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BRIDGING THE STANDARDISATION GAP: A LIFECYCLE FRAMEWORK FOR AUTO-ID IOT INTEGRATION WITH BIM IN POST-DISASTER RECONSTRUCTION

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SUMMARY: *Post-disaster reconstruction places extreme demands on information management. Supply chains fracture, coordination breaks down, and the component data needed to move from temporary housing to permanent rebuilding is rarely retained. Building Information Modelling (BIM) and Internet of Things (IoT) technologies together offer a route to that continuity, yet construction-oriented guidance for staging automatic identification (Auto-ID) device deployment within BIM information management remains absent, and deployments stay fragmented. This study develops a baseline framework for that setting. Its scope is the Auto-ID class of IoT edge devices, principally radio-frequency identification (RFID) and near-field communication (NFC) transponders acting as data carriers, and it excludes environmental and structural sensing. Adopting a Design Science Research (DSR) paradigm, the research proceeds in two empirical stages. Stage 1 is a requirement analysis drawn from a precursor questionnaire of 110 registered architects working on post-disaster housing, which establishes the operational baseline. Stage 2 is an evaluation survey completed by 113 architecture, engineering and construction (AEC) professionals, which assesses the resulting framework. The result is a five-phase technical guideline covering initial engagement, application selection, interoperability, stakeholder alignment and security assurance, with security treated as a gate repeated at each phase. These micro-scale phases are mapped onto the macro-scale disaster management cycle to give an integrated lifecycle model. The study also proposes the Data-to-Design Handover, a mechanism that carries component integrity data from temporary housing units into generative design for permanent reconstruction. Respondents rated all five phases as important in aggregate, with stakeholder alignment rated highest and interoperability lowest, and 68.1% reported that referenceable guidelines would raise their likelihood of adopting Auto-ID solutions. The evaluation is descriptive and perception based. The handover mechanism and the progression towards a mature predictive digital twin are conceptual propositions that were not tested, and the framework awaits implementation in live projects.*

KEYWORDS*: building information modelling (BIM), internet of things (IoT), auto-ID, digital twin, post-disaster reconstruction.*

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1. INTRODUCTION

The architecture, engineering and construction (AEC) sector is undergoing digital transformation, driven by the integration of BIM and Digital Twin technologies. Within these collaborative environments, IoT networks and their connected edge devices act as conduits for real-time data acquisition and lifecycle management (Duan & Cao, 2020; Preut et al., 2021). However, despite established versatility in logistics, material tracking and asset identification, adoption of automatic identification (Auto-ID) device technologies in construction remains limited and fragmented. General-purpose IoT standards exist, and information management standards such as ISO 19650 govern the environment these devices feed, but no construction-oriented guidance stages the deployment of Auto-ID devices within a BIM information management workflow. Deployments therefore remain ad hoc, which limits what the sector can draw from interconnected digital ecosystems (Xue et al., 2018). This study concerns that specific class of device, principally radio-frequency identification (RFID) and near-field communication (NFC) transponders acting as data carriers, and it does not address environmental or structural sensing.

The consequences of this standardisation deficit are most critically exposed during complex, high-stakes operations, such as post-disaster reconstruction. In these extreme environments, traditional supply chains and communication channels frequently collapse. The scale of such disruption is considerable. The 2023 earthquakes in Türkiye, for example, caused extensive damage and major economic losses across the construction and real estate sectors. Direct damage to the real estate sector was estimated at USD 27.7 billion, with USD 18 billion attributed to residential buildings and the remaining USD 9.7 billion to non-residential buildings (Alam & Ali, 2023). This makes logistical coordination and rapid assembly the primary value drivers for recovery. Establishing what this paper terms a primitive digital twin for Temporary Housing Units (THUs), meaning a digital record populated with component identity, location and condition data but without predictive capability, and carrying that component data forward into permanent reconstruction, depends on continuity of information across organisational and temporal boundaries. In this context, Auto-ID devices serve as secure data carriers, bridging physical assets with digital twin ecosystems. A gap therefore persists between macro-scale disaster management requirements and micro-scale technological adoption guidance.

To address this gap, the study adopts a Design Science Research (DSR) paradigm (Hevner et al., 2004) to develop, evaluate and synthesise a guideline framework for Auto-ID adoption in BIM-enabled construction. The research proceeds through two empirical stages. Stage 1 derives socio-technical requirements from a targeted subset of field data on an extreme use-case scenario, post-disaster reconstruction, and, read with the literature, establishes baseline needs for data security, stakeholder alignment and circular data handover. Stage 2 evaluates the resulting five-phase framework through a survey of 113 AEC professionals, which records their perceptions of the importance of each phase and their disposition towards adoption. The Stage 1 sample was drawn from Türkiye and the Stage 2 sample from the United Kingdom, so the evaluation is read as indicative for comparable national contexts rather than as globally representative.

This paper aims to provide an artefact that guides industry practitioners through the complexities of IoT integration. The study is guided by a central question, namely how a referenceable Auto-ID and BIM guideline framework can connect micro-scale technical phases with the macro-scale disaster management cycle to support circular reconstruction. In contrast to prior efforts that treat these capabilities in isolation, the contribution is a single referenceable guideline that integrates them across the asset lifecycle. By synthesising the theoretical disaster management cycle with professionally evaluated technical adoption phases, the study sets out how staged Auto-ID workflows could support a move from fragmented emergency responses towards a more cohesive, secure and data-driven circular process.

The remainder of this paper is structured as follows: Section 2 reviews the theoretical background of IoT networks and digital twin technologies alongside their critical role in complex scenarios. Section 3 details the DSR methodology and the multi-stage empirical approach. Section 4 presents the development of the framework, the empirical survey results and the integrated lifecycle synthesis model. Section 5 discusses the findings in relation to the literature and sets out the practical and theoretical implications together with the limitations and future research directions. Finally, Section 6 concludes the research.

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2. LITERATURE REVIEW AND BACKGROUND

This section presents a structured narrative review. It examines the literature thematically, covering IoT and BIM integration, digital twins, coordination and data fragmentation in extreme scenarios, and the standardisation gap. A narrative design was adopted in preference to a systematic protocol because the review draws on four heterogeneous bodies of literature whose purpose is to ground the design of the artefact rather than to map a single field exhaustively. This selective use of the knowledge base is consistent with the rigour cycle of DSR (Hevner et al., 2004). The sources comprise peer-reviewed studies, international standards and established reference texts in construction informatics and disaster management, and the thematic literature is concentrated from 2017 onwards, a period that includes the publication of the ISO 19650 series and the rapid growth of digital twin research in construction. Earlier works are retained where they provide methodological foundations. Each theme identifies a specific limitation that the proposed framework addresses, and the comparative positioning against representative works is summarised in Table 3. Sources were identified through a purposive, expert-led search rather than a protocol-driven systematic search. Bibliographic databases and the ISO and IEC catalogues were searched using combinations of the terms BIM, IoT, RFID, NFC, Auto-ID, digital twin, interoperability, standardisation and post-disaster reconstruction, and the set was extended by backward citation tracking from the studies retained. Inclusion required a peer-reviewed source in English addressing construction or the built environment, or a published standard within scope. Sources were excluded where IoT was treated only as a general computing topic without a construction application, where the device class fell outside Auto-ID and no lifecycle argument was made, or where no full text was available. Because the search was purposive, no count of screened or retained records is reported, and the review makes no claim to exhaustive coverage. The sources cited in Sections 2.1 to 2.4 form the core thematic set used to ground the artefact, and additional sources are cited in later sections where they support specific methodological, empirical or technical points.

Table 1: Terminology used in this paper, aligned with ISO/IEC 20924:2024.

Term	Use in this paper
Auto-ID device	Physical hardware at the network edge that captures, stores or carries component data. In this study the class is restricted to RFID and NFC transponders acting as data carriers.
Auto-ID	Automatic identification technologies that resolve a physical item to a unique digital identity without manual entry, principally RFID and NFC here.
RFID transponder (tag)	A passive or active radio-frequency device carrying an identifier and, where writable, component data. Air interface behaviour at 860 to 960 MHz is defined in ISO/IEC 18000-63:2021 (International Organization for Standardization, 2021).
NFC	Short-range induction coupling at 13.56 MHz for close-proximity reads, used here for handheld verification of component identity on site.
Reader	The interrogating device that communicates with transponders and passes data to the network layer.
Sensor	A device that measures a physical quantity such as strain, temperature or vibration. Sensors are named only where the literature is cited and fall outside the scope of this framework.
IoT network	The connected ecosystem that links edge devices and readers to the Common Data Environment defined in ISO 19650.
Digital twin	A digital representation of a physical asset maintained through data exchange across its lifecycle (ISO/IEC 30173:2023, International Organization for Standardization, 2023).
Primitive digital twin	As used here, a twin populated with component identity, location and condition data but without predictive capability.
Mature digital twin	As used here, a twin holding a continuous lifecycle record sufficient to support predictive maintenance and reuse decisions. This state is proposed rather than demonstrated.

This study concerns Auto-ID class IoT edge devices, principally radio-frequency identification (RFID) and near-field communication (NFC) transponders, which operate within an IoT network connected to BIM through the

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Common Data Environment defined by ISO 19650 (International Organization for Standardization, 2018). Throughout the paper, the term Auto-ID device refers to the physical hardware that captures and carries component data, and the term IoT network refers to the connected ecosystem that links these devices to BIM. RFID and NFC are treated as representative Auto-ID technologies, which is why the security vulnerabilities summarised in Table 9 draw on RFID-specific literature. This scope excludes the wider class of environmental and structural sensing devices, which fall outside the data-carrier function examined here. Terminology follows ISO/IEC 20924:2024, which provides the vocabulary for IoT and digital twin (International Organization for Standardization, 2024a). Table 1 sets out the terms as they are used here. The word sensor is reserved for devices that measure a physical quantity and is not used interchangeably with transponder or edge device, and the terms primitive and mature digital twin describe stages of data completeness in this framework rather than established categories in the standard.

Research concerning the application of IoT ecosystems, specifically physical IoT networks, within the construction sector has increased steadily over the past two decades (Duan & Cao, 2020). However, widespread industry adoption has remained limited (Xue et al., 2018). As the topic has not yet reached full maturity (Brandín & Abrishami, 2021), this suggests that underlying systemic issues inhibit its continued development, and this underscores the need for referenceable guidance. Specifically, the highly fragmented nature of IoT deployments, which are often developed as bespoke or ad hoc solutions, has severely restricted broader adoption due to a lack of referenceable standards (Duan & Cao, 2020).

Despite these barriers, Auto-ID devices remain a highly versatile form of identification and tracking technology for AEC applications (Brandín & Abrishami, 2021; Duan & Cao, 2020). The inherent benefits of these edge devices include simultaneous multi-node reading, data writability, reusability and automated tracking capabilities (Wijerathna et al., 2026). Consequently, IoT integration has demonstrated positive impacts across various domains. These range from logistics and prefabrication to health and safety and building lifecycle management (Brandín & Abrishami, 2024; Seyis & Sönmez, 2023; Zhai et al., 2019). To fully conceptualise the necessity of standardising these fragmented applications, the following sections review the integration of IoT within BIM environments. This culminates in an analysis of its critical role during extreme, complex scenarios such as post-disaster reconstruction.

2.1 IoT technology in BIM-enabled construction

BIM is a digital process that provides AEC professionals with the means for smarter building management, designing, planning and constructing by developing asset information in a collaborative digital 3D environment (Sacks et al., 2018). It was developed within the construction and built environment industry due to stakeholders' need for better digital integration of construction site events. This approach enables the submission of higher quality projects and provides more control over elements such as programme scheduling, cost management and quantity take-offs (Nguyen & Adhikari, 2023). Project design consultants, professional consultant teams and on-site contractors, among many other disciplines, can benefit from and apply BIM technology.

