

Article

Toward Frequent Robotic Digitalization of Construction Sites: A Field-Grounded Roadmap

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Abstract

Construction sites remain a sparse source of digital information, even though up-to-date knowledge of site conditions underpin planning, progress control, and safety. This paper contributes a field-grounded roadmap toward frequent robotic digitalization of construction sites. It shifts attention from robotic capture capability to the capture-to-consumption chain required for operational use and treats organizational consumption as the primary driver of digitalization frequency. The roadmap is presented as a hypothesis rather than a validated finding and is grounded in a longitudinal embedded single-case study of a large, multi-year renovation project in Sweden. The study included weekly inspections during periods over two years using a quadruped uncrewed ground vehicle (UGV), comparison sprints with helmet-mounted capture, and a test of BIM-anchored digital site utilization plan (SUP) revision. No operational frequency target was aimed for or achieved. Instead, the study aimed to identify capabilities and constraints that must be addressed and tested to enable such operation. In particular, the paper proposes the SUP as a bidirectional interface that both receives robot-derived revisions and provides machine-readable routes, constraints, and reporting requirements for robotic operation.

Keywords: construction robotics; site utilization plan; uncrewed ground vehicle; building information model; progress monitoring; inspection; roadmap; maturity framework; automation; construction management

1. Introduction

A construction site manager juggles numerous tasks to keep daily operations running smoothly. Managing deviations and ensuring that progress aligns with the plan imposes a significant cognitive load on site personnel, while the information required to support these decisions is often collected manually and inconsistently across projects. Methodologies and technologies capable of transforming construction sites from limited sources of digital information into rich digital information environments are emerging, including uncrewed ground vehicles (UGVs), 360-degree cameras, and laser scanning technologies [1–3]. However, a gap remains between demonstrating that robots can capture data on construction sites and establishing robotic digitalization as a routine operational capability that continuously supports site management.

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A natural anchor for such output is the Site Utilization Plan (SUP), also referred to as the jobsite layout plan. The SUP is a mandatory representation of the construction site encompassing the physical layout, material storage, transportation routes, and safety measures, and it governs the work environment on site [4,5]. Unlike manufacturing facilities with fixed layouts, construction projects require dynamic site layouts. However, SUPs typically exist as static documents that are disconnected from the Building Information Model (BIM), are revised manually, and may become outdated or overlooked [5,6]. An up-to-date SUP is therefore a prerequisite for effective project planning, construction management, and safety control. Accordingly, a dynamic, BIM-integrated SUP that adapts to data collected on site has been proposed as a desirable future state [5,7].

Prior work has demonstrated individual links in this chain, including UGV-based reality capture aligned with BIM [6], 360-degree imagery for stakeholder engagement and project monitoring [8], computer vision-based progress monitoring [9,10], and BIM-based site layout planning [7]. What remains missing is a synthesis of the technical, informational, and organizational requirements needed for the entire chain to operate frequently enough to support management decisions. For example, enabling a morning coordination meeting to rely on the previous evening's site state. In this roadmap, frequent robotic digitalization refers to completing the entire capture-to-consumption cycle within both the timescale of relevant site changes and the management decision interval.

This paper presents a roadmap for the robotic digitalization of construction sites. The roadmap is derived from experience gained during a multi-year longitudinal field programme conducted at a large renovation project in Lund, Sweden. During the programme, a Boston Dynamics Spot quadruped UGV performed weekly inspection rounds during selected periods over two years. Helmet-mounted capture was used in comparative field tests, captured data were linked to a BIM-anchored digital SUP within a commercial construction management platform, and a purpose-built data refinement pipeline was developed to align repeated inspections and establish an evidence layer supporting digital twin revision. In addition, mission flexibility was investigated by combining inspection and surveillance tasks using thermal imaging, AI-based anomaly detection, and behaviour tree-controlled route deviation. The guiding research question is:

What is needed to enable frequent robotic digitalization of construction sites across data acquisition, data refinement and analysis, information integration, and site and organizational readiness?

