services connect the modules through identifiers, event states, permissions, interfaces, and audit records.

All 22 Core and 6 Supporting requirements received an identifiable structural location, and four scenario walkthroughs reached conceptually complete paths from information generation to authorised closure or reopening. These results support internal completeness and process continuity only. They do not establish expert consensus, software operation, or field-performance improvement. The main contribution is therefore an auditable management design: it shows how fragmented digital evidence can become spatially located, responsibility-linked, and closure-oriented without assigning unverified capabilities to BIM or automation.

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## Author contributions

Conceptualization, Fang Li; methodology, Nurazim Ibrahim; validation, Fang Li; formal analysis, Nurazim Ibrahim; investigation, Fang Li and Nurazim Ibrahim; resources, Fang Li; data curation, Nurazim Ibrahim; writing—original draft preparation, Fang Li; writing—review and editing, Nurazim Ibrahim; visualization, Fang Li; supervision, Fang Li; project administration, Nurazim Ibrahim. All authors have read and agreed to the published version of the manuscript.

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## Data availability

Not applicable.

## Declarations

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The authors declare that there is no conflict of interest.

### Ethics approval

Not applicable.

### Consent to participate

Not applicable.

### Consent for publication

Not applicable.

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## Appendix A

### Full functional-requirement register and primary V1.0 locations

This supplement reports the 28 first-level requirements retained from the empirical requirement-derivation stage. “Mapped” indicates a conceptual location in Framework V1.0; it does not indicate software implementation or performance.

**Table A1**

*Functional requirements and primary structural locations*

| ID | Priority | Requirement (condensed without changing intent) | Primary V1.0 location |
|---|---|---|---|
| FR-1.1 | Core | Associate foundation-pit monitoring points with BIM spatial objects, excavation zones, support sections, and construction stages. | Module 1; BIM index |
| FR-1.2 | Core | Ingest monitoring data in real or near-real time and compare them with thresholds configurable by geological zone and construction stage. | Module 1; data/rule services |
| FR-1.3 | Core | Generate alerts containing BIM location, measured value, threshold, associated activity, and responsible subcontractor. | Module 1; event service |
| FR-1.4 | Core | Record notification, corrective action, responsible party, and response time against the originating alert. | Module 1; common loop |
| FR-1.5 | Supporting | Provide historical monitoring trends by point, zone, and period, with export for regulatory reporting. | Module 1; query/export |
| FR-1.6 | Supporting | Associate rainfall and temperature context with monitoring data for collapsible-loess risk assessment. | Module 1; contextual interface |
| FR-2.1 | Core | Link core-tube BIM objects with climbing-formwork position, cycle number, and next-move readiness. | Module 2; BIM index |

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| | | | |
|---|---|---|---|
| FR-2.2 | Core | Associate verticality results with the corresponding floor and structural component, including deviation and conformance status. | Module 2; survey/quality service |
| FR-2.3 | Core | Link concrete placement, strength-test, and curing records to BIM floor objects for component-level traceability. | Module 2; quality service |
| FR-2.4 | Core | Link reinforcement, formwork, and finish inspection records and geolocated photo evidence to BIM component IDs. | Module 2; quality/event service |
| FR-2.5 | Core | Display integrated floor status for formwork, curing, verticality, inspection sign-off, and schedule milestones. | Module 2; status view |
| FR-2.6 | Supporting | Generate traceability reports by floor, component, or stage with an auditable sign-off chain. | Module 2; audit/export |
| FR-3.1 | Core | Associate tower-crane and hoist status with BIM equipment objects and schedule activities. | Module 3; equipment/programme interfaces |
| FR-3.2 | Core | Register floor-specific transport demand by trade and material and link quantities to schedule work packages. | Module 3; demand service |
| FR-3.3 | Core | Provide a coordination view of equipment availability, pending demand, and schedule conflicts, including queue/overload prompts. | Module 3; coordination view |
| FR-3.4 | Core | Generate warnings for overlapping assignments or capacity exceedance, with traceable resolution prompts. | Module 3; rule/event services |
| FR-3.5 | Supporting | Record assignments, actual execution times, and conflict events for post-shift review and schedule adjustment. | Module 3; task log |
| FR-3.6 | Supporting | Coordinate equipment maintenance windows with daily transport planning. | Module 3; maintenance interface |

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| | | | |
|---|---|---|---|
| FR-4.1 | Core | Define and update BIM-based work-at-height hazard zones in line with construction progress. | Module 4; BIM zone index |
| FR-4.2 | Core | Associate lawful and reliable personnel/work information with hazard zones for proximity-based prompts and awareness. | Module 4; personnel/zone interface |
| FR-4.3 | Core | Maintain a safety-event chain from identification and grading through notification, action, reinspection, and closure. | Module 4; common loop |
| FR-4.4 | Core | Escalate overdue hazards according to project-configured risk-grade rules. | Module 4; reminder/escalation service |
| FR-4.5 | Core | Support photo-based reporting with BIM-linked floor, zone, and component location. | Module 4; event service |
| FR-4.6 | Supporting | Retain the complete safety-event history, timestamps, responsibility records, and authorised sign-off. | Module 4; audit log |
| FR-CL.1 | Core | Provide a common loop across modules from data acquisition and BIM association to judgement, warning, action, reinspection, and traceability. | Shared event/task service |
| FR-CL.2 | Core | Provide a cross-module dashboard with unified status indicators and BIM-based spatial navigation. | Shared dashboard/index |
| FR-CL.3 | Core | Apply role-based access so each participant can view and act on information within assigned responsibility. | Shared access-control service |
| FR-CL.4 | Core | Maintain traceability among evidence, problem, need, requirement, framework element, and later design revisions. | Traceability matrix/change log |