More formally, BIM is defined as an integrated information management process governed by the International Organization for Standardization (ISO) 19650 (2018). This framework shifts the focus from static geometric modelling to a holistic information management cycle across the entire asset lifecycle. Under ISO 19650, the Common Data Environment provides the information management infrastructure into which data from Auto-ID devices are intended to flow (Mêda et al., 2021). As Table 2 records, the standard does not specify device identity, read-event data or the exchange between the edge device and the Common Data Environment. Notably, the reviewed literature concerning BIM and IoT integration discusses information security mainly through data protection and secure exchange concerns. However, it often fails to link these concerns to a specific information security management standard such as ISO/IEC 27001 (Das et al., 2021).

2.2 BIM digital twin technology relative to construction

A collaborative digital 3D environment often exists through the means of a Digital Twin based on a physical asset. A digital twin represents a digital replica of the built asset, which in BIM is a building intended for or completed through construction. By creating a digital version of a building for use before, during and after construction, AEC professionals can improve design accuracy (Pan & Zhang, 2021; Z. Yang et al., 2024), more effectively plan and optimise a concept or increase productivity on site (Afzal et al., 2023; Omrany et al., 2023). They can also analyse building thermal comfort (Mousavi et al., 2024), discover risks and problems digitally before they occur on site

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(Boje et al., 2020), perform “what-if” scenarios to test potential solutions (Pan & Zhang, 2021; Su et al., 2023) and also to record as-built data from construction sites (Sheikhkhoshkar et al., 2024). Interoperability is a core feature of BIM. It facilitates communication between the various systems, including digital software, general IoT networks and specific edge device technologies (Piras et al., 2024).

BIM can manage live real-life data (Abdelalim et al., 2025; Brandín & Abrishami, 2021), fed to a digital twin in real time (Ghansah & Lu, 2024). This includes the real-time synchronisation of data (Brandín & Abrishami, 2024), integration with virtual reality platforms (Banfi et al., 2022) and real-time progress monitoring from the site through IoT hardware (Hu et al., 2024). This paper focuses on the integration of real-time data fed from IoT networks and their connected Auto-ID tags into BIM.

2.3 Coordination and data fragmentation in extreme scenarios

The efficacy of the digital twin and real-time tracking systems discussed in the previous section is tested most severely in disrupted environments. The escalation of global disaster risks exposes the inadequacies of current systems in transitioning from short-term emergency response to permanent urban recovery (Blackman et al., 2017). In these contexts, current disaster management practices are frequently hindered by fragmented supply chains, isolated data silos and operational disconnects (Puri et al., 2024). Bridging this gap between emergency shelters and permanent reconstruction poses a substantial logistical challenge for traditional supply chains. Specifically, the lack of coordination during the deployment of THUs often results in a linear, single-use lifecycle (Mohammadi et al., 2024). This acts as a 'second disaster' for the affected communities (Ghanbarzadeh Ghomi et al., 2021).

In these disrupted and time-critical environments, real-time tracking technologies must be integrated into the supply chain. This integration bridges the gap between physical building elements and the digital information management framework (Abrishami & Jayaram, 2025). Literature indicates that this cyber-physical connection is typically achieved through Auto-ID devices (RFID and NFC transponders) operating within an IoT network (Y. Yang et al., 2024), which in a BIM-enabled project links them to the Common Data Environment. Through these technologies, continuously updated digital twins function as digital 'material passports' that track the history and condition of building components. These models serve as decision-support tools for the end-of-life strategies of post-disaster buildings (Kaplan & Abrishami, 2026; Mêda et al., 2021).

2.4 The lack of standardisation and the resulting fragmentation barrier

As established in the preceding sections, while the operational need for Auto-ID devices is acute, particularly in complex scenarios, the absence of construction-specific deployment guidance affects the performance of communications, data management, security and interoperability (Wijerathna et al., 2026). The literature also reports that Auto-ID device technology standards are highly fragmented, which impairs interoperability (Osadcha et al., 2024). The lack of standards encompassing the use of IoT technologies is also evident in auxiliary disciplines within construction, including for wearable safety devices on sites (Seyis & Sönmez, 2023). This limitation and fragmented situation regarding IoT technology standardisation in construction applications therefore directly inhibits BIM interoperability and limits its application opportunities (Duan & Cao, 2020). The gap is one of application rather than of standards in general. A body of normative work already addresses IoT at the level of vocabulary, architecture, interoperability and security (International Organization for Standardization, 2019, 2022, 2024a, 2024b), and the Auto-ID air interface is itself specified in detail (International Organization for Standardization, 2021). ISO 19650 governs the information management environment into which device data must flow, defining information requirements, containers, states and the Common Data Environment across the delivery and operational phases, with a security-minded companion part (International Organization for Standardization, 2018, 2020). What none of these instruments provides is guidance on how an Auto-ID deployment should be staged inside a BIM-enabled project: which devices suit which application, how device identity and read events are represented as information containers, at what cadence data passes from the edge to the Common Data Environment, who is accountable for it under an appointment, and how these decisions change in an extreme environment. Table 2 maps the relevant instruments against what each leaves open for this purpose.

Guidelines for deploying Auto-ID device technology in BIM-enabled construction need to settle several preliminary matters. The framework developed in this study addresses the major barriers identified in the reviewed literature. The implementation of Auto-ID devices in BIM depends on a detailed understanding of the context in which they will be deployed. That context affects suitability and deployment in several respects. These factors

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include specific requirements regarding hardware and software interfaces, such as interoperability, the scope or scale of deployment, data management and security. Current literature indicates solutions that are often isolated to specific or singular applications in construction, such as simple position monitoring of components or equipment (Gao et al., 2024; Xue et al., 2018). Some literature discusses the communication spectrums involving specific IoT hardware suitable in BIM-enabled construction (Khan et al., 2024), while others refer to the extensive lack thereof in connected tracking technologies (Almatari et al., 2024). Several studies identify barriers to IoT adoption and propose adoption models, strategies or linkage guidelines. What the reviewed literature does not offer is a staged framework that brings barriers and practice responses together in one reference. Guidance is particularly thin on how BIM information management standards, regulatory communications, spectrum compliance, deployment risk, data security and site suitability interact across a project. Framework-level guidance addressing these issues is still needed if adoption of Auto-ID devices in BIM-enabled projects is to move beyond ad hoc practice.

Table 2: Mapping of relevant standards against what each leaves open for Auto-ID deployment in BIM-enabled construction.

Category and instrument	**What it governs**	**What it leaves open for Auto-ID in a BIM workflow**
Information management: ISO 19650-1:2018 and ISO 19650-5:2020	Concepts, principles and information management process across the asset lifecycle, the Common Data Environment, and a security-minded approach to information.	No treatment of device identity, read-event data, edge-to-CDE exchange cadence, or the accountability of a device layer within an appointment.
IoT vocabulary: ISO/IEC 20924:2024	Terms and definitions for IoT and digital twin.	Vocabulary only. No deployment process and no construction context.
IoT architecture: ISO/IEC 30141:2024	Reference architecture, entities and domains for IoT systems.	Generic across sectors. Does not map to BIM information containers or to project delivery roles.
IoT interoperability: ISO/IEC 21823-1:2019	Framework and facets of interoperability for IoT systems.	Does not address interoperability between an IoT network and a BIM Common Data Environment, which is the exchange this study concerns.
IoT security: ISO/IEC 27400:2022	Security and privacy guidelines for IoT, with controls for developers and users.	Not aligned to project stages or to the appointment structure of ISO 19650, and silent on the physical exposure of tags on a construction site.
Digital twin: ISO/IEC 30173:2023	Concepts and terminology for digital twins.	No maturity progression tied to a construction lifecycle and no treatment of data handover between temporary and permanent assets.
Auto-ID air interface: ISO/IEC 18000-63:2021	Air interface parameters for UHF RFID at 860 to 960 MHz.	Device-level only. Regional spectrum permissions still apply, and nothing connects the read to an information container.
This study	A five-phase adoption guideline staging Auto-ID deployment within BIM-enabled projects and mapped onto the disaster management cycle.	Proposed as an early-stage baseline. Not yet tested in a live project.

Table 3 positions the framework against representative work across four areas. The areas follow the components of the research question. IoT and RFID integration in BIM-enabled construction establishes what the data-carrier layer can already do. Digital twin frameworks and maturity models establish the target state that continuous component data is meant to support. Information management standards and interoperability reviews establish the normative basis the framework must sit within. Post-disaster digital frameworks establish the environment the artefact is designed for. The comparison criteria follow the framework requirements in the same way. Lifecycle scope tests whether a study spans the disaster cycle rather than a single stage, standardisation tests whether it offers referenceable guidance, disaster context and cyber-physical security correspond to the setting and to Phase 5, and evidence base records how far each contribution has been tested, which is the basis on which this study positions

its own claims. The comparison shows that the individual capabilities the framework draws on are already established in the literature. What remains absent is their integration into a single referenceable guideline for the extreme-environment context.

Table 3: Comparative positioning of the proposed framework against representative BIM, IoT, digital twin and standardisation approaches drawn from the cited literature.

Source	Type and focus	Lifecycle scope	Standardisation	Disaster context	Cyber-physical security	Evidence base
Xue et al. (2018)	RFID to BIM linkage: status quo, trajectory and practitioner guidelines	Construction and asset tracking	Practitioner guidance, not normative	No	Limited	Literature review
Zhai et al. (2019)	IoT-enabled BIM platform for modular integrated construction	Manufacturing and on-site assembly	Platform architecture	No	Not addressed	Implemented case study (Hong Kong)
Hu et al. (2024)	BIM-enabled digital twin with wireless sensing for structural health monitoring	Operation and maintenance	Technical framework	Indirect (structural monitoring)	Not a focus	Technical demonstration
Khan et al. (2024)	RFID localisation with IoT and security integration	Construction and site operations	Technical method	No	Explicit (localisation security)	Technical and experimental
Boje et al. (2020)	Semantic construction digital twin: review and research directions	Construction and operation	Research agenda	No	Not a focus	Review and conceptual
Mêda et al. (2021)	Incremental digital twin for circular construction, material passports	Whole lifecycle with circular end-of-life	Conceptual	No	Not a focus	Conceptual
Lee et al. (2021)	Digital twin and blockchain for accountable information sharing	Design and construction information sharing	Framework	No	Explicit (blockchain integrity)	Framework with demonstration
ISO (2018, 2020)	Information management using BIM, with a security-minded companion part	Whole asset lifecycle	Normative international standard	No (general)	Security-minded, not IoT-specific	Consensus standard
Sarigul and Gunaydin (2026)	Integrated BIM, GIS and interoperable technologies in lifecycle management	Whole lifecycle, interoperability	Identifies needs only	No	Not central	Systematic literature review
Tak et al. (2026)	BIM and generative design for modular, circular post-disaster housing (precursor study)	Post-disaster housing, circular reconstruction	Process framework, not device standardisation	Yes (core)	Not a focus	Conceptual framework and requirement survey
This study	Five-phase Auto-ID adoption guideline mapped onto the disaster management cycle, with a Data-to-Design handover	Preparedness to permanent reconstruction, with circular handover	Referenceable guideline (baseline)	Yes (core)	Explicit, Phase 5 repeated at every gate	Perception survey, descriptive; not yet implemented

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The IoT and BIM integration studies report working applications, several of them implemented. Zhai et al. (2019) deliver a platform tested on a modular project, Hu et al. (2024) connect wireless sensing to a digital twin for structural monitoring, and Khan et al. (2024) address localisation with explicit security. These works optimise specific tasks rather than provide standardised lifecycle guidance, and none target the disaster context. The digital twin studies advance the concept along separate lines. Boje et al. (2020) set out research directions for semantic digital twins, Mêda et al. (2021) conceptualise incremental twins for circular construction, and Lee et al. (2021) add blockchain for information integrity. Each remains general in scope. ISO 19650 provides the normative basis for information management across the asset lifecycle, and its security-minded part addresses information security in general terms (International Organization for Standardization, 2018, 2020), yet neither part prescribes IoT edge device deployment or the extreme-environment context. Sarigul and Gunaydin (2026) confirm the interoperability needs without offering deployable guidance.