Methodologically, the study is a longitudinal embedded single-case field study whose observations are synthesized into a staged framework (Section 3.1). As such, it is closer to maturity framework development [11] than to controlled experimentation. The field programme motivates the following testable hypothesis: once repeatable data capture has been established, further increases in operational frequency depend increasingly on a persistent evidence layer, machine-readable site information, revision interfaces, planned machine routes, and organizational routines that actively consume robotic output.

The paper makes three contributions. First, it presents a roadmap structured around six capability levels and four enabler tracks, extending the staged deployment model introduced in our earlier field study on automated SUP revision. The lower capability levels (L1–L3) are grounded in routine or repeated field operation, whereas the upper levels (L4–L5) are informed by feasibility demonstrations and identified constraints. Second, empirical evidence from the longitudinal field programme is mapped to the roadmap on a cell-by-cell basis using an explicit evidence-status classification (field

demonstrated, feasibility demonstrated, or proposed), thereby making the strength of each claim transparent. Third, the paper identifies the constraints that affect digitalization frequency and discusses their implications for tool vendors, BIM standardization, and construction management practice.

The remainder of the paper is organized as follows. Section 2 reviews related work on SUPs, site data collection, BIM, and robotic inspection platforms, and delineates the scope of the proposed roadmap in relation to related concepts. Section 3 describes the research methodology, the longitudinal field programme, and the associated subsystems. Section 4 presents the roadmap, while Section 5 maps the field evidence onto it. Section 6 discusses the key constraints, implications, and limitations of the proposed roadmap, and Section 7 concludes the paper.

2. Background

2.1. Site Utilization Plans and the Temporal Dimension

SUPs regulate the arrangement of construction sites in much the same way that layouts govern permanent factories or warehouses. They encompass temporary facilities and site elements such as work sheds, cranes, material storage areas, transport routes, assembly areas, defibrillators, and fire extinguishers [4,12]. SUPs are unique to each project and therefore require careful tailoring [13], yet they are often prepared under significant time pressure [14].

Conventional SUPs typically consist of static two-dimensional representations, including CAD drawings, PDF documents, and hand-drawn sketches [12]. As a result, they fail to capture the dynamic nature of construction sites, and objects defined at the outset of a project may remain unchanged throughout its duration [7]. Dynamic SUPs retain the same object types but incorporate a temporal dimension, enabling more flexible use of construction space by allowing different objects to occupy the same location at different times [7,15]. Creating dynamic SUPs requires the identification of relevant objects and areas, the definition of their spatial dimensions, and the allocation of time intervals. The associated information management effort is labour-intensive, and automated or standardized data collection has therefore been proposed as a means of achieving scalability [7]. This positions the SUP not only as a natural consumer of frequent robotic digitalization outputs but also as a carrier of machine-readable information required for robotic operation.

2.2. Data Collection and Progress Monitoring on Site

Project control depends on systematic data collection to enable comparisons between planned models and actual site conditions [3,16]. Technology-supported data acquisition is therefore essential, with data reliability representing a critical concern [3]. Effective data management and analysis are prerequisites for transforming collected data into actionable information and decision support [17].

Image-based monitoring has gained considerable prominence [9,16, 18], including approaches based on time-lapse photography overlaid on 4D models [9], 360-degree cameras mounted on quadruped UGVs and integrated with BIM [6], and 360-degree panoramas converted into navigable information layers for project stakeholders [8]. However, lighting conditions, dynamic site environments, and physical obstructions can degrade image quality and disrupt data acquisition [17]. Manual inspection remains both time-consuming and prone to human error [19–21]. This has motivated the development of robotic alternatives [6], although path planning in dynamic environments remains an active area of research [22].

A parallel research stream focuses on structuring as-built data for comparison with planned models rather than allowing newly acquired data to overwrite existing information. For example, BIM-based point cloud processing can detect deviations by matching scanned or photogrammetric geometry to model elements [23], while more recent approaches integrate point clouds, BIM semantics, and computer vision to refine and contextualize the observed site state [24]. Nevertheless, converting recurring observations into revisions of planning information remains a significant challenge [9], and the accumulated as-built record itself must be systematically structured and managed as inspections are repeated [23, 24].