The precursor study by Tak et al. (2026) addresses the macro-scale post-disaster housing process through BIM and generative design, but it does not standardise the IoT data-carrier layer that connects physical assets to that process. The present study occupies this space. It contributes a five-phase adoption guideline mapped onto the disaster management cycle, treats cyber-physical security as a requirement that recurs at every phase, and defines the Data-to-Design handover that supports circular reconstruction. The evaluation is a descriptive professional assessment rather than a field implementation. The framework is therefore presented as an early-stage baseline that consolidates dispersed capabilities for the extreme-environment context and that future work can test in live projects.

2.5 Theoretical gap and transition to empirical analysis

The preceding literature review establishes that while the integration of BIM and IoT ecosystems offers substantial capabilities for lifecycle management, their industry-wide adoption remains constrained by fragmented practice and by the absence of construction-oriented deployment guidance. The reviewed studies indicate that the consequences are sharpest in extreme use-cases such as post-disaster reconstruction, where isolated data silos interrupt the continuity of component information on which circular reuse depends.

Studies articulate the potential of digital twins and Auto-ID tags to act as 'material passports' in these environments, but the reviewed literature offers few deployable implementation frameworks. Furthermore, there is a distinct lack of empirical requirement analysis regarding the specific operational benefits field professionals expect from these technologies during complex and high-stakes coordination.

While precursor research reports that data continuity underpins circularity and the mitigation of the 'second disaster' phenomenon (Tak et al., 2026), translating this theoretical knowledge base into a deployable and multi-phase operational guideline requires defining the actual technological expectations of the sector using field data. Consequently, this study addresses this theoretical gap by employing a DSR paradigm. The empirical findings derived from the extreme use-case scenario, presented in Section 4.1, serve as the baseline to define the structural and operational boundaries of the proposed IoT integration framework.

3. RESEARCH METHODOLOGY

This study adopts the DSR paradigm to develop and evaluate a guideline framework for IoT integration in BIM-enabled construction (Hevner et al., 2004). The DSR approach suits this investigation because it centres on the creation of a practical artefact, in this case a five-phase technical framework. The artefact responds to the fragmentation observed in Auto-ID deployment. It is not claimed to resolve fragmentation across the sector, since that would require evidence of implementation the study does not hold. This challenge is widely documented in general AEC literature (Duan & Cao, 2020) and is specifically evidenced in post-disaster coordination contexts (Tak et al., 2026).

The methodology runs through two empirical stages designed to connect macro-scale requirements with micro-scale industry practice. The two stages are referred to throughout as Stage 1 and Stage 2, which keeps them distinct from the five phases of the framework itself. Stage 1 identifies the foundational socio-technical requirements derived from an extreme use-case scenario, post-disaster reconstruction. Stage 2 is the structured evaluation of the proposed artefact by a cohort of AEC professionals, which records their perceptions of its importance and applicability.

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Table 4: Mapping the research process to the DSR cycles, adapted from Hevner et al. (2004).

DSR Cycle	Application in this Research	Empirical Data & Sources
1. Relevance Cycle *(Environment & Problem Space)*	Identifying the coordination bottlenecks, data silos and standardisation deficits in high-stakes construction environments.	**Stage 1 Data:** Questionnaire of 110 architects regarding post-disaster THU reconstruction (Extreme Use-Case).
2. Rigour Cycle *(Knowledge Base & Foundations)*	Extracting theoretical parameters for lifecycle intelligence, Auto-ID standardisation and cyber-physical security.	**Literature Review:** BIM interoperability, IoT technical standards and Circular Economy concepts.
3. Design Cycle *(Build & Evaluate Artefact)*	**Build:** Developing the 5-phase guideline framework (Initial Engagement to Security Assurance). **Evaluate:** Assessing the perceived relevance of the framework, stakeholder disposition and stated adoption intention.	**Stage 2 Data:** Structured quantitative survey of 113 diverse AEC professionals (Design consultants, Site teams, BIM consultants).
Research Contribution *(Outcome)*	Synthesising macro and micro scales to conceptualise the 'Data-to-Design Handover' mechanism.	**Final Artefact:** The Integrated Lifecycle Framework for IoT-BIM Adoption (Section 4.4).

To ensure methodological rigour, the research process is mapped against the three core cycles of the foundational DSR paradigm (Hevner et al., 2004). Table 4 provides a detailed mapping of these cycles (Relevance, Rigour and Design) to the specific activities and empirical data sources of this study. This structure keeps the artefact grounded in the existing literature through the rigour cycle and responsive to the requirements identified in the extreme use-case environment through the relevance cycle. Following the three-cycle view of design science (Hevner et al., 2004), the relevance, rigour and design cycles describe the methodological logic of the study and are distinct from the two empirical stages that supply the data. The relevance cycle draws on the Stage 1 requirement survey, the rigour cycle on the existing literature, and the design cycle builds the framework and evaluates it through the Stage 2 survey. The research contribution shown in the final row is the synthesis that results from the three cycles rather than a fourth cycle.

The five phases were derived in three steps. First, the barriers and enablers reported in the reviewed literature were extracted and grouped by the type of decision each one demands of a project team, which produced clusters concerned with awareness, technology selection, interoperability, stakeholder commitment and security. Second, the Stage 1 requirements were mapped onto those clusters to check that each corresponded to an operational need reported by practitioners rather than to a purely theoretical concern. Third, the clusters were ordered as an adoption decision sequence, which runs from deciding whether to engage, through selecting applications and securing interoperability, to aligning stakeholders and assuring security. The sequence is one of adoption decisions rather than of construction activities, and the mapping to project and disaster chronology is made separately in Section 4.4. Table 5 records the derivation, and the resulting phases are stated in full in Table 7 before their evaluation is reported.

3.1 Stage 1: Problem identification and requirement analysis

Stage 1 established the foundational requirements for the framework by identifying the socio-technical barriers in high-complexity environments. This stage integrated a comprehensive literature synthesis with empirical insights derived from a precursor investigation. That investigation used a questionnaire involving 110 registered architects

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to evaluate the potential utility and operational parameters of specific IoT edge technologies across logistical and human-centric phases of post-disaster reconstruction.

The data used in this stage was extracted as a targeted subset from a broader empirical investigation into post-disaster housing dynamics. While the overarching survey encompassed diverse architectural and logistical dimensions, this study exclusively isolates the data subset directly pertaining to technological coordination and IoT utility. The extraction provides an operational baseline for the framework without introducing out-of-scope variables. Analysing the requirements of an extreme use-case allowed this stage to establish where data security, stakeholder alignment and real-time synchronisation matter most to practitioners.

The precursor questionnaire was administered online to registered architects, and participation was voluntary with informed consent obtained before completion. The item analysed in the present study was a multiple-response question asking respondents to identify the areas in which IoT integration could assist post-disaster housing, and the responses are reported in Table 6 as valid percentages of the 110 respondents. The precursor sample comprised registered architects practising in Türkiye.

Table 5: Derivation of the five framework phases from the reviewed literature and the Stage 1 requirements.

Framework phase	**Barriers and enablers from the literature**	**Corresponding Stage 1 requirement**	**Addition made by this study**
Phase 1 Initial engagement	Stakeholders unaware of value-added applications beyond basic tracking (Xue et al., 2018; Sarigul & Gunaydin, 2026). Lack of knowledge of new technologies reported as a challenge (Abdelalim et al., 2025).	Endorsement of IoT for coordinating humanitarian aid (76.4%) and construction process (60.0%) indicates expected value.	Positions engagement as a formal decision point with a feasibility output, rather than an informal conversation.
Phase 2 Applications	Deployments isolated to single applications such as position monitoring (Gao et al., 2024; Xue et al., 2018). Supply chain and lifecycle gains reported where scope is wider (Wang et al., 2020; Zhai et al., 2019).	Requirement for logistical coordination and construction process management across the response, rather than location tracking alone.	Ties application selection to the intended lifecycle outcome and to the read-error validation available from the device class.
Phase 3 Interoperability and fragmentation of standards	Fragmented device standards inhibit interoperability (Duan & Cao, 2020; Osadcha et al., 2024; Wijerathna et al., 2026).	Data collection on affected individuals (70.9%) requires records that survive handover between organisations.	Frames interoperability as an exchange requirement between the IoT network and the Common Data Environment, not only between devices.
Phase 4 Stakeholder alignment	Misalignment and disconnected business units drive fragmentation (Duan & Cao, 2020). Adoption depends on cost and buy-in (Wang et al., 2020).	Coordinating humanitarian aid received the highest endorsement (76.4%). The requirement for multi-actor coordination is inferred from this result together with the construction-process item (60.0%).	Makes alignment a gate with a defined output, and links it to the establishment of the primitive digital twin.
Phase 5 Security assurance	Cyber-physical vulnerabilities recognised but under-treated in construction IoT research (Gamil et al., 2020; Seyis & Sönmez, 2023). Device-level threats catalogued in the security literature (Kumar et al., 2021).	Stage 1 respondents expected IoT to assist with collecting data on affected individuals (70.9%), which implies confidentiality requirements.	Defines security as an assurance gate repeated at every phase rather than a closing activity, aligned with the security-minded approach of ISO 19650-5.

3.2 Stage 2: Design, development and evaluation

In Stage 2, the initial guideline framework was developed and then evaluated for its perceived relevance among AEC professionals. The five phases as evaluated are stated in Table 7. The evaluation used a structured quantitative survey completed by 113 AEC professionals. The target population comprised diverse practitioners, including design consultants, site team members and BIM consultants. The evaluation recorded the perceived importance of each of the five framework phases, professional disposition towards existing standards, and the reported likelihood of engaging with these technologies under the proposed guidelines. The instrument used the term RFID throughout, since that is the Auto-ID technology most familiar to practitioners. Responses are therefore reported here as perceptions of Auto-ID solutions, and they should not be read as covering the wider IoT device population.

The survey was administered online and distributed to practising AEC professionals in the United Kingdom through the Chartered Institute of Building (CIOB). Participation was voluntary, each respondent received a participant information sheet, and informed consent was recorded before completion. Only fully completed questionnaires with recorded consent were retained for analysis, which produced the final sample of 113. Because distribution was mediated by the professional body rather than issued to a closed list of named invitees, the number of practitioners reached cannot be established and a response rate is therefore not reported. Respondents identified their project roles from a closed list with multiple selections permitted (Table 10).

The instrument comprised closed-format items in five areas: familiarity with and disposition towards established built environment standards and guidelines, current areas of BIM use, the areas in which IoT integration was expected to deliver benefit, the evaluation of the proposed framework, and the respondent's project role. The framework items asked respondents to rate the importance of each of the five phases on a labelled scale whose central anchor was 'Important', a design choice examined in Section 5.3, and a closing item recorded the likelihood of engaging with Auto-ID solutions if suitable application and process guidelines were available. The item wording and response options, as recorded in the analysis outputs retained with the study, are reported in Appendix A (Table A1). The original survey instrument is no longer held by the research team. The items were drafted from the barriers identified in the literature and reviewed by the research team for coverage and clarity before distribution, which supports face validity. No pilot study or formal content validity index was undertaken. Ethical approval for both survey stages was granted by the Faculty of Technology Ethics Committee of the University of Portsmouth (reference TECH2023-M.Y.T-01), and responses were analysed in aggregate with no identifying information reported. Stage 2 employs descriptive statistics to assess professional perceptions of the proposed artefact. Frequencies are reported in full, together with mean ratings, a relative importance index and Wilson score intervals for the principal proportions. Inferential models and reliability coefficients were not computed. This descriptive approach aligns with the exploratory character of DSR evaluation, and its consequences for the strength of the claims are set out in Section 5.3. The primary objective is to establish the perceived relevance and importance of the framework phases and respondents' stated adoption intention, rather than to test correlational hypotheses (Peffers et al., 2007).

4. RESULTS

In accordance with the DSR paradigm, this section presents the sequential development and evaluation of the proposed artefact. The framework addresses Auto-ID integration with BIM, using RFID and NFC transponders as the representative device class. These devices are treated as data carriers because that is the function reported in the reviewed implementations, not because their performance in extreme environments has been established here. The account begins with the Stage 1 requirement analysis, followed by the formulation of the five-phase framework and its evaluation by AEC professionals in Stage 2. This culminates in an integrated lifecycle synthesis model.