2.3. BIM as the Information Backbone

BIM serves as both a process and a software-supported approach for improving decision-making throughout the project life cycle [25, 26]. It integrates project information into a shared digital model that is accessible to multiple stakeholders and supports applications such as schedule simulation, quantity take-off, and project coordination. BIM also underpins frameworks that combine image processing, machine learning, and virtual reality to support automated construction monitoring [10].

For SUP applications, parametric objects are particularly important because they facilitate efficient and economically viable planning [12]. From a robotics perspective, however, current BIM practice remains primarily human oriented. Existing classifications and information structures generally lack machine-readable taxonomies and interfaces that support mission generation, execution, and reporting.

Beyond serving as a repository of project information, BIM has the potential to provide machine-readable information that directly supports autonomous robotic operations. For example, Karimi et al. translate IFC/BIM models into topological and metric maps, exposing semantic site information that enables robots to optimize navigation according to construction-relevant criteria rather than distance alone [27].

2.4. Robotic Platforms for Site Data Collection

UGVs have been deployed in applications such as asbestos rehabilitation [28]. They are also regarded as a promising class of platforms for material transport and waste handling [29] and have been used for BIM-enabled reality capture in construction [6]. Surveys of inspection robotics for civil infrastructure indicate that the field is developing rapidly, and many of the resulting findings are expected to be transferable to building construction environments [30].

The quadruped platform used in this study should therefore be regarded as a representative example of a broader class of mobile robotic systems rather than as a unique technological solution. Design studies of mobile construction robots emphasize the challenges posed by dynamic construction environments [31], while technology implementation research highlights the importance of staged testing and gradual adoption before organization-wide transformation can be achieved [32]. Similarly, emerging staged frameworks for the digitalization of construction-site operations describe capability development as a coordinated and assessable progression. One example is the digital maturity assessment framework developed within the Swedish Smart Built Environment programme [11]. Whereas that framework assesses the maturity of digital construction-site operations, the roadmap proposed in this paper focuses specifically on the capabilities required to establish frequent robotic capture-to-consumption workflows.

2.5. Scope: Digitalization, Progress Monitoring, SUP Revision, and Digital Twins

Four related but distinct concepts recur in the literature and should be distinguished:

- Construction-site digitalization is the overarching process of converting the evolving physical state of a construction site into digital information.
- Progress monitoring is one analytical application of this information, involving the comparison of the observed site state with the planned state to assess construction progress [9,10,19].
- SUP revision is a specific information-consumption pathway in which observations are used to update the site utilization plan and associated safety information [5,7].
- Digital twin maintenance has a broader scope, aiming to keep a comprehensive and semantically rich virtual representation synchronized with its physical counterpart, potentially extending beyond the construction phase. The need to maintain and manage accumulated site data has also been recognized by Sacks et al. [33] and is discussed further in Section 6.3.

The roadmap proposed in this paper focuses on the digitalization process that precedes these downstream applications, while explicitly introducing an intermediate evidence layer that decouples data acquisition from progress monitoring, SUP revision, and digital twin maintenance.

3. Materials and Methods

3.1. Research Design and Roadmap Synthesis Method

The study was designed as a longitudinal embedded single-case field study. Within a single host project, three embedded units of analysis were investigated, each generating artifacts and documented field experience:

1. Field test of SUP revision comparing helmet-mounted and UGV-borne 360-degree video capture linked to a digital SUP.
2. Development and evaluation of a data pipeline for repeated robotic inspections, intended to serve as a historical evidence layer supporting regulatory claims and operational needs.
3. Mission-flexibility experiments that extended inspection rounds with surveillance capabilities.

Following a gradual-introduction approach [32], autonomous equipment was incrementally integrated into the workflow of an ongoing construction project and used in weekly operations during selected periods over two years. An interdisciplinary research team with expertise in robotics and construction-management examined both the digitalization process itself and the practical use of its outputs. The roadmap synthesis focuses on construction-site digitalization, specifically the robotic capture-to-consumption chain on active construction sites. It encompasses data acquisition, data preparation and analysis, and the subsequent revision of planning information. Progress monitoring and surveillance constitute the two principal consumption pathways examined in the field tests, with SUP/BIM suggested as the primary information interface. SUP is selected because it is mandatory planning artifact, governs site operations, and as discussed in Section 3.3, provides a carrier for machine-readable information required for robotic operation.

The roadmap connects these concepts through a proposed intermediate step: frequent robotic observations should not directly overwrite either the digital twin or the SUP. Instead, they should first accumulate in a persistent production-phase evidence layer. This layer comprises inspection data that have undergone limited preprocessing, including alignment, subdivision, cataloguing, and coarse referencing to BIM elements and SUP objects. Progress assessment, safety review, SUP revision, and digital twin

updating are then treated as downstream applications of this evidence layer, rather than as direct outputs of data capture.

3.1.1. Data Sources and Documentation

The collected material comprises operational records from approximately 40 UGV inspection rounds conducted over a two-year period, including per-round data folders containing point clouds and video, as well as documented incidents such as stops, falls, localization losses, and route conflicts. Additional sources include SUP field tests comprising 15 helmet-mounted inspection rounds and two route-matched UGV inspection rounds conducted using an SUP model, with revisions performed manually in the Dalux release 2023.1 application; two student thesis projects [34,35]; and formal work-package reports submitted to the funding bodies and reviewed by the project partners, including the host contractor. Table 1 links each source of evidence to the documentation it produced and to the corresponding roadmap elements it informs.

Table 1. Traceability of empirical evidence sources to roadmap elements.

Evidence Source	Scope	Documentation	Roadmap Elements Supported
Longitudinal UGV operations	Approximately 40 inspection rounds conducted over a two-year period across multiple construction phases	Per-round data folders (point clouds and video); incident logs (stops, falls, localization losses, and route conflicts); partner-reviewed project reports	L2 cells across all tracks; risk catalogue and route- and marker-maintenance constraints; observations on inspection frequency versus rate of change
SUP revision field test	15 helmet-mounted inspection rounds and 2 route-matched UGV inspection rounds conducted over a two-week sprint on two floors of one building	Dalux project containing the SUP model and per-round revision filters; published field-test report; route and timing logs	L1 cells across all tracks; latency constraint (T4); basis for the staged level structure (deployment table)
Data refinement pipeline	Pipeline development and testing using inspection rounds from the host site	Source code repository; processed datasets and visualizations; work-package report; MSc thesis [35]	L3 cells (T1–T3); L4/T2 metric and change-detection feasibility; lessons learned for sensing
Mission flexibility experiments	Deviation-route method and thermal detection evaluated on campus and at the host site	Behaviour-tree mission descriptions; thermal dataset and trained YOLOv8 model; MSc thesis [34]; work-package report	L5 cells (T1–T3); economic potential of multipurpose missions; open research questions on BIM-based route generation

3.1.2. Analysis Procedure

The roadmap was developed through a four-step process. First, recurring constraints and enabling conditions were identified from the documented records of all three embedded units and grouped into thematic categories, resulting in the four enabler tracks (T1–T4). Second, capability levels were organized according to the primary constraint addressed, beginning with the staged deployment model developed during the SUP field test and subsequently refined against the track structure. A new level boundary was introduced wherever the field records indicated a qualitative shift in the factor constraining operational frequency. Third, each level-by-track cell was populated with the corresponding requirement, whether directly observed or logically inferred, and assigned an evidence status traceable to the empirical evidence presented in Section 5: **field demonstrated** (supported by routine or repeated field operations), **feasibility**

demonstrated (constraints remain), or **proposed** (requirement identified but not yet attempted). Fourth, the resulting level structure was cross-checked against published staged frameworks, particularly digital maturity assessment approaches for construction-site operations [11] and technology implementation perspectives [32], to ensure that the proposed levels remained aligned with established conceptual frameworks while retaining a clear grounding in field evidence.

3.1.3. Positioning

This procedure constitutes a traceable synthesis: each roadmap cell can be traced to its corresponding evidence source through Table 1. However, no independent coding or external validation panel was employed. Accordingly, the roadmap should be interpreted as a structured set of testable claims, with its scope, underlying assumptions, and remaining sources of bias discussed in Section 6.4.