4.1 Stage 1 findings: Empirical requirements for extreme scenarios

To establish the foundational requirements for the guideline framework, empirical data was gathered to understand the specific operational demands within extreme scenarios. A survey of 110 registered architects working in post-disaster housing contexts recorded the areas in which respondents expected IoT integration to assist. The data in Table 6 shows a distinct pattern of professional endorsement. A clear majority of practitioners perceived Auto-ID devices as effective tools for backend logistical operations. These include coordinating humanitarian aid (76.4%),

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collecting affected individuals' data (70.9%) and managing the construction process (60.0%). Understanding the needs of affected individuals was endorsed by 59.1%.

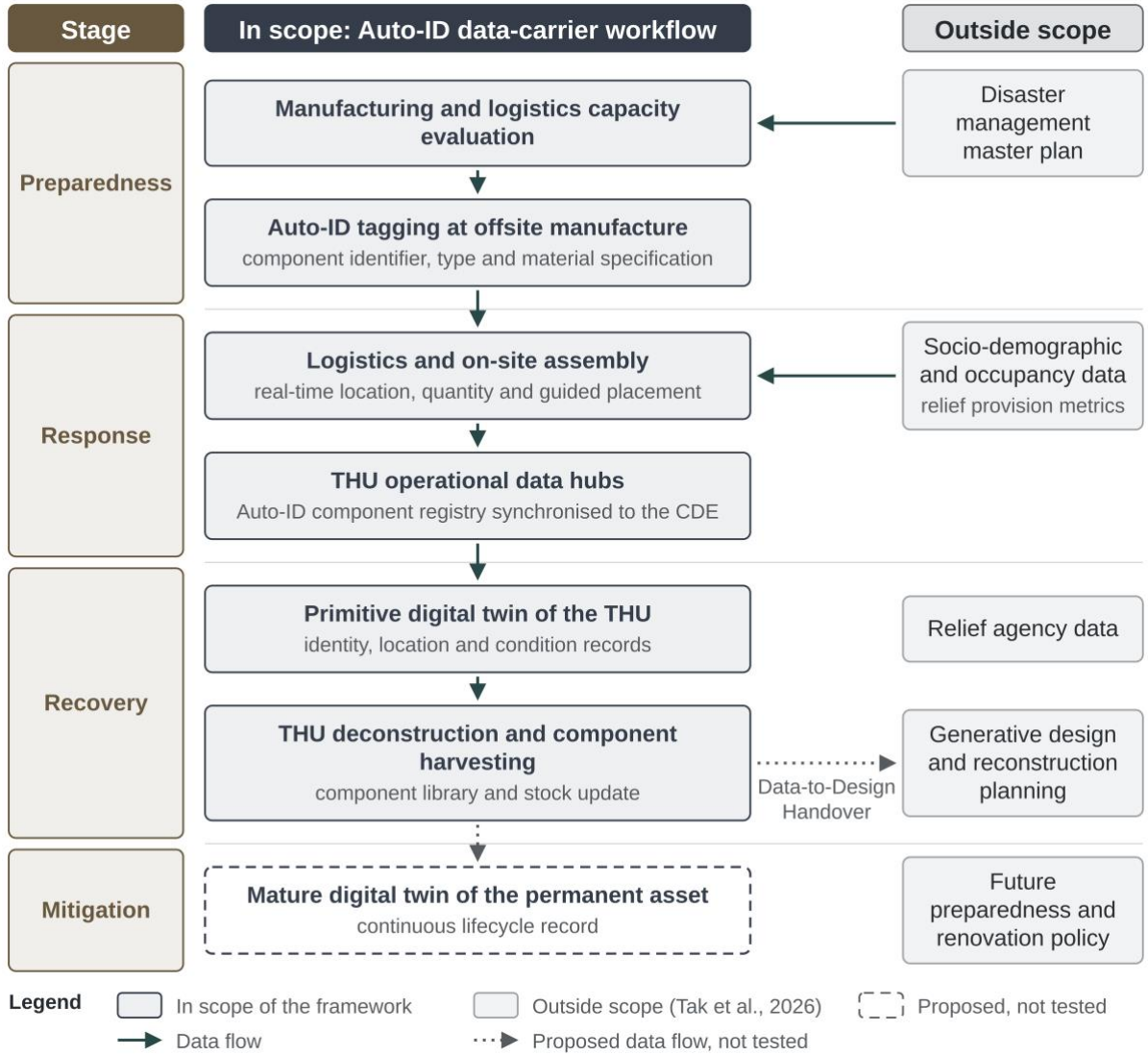


Figure 1: System boundary of the proposed framework across the disaster management cycle.

Conversely, the data indicated notably lower expectations for Auto-ID devices in two of the human-centric applications. Collecting affected individuals' opinions about the reconstruction of their houses (37.3%) and measuring post-resettlement satisfaction levels (30.9%) received markedly less endorsement. These contrasting figures indicate that respondents see Auto-ID devices as suited to machine-to-machine coordination and physical asset tracking rather than to participatory design. The pattern points to a framework that deploys these devices where respondents perceived them to be useful, in logistics and digital twin synchronisation, and that assigns participatory tasks to complementary systems.

Based on these empirical insights, Figure 1 delineates the conceptual system boundaries established for this study. The operational scope is confined to the Auto-ID data carrier mechanisms proposed to support the circular reconstruction cycle. As established in precursor research (Tak et al., 2026), these complex processes are managed by complementary frameworks. The current study proposes staged technical guidance intended to support data handover between the physical asset and those digital design ecosystems.

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The Stage 1 findings indicate that respondents associate extreme use-cases such as post-disaster reconstruction with logistical coordination and secure data continuity rather than with human-centric design interfaces. The guideline framework was therefore developed around technical workflows and lifecycle interoperability. The framework may be transferable to BIM-enabled projects outside post-disaster reconstruction, but it was derived from the post-disaster case and this potential transferability has not been tested.

Table 6: Stage 1 survey results, showing the areas in which respondents expected IoT integration to assist post-disaster housing (n = 110, multiple responses permitted).

Which areas can IoT integration in post-disaster housing assist with? (Tick all that apply.)	Valid Percent
Coordinating humanitarian aid	76.4%
Collecting affected individuals' data	70.9%
Understanding affected individuals' needs.	59.1%
Coordinating construction process	60.0%
Collecting affected individuals' opinions about reconstruction of their houses	37.3%
Measuring the satisfaction levels of affected individuals after they have resettled in their homes.	30.9%
None of them	3.6%
I don't know	11.8%

4.2 Guideline framework development

The major socio-technical barriers identified through the literature and the empirical findings were synthesised into a five-phase guideline framework (Table 7), following the derivation set out in Table 5. The parameters are informed by the logistical demands of post-disaster reconstruction. In such environments, transponders serve as data carriers rather than as inventory labels, which is what allows lifecycle information to persist across handovers. Table 8 then specifies each phase in operational terms, giving its objective, inputs, activities, actors, output, decision point and completion criterion, and Sections 4.2.1 to 4.2.5 discuss each in turn.

Table 7: The five phases of the guideline framework evaluated in Stage 2. The item wording respondents saw is given in Table A1.

Phase 1	Initial engagement in Auto-ID device technology in BIM-enabled construction, including concepts of best-practice and passive data validation.
Phase 2	Spectrum of Auto-ID device technology applications available for BIM-enabled construction.
Phase 3	Fragmentation of standards and interoperability of Auto-ID device technology in BIM-enabled construction.
Phase 4	Stakeholder alignment in Auto-ID device solutions for BIM-enabled construction.
Phase 5	Security vulnerabilities of and security countermeasure standards for Auto-ID device technology deployed in BIM.

4.2.1 Phase 1: Initial engagement

BIM plays a vital role in various aspects of the construction industry and the built environment. Many of these aspects are tied to critical processes (Sacks et al., 2018) and the use of a digital twin (Hu et al., 2024). Some stakeholders may be unaware of the additional value-added application opportunities available to improve and satisfy their unique requirements for Auto-ID solutions in BIM-enabled construction (Sarigul & Gunaydin, 2026; Xue et al., 2018). For instance, using connected edge devices merely to locate items stored on site or monitor intrusion underutilises the technology (Zhai et al., 2019). Conversely, advanced Auto-ID devices can enhance the performance of the entire supply chain process or lifecycle maintenance operations (Wang et al., 2020).

Stakeholders that use IoT hardware in BIM-enabled construction can often benefit from further developments in BIM that go beyond their basic requirements. Therefore, all stakeholders (clients, agents and consultants) must be suitably informed about the use of BIM alongside the various Auto-ID solution opportunities available to them.

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Lack of knowledge of new technologies is reported as a challenge in digital facility management (Abdelalim et al., 2025), which makes the advice that consultants give to clients material to the outcome.

Table 8: Operational specification of the five framework phases.

Phase	Objective	Inputs	Key activities	Actors	Output and completion criterion
1 Initial engagement	Establish informed engagement and decide whether Auto-ID is warranted.	Organisational and exchange information requirements, project brief, asset register.	Review of applications beyond basic tracking, appraisal of passive read-error validation, indicative cost and benefit appraisal.	Client, lead appointed party, BIM consultant.	Auto-ID feasibility statement issued to the Common Data Environment. Complete when the client records a proceed or stop decision.
2 Applications	Select the application scope and device class for the project.	Feasibility statement, construction methodology, offsite manufacturing plan.	Mapping of candidate applications to lifecycle outcomes, selection of device class, definition of read points and data fields.	BIM consultant, contractor, specialist supplier.	Application and device specification. Complete when read points and data fields are agreed and recorded.
3 Interoperability	Reduce fragmentation between the IoT network, the Common Data Environment and stakeholder systems.	Device specification, software schedule, information delivery plan.	Interface testing, resolution of frequency interference and crosstalk, definition of exchange format and cadence to the CDE.	BIM consultant, information manager, software vendors.	Exchange specification and interface test record. Complete when a test exchange reaches the CDE in the agreed format.
4 Stakeholder alignment	Secure commitment, resources and accountability across the supply chain.	Exchange specification, cost plan, appointment documents.	Allocation of responsibility for device data, budget confirmation, agreement on access rights and on the primitive digital twin.	Client, contractor, consultants, operator of the temporary housing.	Responsibility matrix and funded deployment plan. Complete when responsibilities are assigned in the appointment.
5 Security assurance	Assure the cyber-physical integrity of the device layer and its data.	Outputs of the preceding phase, threat register (Table 9), ISO 19650-5 security-minded approach.	Threat assessment, selection of authentication and encryption measures, network segmentation, access control, monitoring arrangements.	Information manager, security adviser, contractor.	Security assurance record for the phase just completed. Repeated at each phase gate, so the framework closes only when the final gate is passed.

4.2.2 Phase 2: Applications

Auto-ID device technology is versatile and ranges widely in BIM utility, albeit with some limitations. Which Auto-ID device technology suits a project should be established as early as possible. The nature of IoT data transmission makes easy use of error-checking processes through read-error-rate evaluation, which can reduce risks and enhance human safety (Khan et al., 2024). These processes validate data transmission in real-time to limit the likelihood of corrupt data being saved or transmitted between physical nodes and readers. This effectively creates a passive second layer of data validation that can flag read errors at the source, thereby reducing the risk that corrupt data enter the Common Data Environment.

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4.2.3 Phase 3: Interoperability and the fragmentation of standards

Fragmentation of standards and applications negatively affects interoperability regarding the management of equipment, operations or resources. This can occur through inefficient coordination among stakeholders, incompatible Auto-ID device hardware and software or disconnected business units. The fragmentation of IoT standards in construction directly inhibits BIM interoperability and limits its application opportunities (Duan & Cao, 2020). Fragmentation of application can also refer to poorly applied Auto-ID solutions that focus only on a specific need without realising the potential for a more complete system. For instance, Auto-ID devices might be deployed solely to record material locations rather than integrating comprehensive construction data for project managers. Potentially limited consideration may have been given to device capability, crosstalk, frequency interference (Khan et al., 2024) or interoperability with consultants' BIM software. Avoiding fragmentation of this kind is likely to reduce stakeholder misalignment. In complex deployments such as disaster recovery, Auto-ID devices are intended to maintain interoperability with broader digital ecosystems and so reduce the risk of isolated data silos. Failure to promptly rationalise these deployments may result in sunk costs if limited interoperability is discovered at a later stage.

4.2.4 Phase 4: Stakeholder alignment

Deploying a comprehensive Auto-ID solution requires considerable effort from stakeholders, who must establish the methods and hardware specifications suited to each application. This guideline is limited to the adoption decisions that precede those choices. Hardware specifications, radio frequencies, electronic layouts and network topologies are project-specific and are recorded as a limitation in Section 5.3.

Auto-ID device deployment costs can vary greatly. Budget alignment is required to establish whether the project scope justifies the investment. Where the lifecycle benefits identified in the literature materialise, they are expected to outweigh the capital cost, although this expectation requires project-specific verification. However, there are applications where deploying devices would add no efficiency and would be redundant. For example, work focusing on bespoke materials that require visual confirmation may be too infrequent to automate. Similarly, ad hoc building repairs requiring unique materials for singular applications might not benefit from automated tracking. Adequate stakeholder buy-in and alignment are needed concerning both resources and finances. Alignment of this kind supports compliance and reduces the risk of technology fragmentation or sunk costs.

Finally, various regulatory requirements and standards may affect a stakeholder's ability to deploy certain Auto-ID device technologies. Compliance is required with the communication spectrum regulations of the operating region. Other technical standards, such as those from the European Telecommunications Standards Institute or ISO, must also be integrated into the deployment strategy. Phase 4 closes with a responsibility matrix and a funded deployment plan, as specified in Table 8, and the assurance gate of Phase 5 is then run before the deployment proceeds.

4.2.5 Phase 5: Security assurance

While BIM-enabled construction sites remain susceptible to the same risks as traditional construction environments, such as incidental events like acts of nature and voluntary attacks like vandalism (Afzal et al., 2023), they also face a broader range of safety and security threats, including unique physical and cybersecurity vulnerabilities arising from advanced technology exploits (Gamil et al., 2020). Some studies mention cybersecurity as a risk to IoT deployments and indicate that further research is still required (Seyis & Sönmez, 2023). Attack statistics for IoT-enabled construction sites are largely undocumented, so the risks to physical devices have to be assessed on the basis of the general security literature. The assessment belongs in early project planning, before detailed design commences. In the United Kingdom this corresponds to stages 0 to 3 of the RIBA Plan of Work, and equivalent pre-design stages exist in other national plans of work. The point that generalises internationally is the timing relative to the ISO 19650 information delivery cycle, where security requirements belong in the exchange information requirements issued with the appointment rather than in a later revision. Security protocols should be established for the anticipated site conditions before transponders, readers and software are deployed. Table 9 presents these vulnerabilities within Auto-ID enabled construction.

The framework treats these vulnerabilities through a security-minded approach applied from the first phase onwards. Phase 5 is therefore an assurance gate that is first run alongside Phase 1 and repeated at each subsequent gate, rather than a closing activity. It was presented to respondents as the fifth phase, and it is retained in that

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position so that the evaluation reported in Section 4.3 corresponds to the framework as assessed. At the framework level, the recommended mitigations include authenticated and encrypted communication for IoT data in transit and at rest, segmentation between site-level IoT networks and the common data environment, role-based access control with device identity management, and continuous monitoring of the data pipeline. These measures align with the security-minded approach of ISO 19650-5 (International Organization for Standardization, 2020). The detailed threat modelling, penetration testing and selection of specific cryptographic and network controls depend on the deployment context and represent a clear direction for future technical work.

Table 9: Security vulnerabilities present in Auto-ID device technology, drawn from the RFID security literature.

Vulnerabilities	Description
Eavesdropping	Involves unauthorised access to transponder data, which attackers can read and record (Kumar et al., 2021).
Spoofing	Accessing a transponder's data, but with capabilities to digitally imitate the transponder's unique identity to trick the reader into accepting it (Gabsi et al., 2021).
Cloning	Similar to spoofing but coupled with the action of physically duplicating an Auto-ID device (Kumar et al., 2021; Singh & Patro, 2021).
Replay	Attacks involving eavesdropping of radio frequencies to impersonate a transponder (Xiao et al., 2020).
Viruses/Worms	Malware attacks on the frontend or backend software that communicates with the Auto-ID device nodes (Kumar et al., 2021).
Denial of service attacks	Radio frequency channels get flooded with noise that disrupts communication (Lounis & Zulkernine, 2020).
Disabling	Attackers access and change the identification of a transponder, causing it to be unrecognisable to the owner's IoT gateway, effectively hijacking it (Singh & Patro, 2021).

Many security countermeasures are available to safeguard Auto-ID device technology deployed on a BIM-enabled construction site. It is important to realistically consider potential risks, the likelihood of attacks and the relevant attack surface to anticipate necessary defences. Recent security literature identifies eavesdropping, spoofing, cloning, replay attacks, denial of service and physical tampering as persistent threats. Modern defences increasingly emphasise protocol-level cryptography and mutual authentication rather than relying exclusively on physical countermeasures (Gabsi et al., 2021; Kumar et al., 2021; Singh & Patro, 2021). For low-cost tracking tags, recent studies propose lightweight authentication and pseudo-random number generation schemes to improve confidentiality and resistance to impersonation attacks (Majumder et al., 2024; Xiao et al., 2020). Physical measures such as shielding and range limitation remain relevant, although they are now generally treated as complementary safeguards (Lounis & Zulkernine, 2020).

4.3 Stage 2 findings: AEC industry evaluation

4.3.1 Professional disposition and technological readiness

This section presents the empirical results of the framework's evaluation by the AEC industry. A total of 113 professionals consented to and fully completed the structured questionnaire.

The sample is concentrated in the UK, which follows from the outreach route through which the survey was distributed. The framework itself draws on international standards, but the evaluation reflects one national market and should be read as indicative for comparable contexts rather than as evidence of a response that generalises across technology markets.

Professional role shapes how respondents judge technological utility, so the composition of the cohort matters to the interpretation. Table 10 sets out the roles represented.

As indicated in Table 10, design consultants formed the largest share of role selections (54.7%), followed by site team members (18.0%) and BIM consultants (15.8%). The weighting towards design professionals is a characteristic of the sample rather than a finding, and it means the results describe how the design side of the

industry views Auto-ID adoption more fully than they describe the contractor view. One reading of the lower participation from site teams is that deployment of these technologies is treated as a contractor-level or ad hoc matter rather than a design-stage decision, although the survey does not test that explanation.

Table 10: Participants' roles in AEC projects. The role item allowed more than one selection, so the counts total 139 across the 113 respondents and the percentages are expressed as a share of responses.

Participants' roles	Number of representatives
Materials/specialist suppliers	2 (1.4%)
Real estate consultants	1 (0.7%)
Specialist consultants	4 (2.9%)
Site team	25 (18.0%)
Client team	9 (6.5%)
BIM consultants	22 (15.8%)
Design consultants	76 (54.7%)

To evaluate the baseline professional environment, participants were asked about their familiarity with, and disposition towards, established industry standards, including National Building Regulations, ISO standards, and the Royal Institute of British Architects (RIBA) Plan of Work. Figure 2 illustrates both items. Each was recorded on the same four-point scale running from not applicable to very beneficial, so the item labelled familiarity is read as the respondents' rating of the benefit of the standards they are familiar with, rather than as a measure of how familiar they are with them. On that item, 81.4% of respondents rated the standards as somewhat or very beneficial, and on the disposition item the figure was 92.9%. This high regard for existing regulatory instruments indicates that respondents are accustomed to working from structured guidance. This is consistent with an explanation in which the constraint lies in the absence of referenceable guidance rather than in professional resistance. The survey measured perceptions, not causes, so this remains an interpretation rather than a demonstrated relationship.

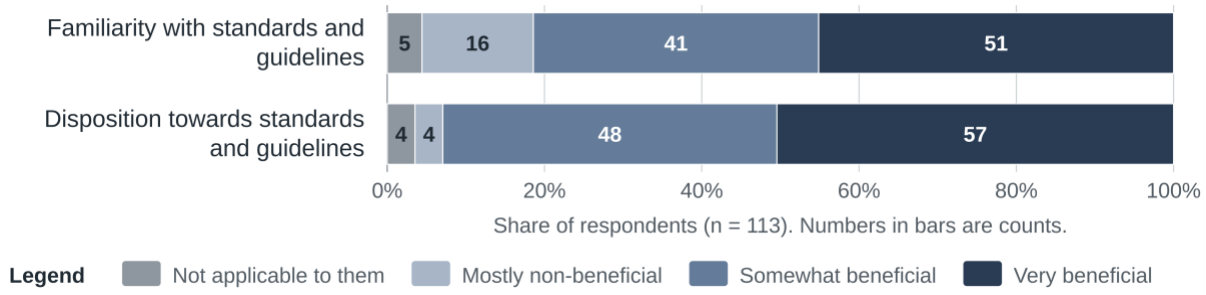


Figure 2: Participant familiarity with, and disposition towards, built environment standards and guidelines.

4.3.2 Identifying the application gap: Current BIM practices versus IoT potential

To further establish the operational context, participants were asked to identify their current areas of BIM use and then to select the areas where they perceived IoT integration would deliver the greatest benefit. A comparison between current BIM use and the perceived potential of Auto-ID solutions shows a clear shift in expectation (Figure 3). Most respondents identified the technology as a beneficial addition to the AEC sector.

While current BIM use concentrates on standard 3D modelling, expectations for IoT application shift towards dynamic and lifecycle-oriented tasks. Building lifecycle management was selected by 8.0% of respondents as a current area of BIM use and by 50.4% as an area where Auto-ID would deliver benefit. Site staff management moves from 8.8% to 43.4% and building supply chain management from 5.3% to 31.0%. Conventional 3D documentation moves in the opposite direction, from 54.9% to 34.5%. Because the item permitted multiple selections, these are shares of respondents rather than shares of a fixed total, and the two items are not directly

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comparable as a single distribution. One category, site management of the construction process, recorded 25 selections for current use and none for perceived potential. The respondent-level records no longer exist, so it cannot be established whether this value reflects the responses given or a recording error in the second item, and the category is therefore excluded from the interpretation that follows.