3.2. Field Site

The host project is a five-year renovation program of a public high school complex comprising several older buildings in Lund, Sweden. The project is managed by one of Sweden's major construction companies. The longitudinal on-site presence provided an opportunity to develop an in-depth understanding of site dynamics, work processes, and stakeholder roles across multiple construction phases. Three buildings were studied during the renovation program. The SUP field test was conducted on two floors of one building during a construction phase involving painting and the completion of installations above suspended ceilings.

3.3. Capture Equipment and Information Chain

The UGV is a Spot Explorer (Boston Dynamics, Inc., Waltham, Ma, USA) quadruped capable of carrying payloads of up to 14 kg and operating for 60–90 min on a single battery charge. The high payload capacity provides an ergonomic advantage over wearable sensing equipment. A Ricoh Theta X 360-degree camera (Ricoh Company, Ltd., city is not publicly disclosed by the manufacturer, Japan) was used for both helmet-mounted and UGV-mounted data capture. Using the same camera in both configurations ensured that the two acquisition modes remained directly comparable and produced data compatible with the same downstream processing tools.

Figure 1 illustrates the iterative information chain for the SUP workflow. A manually created SUP model is imported into Dalux, where 360-degree inspection data are compared with the model. The resulting observations are then used to manually update the SUP in Revit before the next inspection cycle.

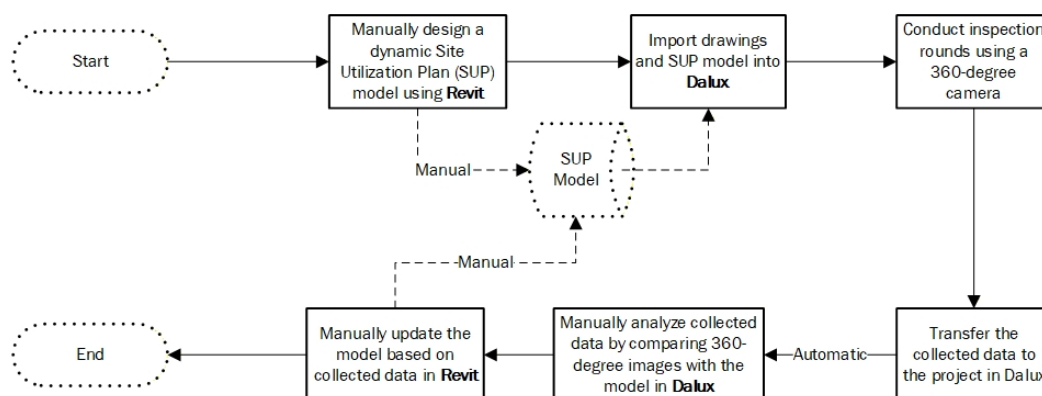


Figure 1. Information chain for the SUP field test. Inspection data are compared with the BIM-anchored SUP, and identified changes are manually incorporated into the model.

Captured video is uploaded to Dalux, a commercial construction management platform used on the project. The Dalux SiteWalk functionality positions inspection videos relative to the BIM, enabling side-by-side virtual inspection. Spot additionally records point clouds from its navigation LiDAR together with pose data, which are also stored for downstream processing.

Autonomous inspection rounds follow pre-programmed routes anchored to fiducial markers (AprilTags) placed on site surfaces. Operator-guided rounds are used during construction phases in which surface conditions and site layouts change too rapidly to maintain the marker infrastructure. For autonomous operation in the vicinity of workers, the platform is classified as an industrial machine and therefore requires a protective safety zone. Consequently, autonomous inspection rounds are recommended outside working hours, which also simplifies compliance with the General Data Protection Regulation (GDPR). This operational approach may have implications for projects involving nighttime construction activities. However, nighttime construction is uncommon in Sweden and was therefore not represented in the present field study.

A geometric three-dimensional SUP was developed in Revit and exported as an IFC model to complement the building IFC model already available in the platform. Four SUP object classes were modelled: material storage areas, waste sorting areas, tool and charging stations, and escape routes. In addition, generic cube-shaped objects were introduced to represent non-modelled items, such as material pallets. Objects remain permanently in the model to simplify revisions, while their visibility is toggled to represent the current site state.