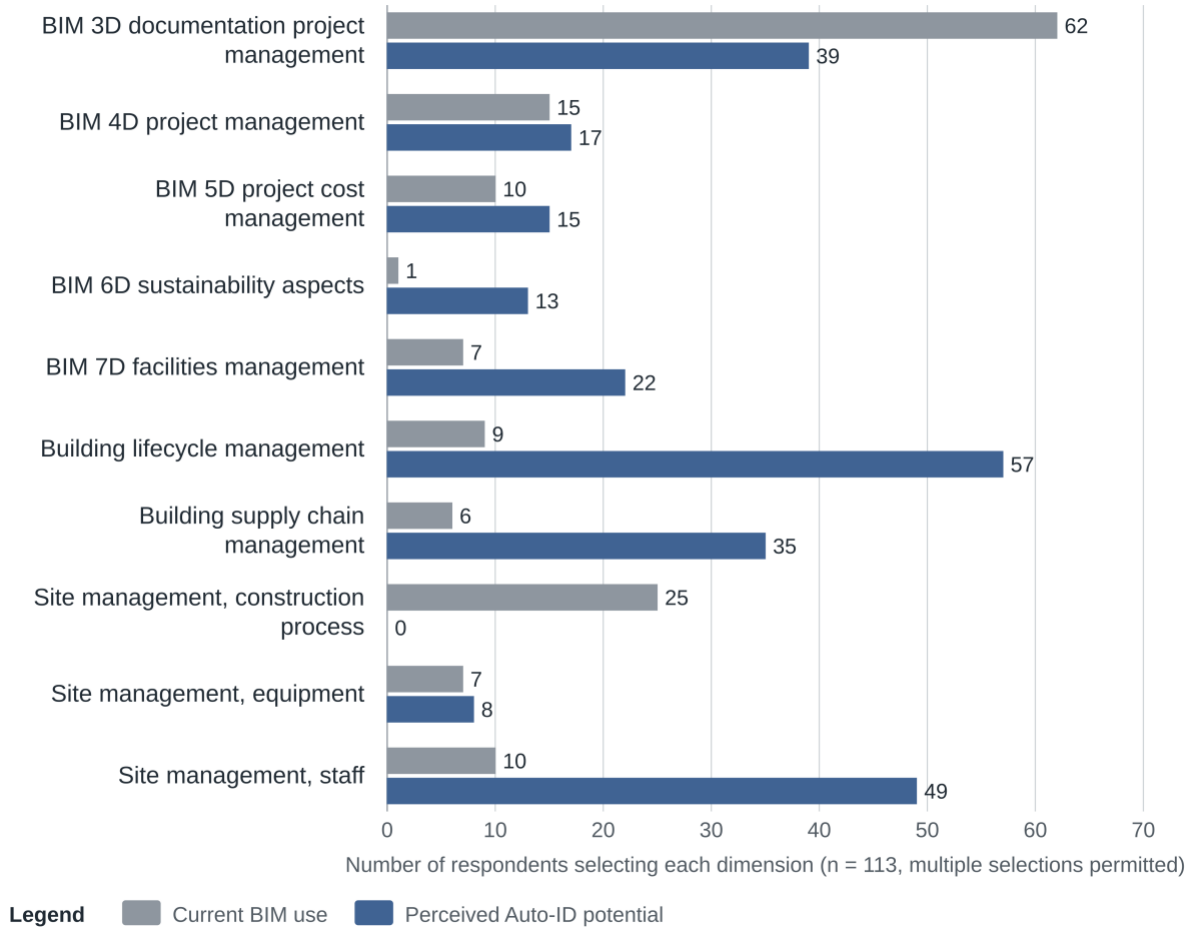


Figure 3: Current BIM use compared with perceived Auto-ID potential across ten BIM dimensions. The construction process category is excluded from interpretation (Section 4.3.2).

This divergence indicates that practitioners do not view Auto-ID as a supplement to existing 3D modelling capabilities. They see it as a tool that supports advanced operational dimensions such as real-time site coordination and long-term asset tracking. The gap between perceived value and reported use is consistent with the premise of the study, that the barrier to entry lies in the absence of implementation guidance rather than in industry resistance. The data establishes the gap. It does not by itself establish its cause.

4.3.3 Evaluation of the Proposed Guideline Framework

To evaluate the practical utility of the proposed five-phase guideline framework, participants were asked to evaluate the importance of each individual phase within the context of BIM-enabled projects. Figure 4 shows the distribution of ratings for each phase.

All five phases attracted majority support at or above the central anchor, but the reception was not uniform. Table 11 reports the full distributions with derived measures. Stakeholder alignment received the highest mean rating at 3.82 on the five-point scale, with 64.6% of respondents rating it very or critically important, followed by security assurance at 3.71. Interoperability and the fragmentation of standards received the lowest mean at 3.23, the lowest proportion of very or critically important ratings at 42.5%, and the highest proportion of ratings below the central anchor at 21.2%. The confidence intervals for the top-two proportions of Phase 4 and Phase 3 do not overlap, so

the ordering of the extremes is unlikely to be an artefact of sampling variation, although no paired test could be applied. The intervals for the three middle phases overlap and their relative order should not be read as meaningful. The central anchor of the scale was labelled Important rather than a neutral term, which may have shifted responses upwards, and Section 5.3 returns to this. The pattern carries a finding that runs against the framing of the study and is discussed in Section 5.1: the phase addressing the standards gap most directly, presented to respondents as fragmentation in RFID solutions (Table A1), is the one they rated least important, while the phases they rated highest concern the organisational and security consequences of that gap.

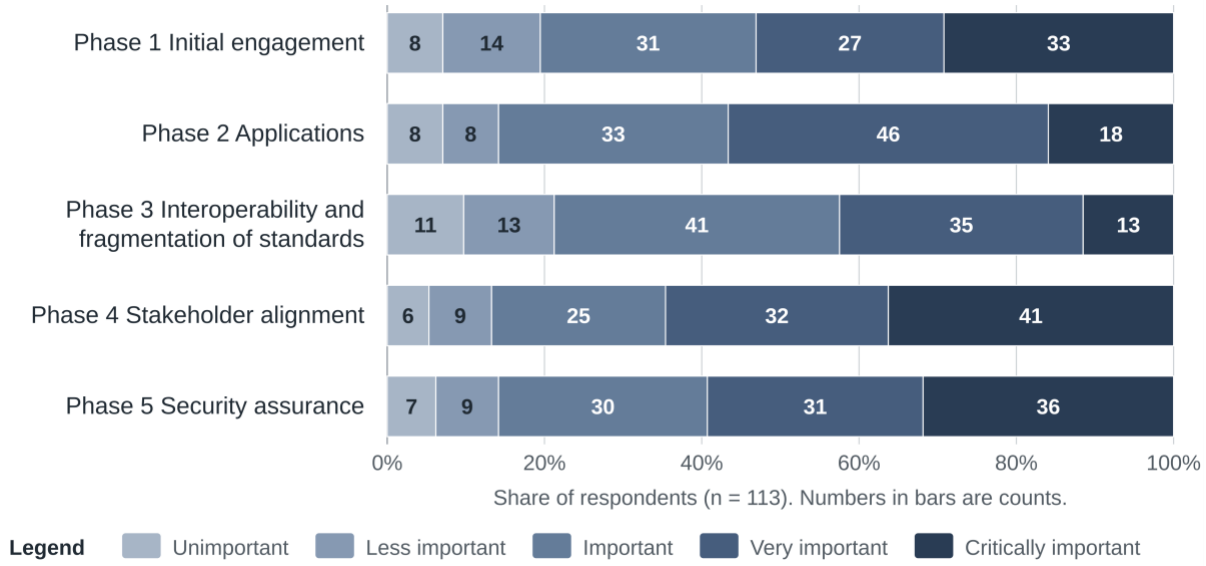


Figure 4: Participants' perceptions of the importance of each of the five framework phases (n = 113).

Table 11: Distribution of importance ratings for each framework phase (n = 113), with mean score on a scale from 1 (unimportant) to 5 (critically important), relative importance index, and Wilson score intervals for the proportion rating each phase very or critically important. RII is the mean rating divided by 5.

Phase	Unimportant	Less important	Important	Very important	Critically important	Mean	RII	Very or critically important, % (95% CI)
1 Initial engagement	8 (7.1%)	14 (12.4%)	31 (27.4%)	27 (23.9%)	33 (29.2%)	3.56	0.712	53.1 (43.9 to 62.0)
2 Applications	8 (7.1%)	8 (7.1%)	33 (29.2%)	46 (40.7%)	18 (15.9%)	3.51	0.703	56.6 (47.4 to 65.4)
3 Interoperability and fragmentation	11 (9.7%)	13 (11.5%)	41 (36.3%)	35 (31.0%)	13 (11.5%)	3.23	0.646	42.5 (33.8 to 51.7)
4 Stakeholder alignment	6 (5.3%)	9 (8.0%)	25 (22.1%)	32 (28.3%)	41 (36.3%)	3.82	0.765	64.6 (55.4 to 72.8)
5 Security assurance	7 (6.2%)	9 (8.0%)	30 (26.5%)	31 (27.4%)	36 (31.9%)	3.71	0.742	59.3 (50.1 to 67.9)

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To gauge the potential effect of such a framework on future industry behaviour, participants were asked whether access to these structured guidelines would increase their likelihood of adopting Auto-ID solutions (Figure 5).

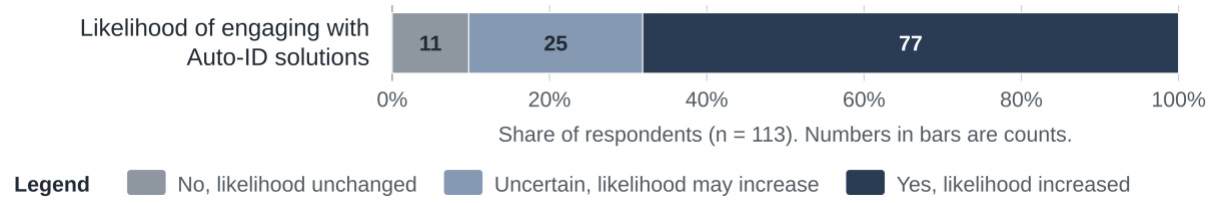


Figure 5: Reported likelihood of engaging with Auto-ID solutions in BIM projects if suitable application and process guidelines were available (n = 113).

As shown in Figure 5, 77 of the 113 respondents (68.1%, 95% CI 59.1 to 76.0) reported that referenceable guidelines would increase their likelihood of engaging with these technologies, 25 (22.1%) were uncertain and 11 (9.7%) reported no change. This supports the proposition that available guidance would change stated intent. Stated intent is not adoption, and the item does not establish that the absence of standards is the principal cause of slow uptake.

The evaluation fed back into the artefact in two ways. The five-phase structure was retained, since every phase attracted majority support at or above the central anchor and no phase was rejected by the cohort. The relative weighting changed. Because stakeholder alignment and security assurance were rated highest while interoperability was rated lowest, Phase 5 was redefined as an assurance gate repeated at each phase rather than a terminal step, and Phase 4 was given an explicit output in the appointment documents, as set out in Table 8. These two refinements were made after the Stage 2 evaluation and have not themselves been evaluated. The revised framework is then synthesised into the integrated lifecycle model in Figure 6.

4.4 Synthesis: Towards an integrated lifecycle model

The final outcome of this research is the synthesis of the macro-scale disaster management cycle with the micro-scale technical adoption framework (Figure 6). The model responds to the fragmentation documented in Section 2 by describing a continuous data loop running from preparedness to permanent reconstruction. The loop is a design proposition. Its components draw on capabilities reported in the literature, but the loop as a whole has not been operated in a project.

During the Pre-Disaster and Preparedness stage, the framework aligns with Phase 1 (Initial Engagement) and Phase 2 (Applications) of the developed guidelines. At this point Auto-ID devices support inventory management and the pre-positioning of off-site manufactured (OSM) components. Planning of this kind responds to the scale of losses and the protracted, resource-constrained housing recovery described in the earthquake literature (Alam & Ali, 2023; Costa et al., 2021). Upon the occurrence of a disaster, the Emergency Response stage triggers Phase 3, which focuses on avoiding fragmentation. In this high-pressure environment, Auto-ID tracking is intended to provide the logistical coordination required for rapid assembly and to reduce the coordination bottlenecks that frequently stall recovery efforts (Puri et al., 2024).

As the process transitions into the THU Operations, the framework invokes Phase 4 (Stakeholder Alignment) to establish a 'Primitive Digital Twin'. This initial digital replica functions as a dynamic repository for component identity, location and condition records (Figure 6). The distinctive element of this synthesis is the Data-to-Design Handover. The Stage 1 data recorded lower practitioner expectations for these devices in human-centric design tasks, and the model accepts that boundary by assigning them the data-carrier role and leaving the design interface to complementary systems (Figure 1), an arrangement explored for generative and modular post-disaster reconstruction by Tak et al. (2026). The handover was not tested in either survey stage, so it is presented here as a specification for future work rather than as a result. Table 12 states it in operational terms, and Figure 7 shows the sequence of exchanges between the actors involved.

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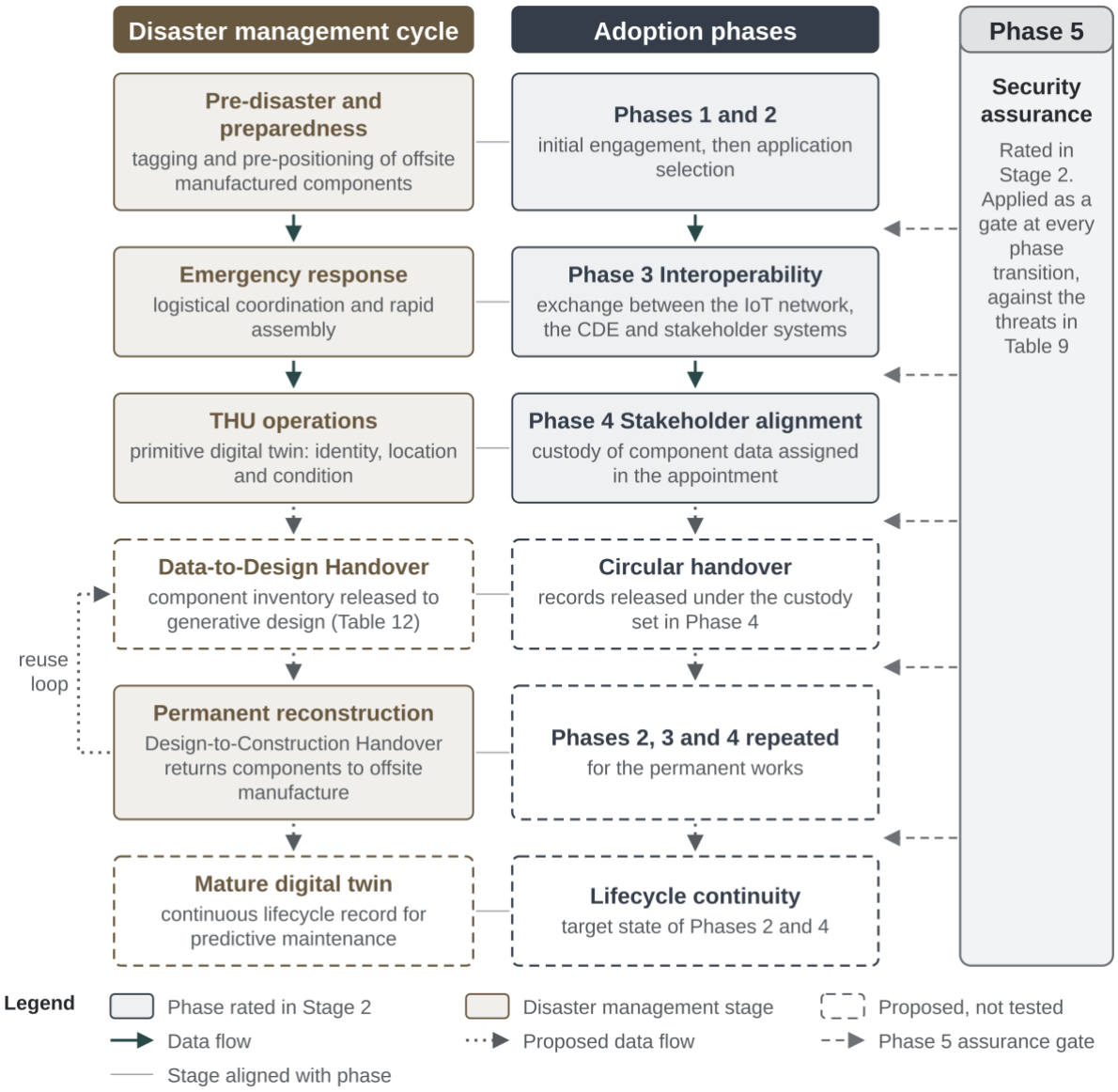


Figure 6: Integrated lifecycle framework for Auto-ID adoption in post-disaster reconstruction.

The final stage, involving the evolution to a mature digital twin, represents the achievement of the lifecycle goals defined in Phase 2 and Phase 4. Where data continuity is maintained across the reconstruction process, the twin could hold a continuous lifecycle record capable of supporting predictive maintenance (Preut et al., 2021). This progression is a proposition of the model and was not observed in this study. Across the whole continuum, Phase 5 operates as a repeated assurance gate rather than a single stage, addressing the cyber-physical vulnerabilities catalogued in Table 9 at each transition (Kumar et al., 2021). The integrated framework therefore sets out how staged adoption could support the development of emergency housing into a more resilient lifecycle process. Whether it does so is a question for implementation research.

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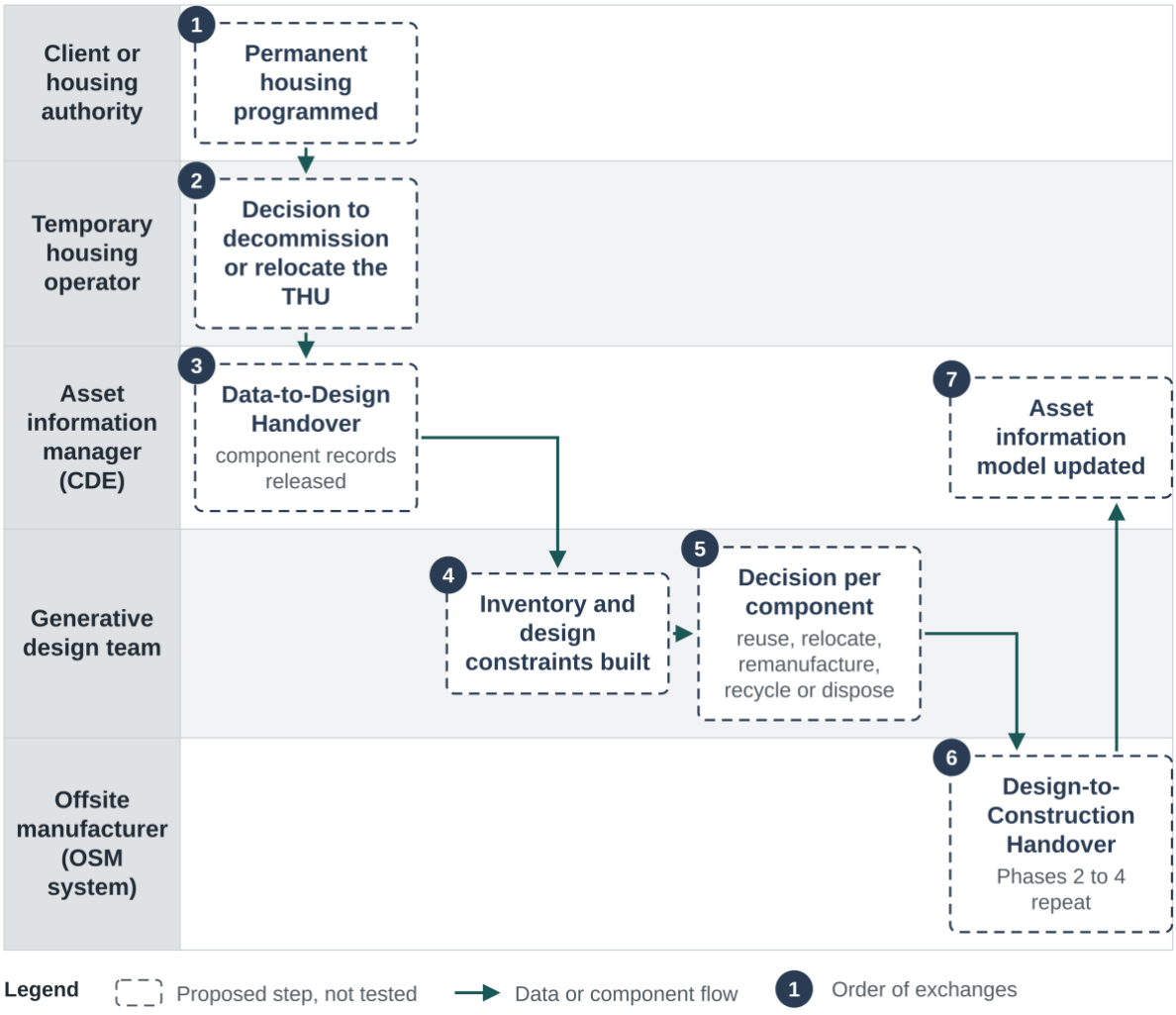


Figure 7: Sequence of exchanges in the proposed Data-to-Design Handover, drawn as a swimlane across the five actors named in Table 12.

4.4.1 Illustrative Application of the Framework

The following scenario illustrates how the framework would operate end to end. It is constructed from the sources already cited in this paper and from the process described in the precursor study. It is an illustration of the intended operation of the framework, not a case study, and no field data support it.

Consider a housing authority responding to an event of the scale reported for the 2023 earthquakes in Türkiye, where direct damage to the real estate sector was estimated at USD 27.7 billion (Alam & Ali, 2023). Before any event, the authority completes Phase 1 and records a decision to tag OSM wall and floor cassettes held in regional stock, and Phase 2 fixes the device class and the data fields written at the factory. The Phase 3 exchange between the reader network and the Common Data Environment is agreed in advance and comes into operation during the emergency response, so that a read at a depot updates an information container rather than a separate spreadsheet. The Phase 4 custody arrangement, which assigns that data to the authority rather than to individual contractors, is also agreed in advance and takes effect during THU operations. Phase 5 is run at each of these gates.

In the emergency response, cassettes are dispatched and assembled as temporary housing units. Reads at dispatch, arrival and assembly populate the primitive digital twin of the settlement, which holds component identity, location and condition but makes no predictions. Over the period of temporary occupation, inspection records accumulate against each component identifier. When permanent reconstruction is programmed, the Data-to-Design Handover specified in Table 12 releases the component inventory to the generative design process described by Tak et al.

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(2026), which allocates sound cassettes to permanent dwellings, sends damaged ones for remanufacture and records the remainder for recycling. The Design-to-Construction Handover returns the allocation to the manufacturer, and Phases 2, 3 and 4 repeat for the permanent works, each with the Phase 5 assurance gate. The component record transfers into the asset information model of the permanent housing, which is the point at which the twin acquires the continuous history the model describes as mature.

The scenario shows what the framework asks of a project and where its untested assumptions sit. It assumes that devices survive dismantling and storage, that custody of the data persists across a change of contractor, and that condition records are complete enough to support reuse decisions. Each is a proposition that implementation research would need to test.

Table 12: Operational specification of the proposed Data-to-Design Handover.

Element	Specification
Trigger	A decision to decommission or relocate a temporary housing unit, taken by the operator once permanent housing is programmed.
Information carried	Component identifier, manufacturing and material record, installation and relocation history, cumulative service duration, inspection and condition records, and any damage events logged against the component.
Source and custody	Data written to and read from the Auto-ID device on the component, mirrored as information containers in the Common Data Environment under ISO 19650, with the asset information manager accountable for custody.
Actors	Temporary housing operator, asset information manager, generative design team, offsite manufacturer, client or housing authority.
Transformation	Component records are converted into a harvestable inventory and into constraints for the generative design process, in which condition and remaining service life determine whether a component enters the permanent design directly, after remanufacture, or not at all.
Decision points	Per component: reuse in place, relocate and reuse, remanufacture, recycle, or dispose. Recorded against the component identifier so the decision remains auditable.
Return path	The Design-to-Construction Handover returns the allocated components to the OSM system for reassembly, which repeats Phases 2, 3 and 4 for the permanent works, each with the Phase 5 assurance gate.
Completion criterion	Every tracked component is allocated to a permanent design or formally closed out, and the resulting record is transferred into the asset information model for the permanent asset.
Status	Conceptual proposition. Not evaluated in Stage 1 or Stage 2 and not implemented in a project.

5. DISCUSSION

5.1 Interpretation of the findings against the literature

Before interpreting the results, it is worth stating plainly which claims rest on the survey data and which are propositions of the design. Table 13 makes that separation, and the discussion that follows observes it.

The empirical findings align with the gaps identified in the literature. The Stage 1 requirement analysis showed that practitioners expected most benefit in coordination and data collection tasks, which the reviewed IoT and BIM studies support at the level of individual capabilities rather than as integrated and standardised guidance (Hu et al., 2024; Xue et al., 2018; Zhai et al., 2019). The Stage 2 evaluation indicated broad professional support for the staged adoption structure, which is consistent with the call in the standardisation and interoperability literature for referenceable frameworks (International Organization for Standardization, 2018; Sarigul & Gunaydin, 2026). The contribution is therefore to consolidate these dispersed capabilities into a single lifecycle guideline, as summarised in Table 3, rather than to introduce a new individual technology.