Because the Dalux platform does not provide functionality for converting captured video into model objects, a manual revision workflow was developed (See Figure 2). Inspection videos and the SUP model are viewed side by side, after which objects are repositioned, and their visibility toggled to match observed site conditions. The resulting model state is saved as a named filter for each inspection round.

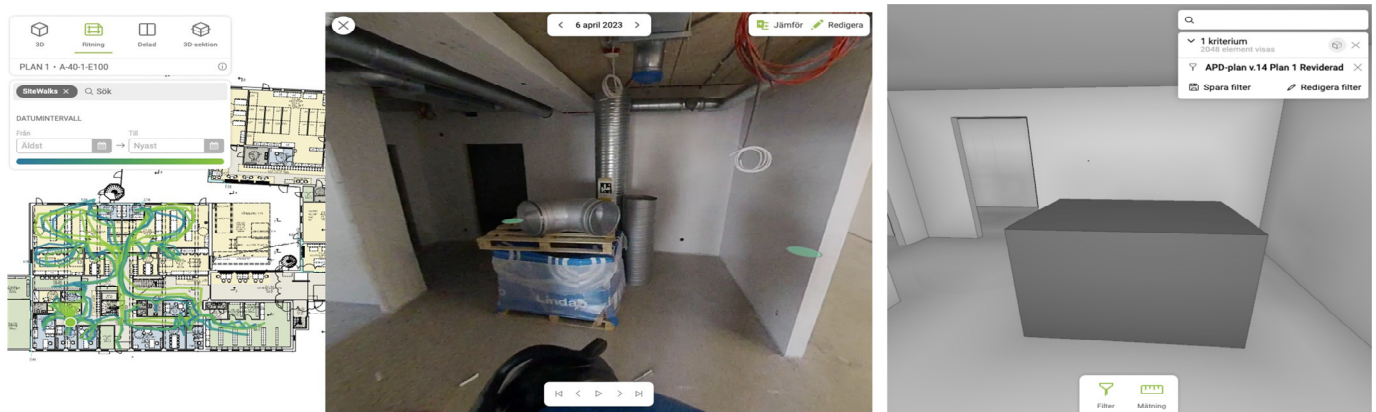


Figure 2. Virtual inspection using a BIM-anchored SUP: floor plan showing the capture position (left), a 360-degree image from an inspection round (centre), and the corresponding SUP/BIM view (right). The grey cube-shaped object is a placeholder that is repositioned and toggled visible or hidden to represent the observed site state.

Compliance with GDPR requires project-specific procedures for informing personnel, limiting access to recorded data, and managing storage and retention, but a detailed treatment of these procedures is beyond the scope of the present study.

3.4. Evidence Layer

Frequent data collection makes selective retention as important as data capture itself. The proposed approach establishes a coarse but persistent spatial reference structure

through which observations remain addressable across multiple inspection rounds while linking regulatory, contractual, and governance requirements to the data that serve as supporting evidence. This enables the retained as-built dataset to be shaped by evidentiary value: observations associated with verification activities or anticipated future needs can be preserved, whereas data with no identified continuing role can be progressively reduced or removed.

The partitioning also provides a common basis for downstream applications. Its spatial resolution can be selected so that multiple partitions jointly describe the progress or condition of a building element, enabling observations to be aggregated for progress tracking, change detection, safety review, and comparison with BIM elements or SUP-defined areas. Persistent partition histories can further identify locations with missing, outdated, conflicting, or rapidly changing observations, thereby directing new inspections, computational resources, and human review to where they provide the best value.

A data-partitioning pipeline establishes the underlying spatial and temporal structure required for these functions. Figure 3 illustrates the proposed evidence layer using a sample room partitioned into cubes with a side length of 0.5 m. The aligned point cloud is divided into these cubes (main panel), each containing the point-cloud excerpt within its volume, image crops extracted from 360-degree footage at the nearest sensor positions (right), and, where available, references to the corresponding BIM elements.