The pattern of professional endorsement observed in Stage 1 mirrors the areas in which implemented IoT and BIM systems have already demonstrated value. The strong endorsement of humanitarian aid coordination, data

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collection and construction process management corresponds to the machine-to-machine domains addressed by the implemented platform of Zhai et al. (2019) for modular integrated construction and by the structural health monitoring twin of Hu et al. (2024). The markedly lower endorsement of participatory and satisfaction-related tasks is consistent with the boundary drawn in the precursor study (Tak et al., 2026), which assigns participatory design to complementary generative design environments rather than to the data carrier layer. The requirement analysis is therefore consistent with the division of responsibilities that Figure 1 sets out, with Auto-ID devices acting as data carriers and complementary systems providing the design interface.

Table 13: Separation of observed results from conceptual propositions.

What the study observed	What the study proposes but did not test
Stage 1: the areas in which 110 architects expected Auto-ID integration to assist post-disaster housing, with logistical coordination endorsed far more strongly than participatory tasks.	That the resulting division of labour, with devices as data carriers and complementary systems as the design interface, is the right one operationally.
Stage 2: the perceived importance of each of the five phases, the ranking among them, professional disposition towards existing standards, and stated likelihood of engagement.	That applying the five phases in sequence improves adoption outcomes, interoperability, circularity or resilience on a project.
A gap between reported current use of BIM dimensions and the areas where respondents expect Auto-ID to deliver benefit.	That the absence of referenceable standards is the principal cause of that gap, rather than one of several contributing causes.
That 68.1% of respondents state referenceable guidelines would raise their likelihood of engagement.	That stated intent converts into adoption in practice.
Nothing was observed about the handover.	The Data-to-Design Handover as specified in Table 12, and the progression from a primitive to a mature predictive digital twin.

The application gap identified in Stage 2 gives empirical form to the fragmentation described in earlier reviews. Duan and Cao (2020) and Osadcha et al. (2024) attribute slow adoption to ad hoc deployments and non-interoperable standards, and Wijerathna et al. (2026) reach a similar conclusion for tracking technologies in construction. The finding that respondents value existing regulatory instruments while the literature reports slow adoption is consistent with a constraint that lies in the absence of referenceable guidance rather than in professional resistance, although the survey cannot separate that explanation from others such as cost, procurement practice or perceived return. This reading is coherent with ISO 19650, which provides the normative basis for information management without prescribing device deployment (International Organization for Standardization, 2018, 2020), and with Sarigul and Gunaydin (2026), who identify interoperability needs without offering deployable guidance. The ordering of the phase ratings deserves attention because it complicates the framing of the study. Practitioners rated stakeholder alignment and security assurance highest and rated interoperability and the fragmentation of standards lowest, which is the phase that addresses the standardisation gap most directly. Two readings are available. The first is that practitioners experience the standards gap indirectly, through the misalignment and security exposure it produces, rather than as a technical problem they encounter in their own work, which would be consistent with a cohort weighted towards design consultants who rarely specify device interfaces. The second is that interoperability is understood as a supplier responsibility and is therefore discounted. Neither reading can be tested with these data. What the result does establish is that a framework justified by a standards gap should not assume practitioners perceive that gap in the same terms, and that the organisational conditions for adoption may matter more to them than the technical ones.

The integrated lifecycle model extends the circularity concepts in the digital twin literature into the disaster context. Mêda et al. (2021) conceptualise incremental twins and material passports for circular construction, Boje et al. (2020) set out a research agenda for semantic construction twins, and Lee et al. (2021) and Brandín and Abrishami (2024) address information integrity and traceability. The Data-to-Design Handover connects these threads by specifying the point at which component data crosses from the physical asset to the design ecosystem within the disaster management cycle. Two boundaries of this comparison require emphasis. First, several of the benchmark studies in Table 3 report implemented systems, whereas the present framework has been evaluated through professional perception alone, so its comparative standing rests on scope and integration rather than on demonstrated performance. Second, the handover mechanism remains a conceptual proposition that the Stage 2

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survey did not test directly. The model is therefore best read as a consolidating baseline whose operational claims await verification in live projects, in line with the limitations set out in Section 5.3.

5.2 Practical and theoretical implications

The findings of this study carry implications for both academic theory and industry practice. Theoretically, the study addresses a gap in the literature on the role of Auto-ID devices in circular and human-centric construction models. By treating the IoT network as the connecting ecosystem and the edge device as a data carrier rather than a design interface, the study offers a position that is consistent with the Stage 1 data and that subsequent work can test. It proposes a structured mechanism for transferring component integrity data to complementary systems, such as generative design, during post-disaster reconstruction. This conceptual bridge may serve as a theoretical reference point for future studies aiming to produce comprehensive international standards and policies.

Practically, the study offers an artefact that practitioners have assessed for relevance. The five phases and their operational specification in Table 8 give AEC stakeholders a reference for structuring an Auto-ID deployment decision, covering scope selection, stakeholder alignment and security assurance. The framework has not been applied in a project, so its practical value remains to be established. A field test would need to run the phases on a live deployment, record where the gates are met or missed, and compare data continuity against a project without them. The framework was derived for post-disaster reconstruction, and its use in other BIM-enabled projects is a potential transfer that has not been tested.

5.3 Limitations and future research directions

Several limitations bound what the study can claim. Firstly, the framework was developed for the post-disaster case and written at a level of generality that may extend further, but that extension has not been tested. Consequently, specific country-level regulatory constraints, such as communication spectrum allocations, radio frequency compliance and local privacy laws, were not detailed. Deployments must therefore be assessed against local policy and should not be applied at face value. Future research should subdivide the framework parameters to explore these specific technical compliance requirements in greater depth. The framework also remains at the level of process guidance and does not specify hardware selection, device classes or network topologies, which depend on the project context and represent a complementary direction for future technical development.

Secondly, the two samples present a specific geographic context. Stage 1 data were drawn from registered architects working on post-disaster housing in Türkiye, and Stage 2 data from a separate group of AEC professionals concentrated in a single national market. Distribution in Stage 2 was mediated by a professional body rather than drawn as a probability sample, so the respondents are a self-selected group of practitioners who chose to reply, the number reached cannot be established and no response rate can be reported. Self-selection of this kind tends to favour respondents already interested in the topic, which may inflate the reported disposition towards adoption. The sample also weights towards design consultants, as Table 10 shows, so the contractor perspective is under-represented. Future studies should replicate the evaluation across other national markets and regulatory environments. Until such replication is undertaken, the evaluation should be read as indicative for comparable national contexts rather than as globally representative.

Thirdly, a methodological limitation concerns the construction of the rating scale used in the evaluation of the framework phases. In the research instrument, the 'Important' option was positioned as the central anchor of the scale. This design choice may have induced a semantic shift because 'Important' typically denotes a positive attribute rather than a neutral midpoint. Consequently, this alignment may have introduced a degree of positive acquiescence bias, which would overstate the perceived importance of some phases. Future iterations of this study should employ a more balanced psychometric scale with a distinct neutral midpoint to give a more precise reading of stakeholder views.

Fourthly, a further methodological limitation involves the reliance on descriptive evaluation. The evaluation describes aggregate perceptions rather than testing relationships, so the study reports no internal consistency statistics such as Cronbach's alpha and no inferential models. For these reasons, the present contribution is best understood as an early-stage framework that consolidates dispersed capabilities, and its operational value requires confirmation through implementation in live projects. Two further constraints follow from the data itself. The respondent-level records for both stages are no longer held by the research team, so the aggregate distributions

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reported in this article are the complete dataset available. This prevents internal consistency testing, cross-tabulation of ratings by professional role and any paired comparison across phases, all of which would have strengthened the evaluation. The evaluation instrument also used the term RFID rather than the broader IoT vocabulary, so the responses describe perceptions of Auto-ID technology specifically. The Stage 2 items also asked about the phases in BIM-enabled projects generally, so the mapping of the phases onto the disaster management cycle is the authors' synthesis and was not rated by respondents. Future work should collect and retain respondent-level data under a data management plan, use a scale with a neutral midpoint, and pair the perception survey with observation of an actual deployment.

6. CONCLUSIONS

This study set out to address the absence of construction-oriented guidance for adopting Auto-ID devices within BIM-enabled projects, with post-disaster reconstruction as the setting. Developing a complete standard lies beyond a single study, so the work established a baseline instead. Adopting a DSR paradigm, it developed a five-phase technical guideline, evaluated it through a perception survey of 113 AEC professionals, and synthesised it with the disaster management cycle.

Three outcomes follow. The first is the framework itself, specified in operational terms and mapped onto the disaster management cycle, which respondents assessed as relevant with stakeholder alignment rated highest and interoperability lowest. That ordering is itself a result, and it suggests the organisational conditions for adoption weigh more heavily on practitioners than the technical ones. The second is the Data-to-Design Handover, specified here as a mechanism carrying component data from temporary housing into permanent reconstruction. It remains a proposition and has not been tested. The third is a reading of the adoption problem in which practitioners report willingness to engage where referenceable guidance exists, with 68.1% stating their likelihood would increase.

The contribution is therefore an early-stage baseline rather than a validated solution. Its claims rest on professional perception in one national market, and the mechanisms it proposes await implementation. The clearest next step is a field test on a live post-disaster or offsite manufacturing project, running the five phases as specified in Table 8 and recording whether the handover in Table 12 can be executed under real custody and procurement conditions. That work would establish whether the framework performs as designed, which this study does not claim to have shown.

ACKNOWLEDGEMENTS

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ETHICS STATEMENT

The study was conducted in accordance with the Declaration of Helsinki and approved by the Faculty of Technology Ethics Committee of the University of Portsmouth (reference TECH2023-M.Y.T-01). The approval covered both the Stage 1 requirement-analysis survey of registered architects and the Stage 2 evaluation survey of AEC professionals. Informed consent was obtained from all participants involved in the study. Each participant received a participant information sheet and provided consent before completing the online questionnaire. Participation was voluntary, and participants were free to withdraw at any point before submission.

DATA AVAILABILITY STATEMENT

All aggregate data supporting this study are reported in full within the article. The complete response distributions for every item are given in Tables 6, 10 and 11 and in Figures 2 to 5. Respondent-level records for both stages are no longer held by the research team, so no further data can be provided.

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APPENDIX A: STAGE 2 SURVEY ITEMS

The items below (Table A1) are reported as recorded in the analysis outputs retained with the study. The original survey instrument is no longer held by the research team, so item wording and response options are given as recorded in those outputs rather than verbatim from the questionnaire. Items 1 and 2 were rated on a four-point scale, items 3 and 4 permitted multiple selections, item 5 used a five-point importance scale and item 6 a three-point scale.

Table A1: Stage 2 survey items as recorded in the analysis outputs.

Item	Wording as recorded	Response options
1	Familiarity with established built environment standards and guidelines, including National Building Regulations, ISO standards and the RIBA Plan of Work.	Not applicable to them; mostly non-beneficial; somewhat beneficial; very beneficial
2	Disposition towards those standards and guidelines.	Not applicable to them; mostly non-beneficial; somewhat beneficial; very beneficial
3	Current areas of BIM use.	BIM 3D documentation project management; BIM 4D project management; BIM 5D project cost management; BIM 6D sustainability aspects; BIM 7D facilities management; building lifecycle management; building supply chain management; site management, construction process; site management, equipment; site management, staff
4	Areas in which RFID integration was expected to deliver benefit.	As item 3
5	Importance of each framework phase, asked as five separate items: Q1 Phase 1, initial engagement in RFID solutions in BIM; Q2 Phase 2, applications of RFID solutions in BIM; Q3 Phase 3, fragmentation in RFID solutions in BIM; Q4 Phase 4, stakeholder buy-in and alignment in RFID solutions in BIM; Q5 Phase 5, security vulnerabilities of RFID solutions in BIM.	Unimportant; less important; important; very important; critically important
6	Likelihood of engaging with RFID solutions in BIM projects if suitable application and process guidelines were available.	No, likelihood unchanged; uncertain, likelihood may increase; yes, likelihood increased
7	Role in AEC projects, multiple selections permitted.	Materials or specialist suppliers; real estate consultants; specialist consultants; site team; client team; BIM consultants; design consultants

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