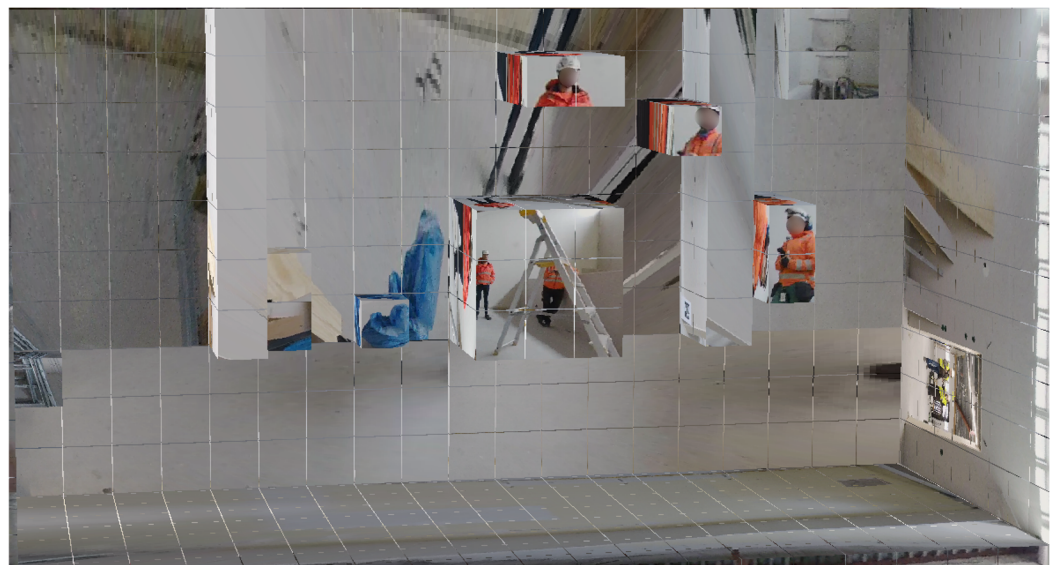


Figure 3. Sample data partitioning. Aligned point cloud and 360-degree image data are partitioned into 0.5 m cubes that form persistent evidence units for automated analysis.

Each cube thereby constitutes a persistent, addressable unit of evidence that can be catalogued, retrieved across repeated inspection rounds, and used as input for automated analysis. The selected resolution represents a pragmatic compromise between spatial localization, a manageable number of partitions, and the dimensions of common interior building elements; no sensitivity analysis of the partition size was performed. The chosen scale is also suitable for applications such as progress tracking.

The visualized cube data were derived from multiple 360-degree video frames captured during a robotic inspection round. For each cube, imagery was selected based on sensor distance to maximize spatial resolution, although variations in lighting reduced visual consistency. Durable data persistence, versioning, detailed provenance, evidence-based retention policies, automated prioritization, query capabilities, multi-scale

aggregation, and external data access remain future capabilities and are discussed in Section 6.4.

3.5. Mission Flexibility and Multi-Purpose Rounds

The third research strand investigates whether a single autonomous inspection round can support multiple purposes, including inspection and surveillance, and identifies the additional robot capabilities required to enable such functionality. Spot was equipped with a thermal camera, and an AI model was developed to detect people in thermal images. The experiments demonstrated the feasibility of combining routine inspection with automated anomaly detection, although detection performance remained sensitive to robot pose and environmental conditions.

The primary capability investigated was controlled deviation from a predefined route. When an anomaly is detected, the robot leaves its standard route, follows a predefined deviation path to inspect the relevant location, and then resumes its original mission. This approach was demonstrated both in a university building and at the construction site. Automatic generation of deviation routes and the extraction of routing constraints from BIM remain open research challenges. Controlled deviation is also relevant to routine inspections, for example when avoiding obstructions or inspecting blocked doors and escape routes.

4. Roadmap-Capability Levels and Enabler Tracks

Our roadmap organizes the transition from traditional manual practice to autonomous digitalization along two dimensions. The vertical dimension comprises six capability levels (L0–L5) that describe the digitalization process. The horizontal dimension comprises four enabler tracks, which may progress at different rates. The capability levels should be understood as reference configurations rather than strict stage gates. However, routine attainment of a given level requires that no critical constraint in any track prevents completion of the intended operational cycle:

- **T1 Data acquisition:** platforms, sensors, localization, and data capture procedures.
- **T2 Data refinement and analysis:** data structuring, metrics, and automated analysis of captured data.
- **T3 Information integration:** machine-readable site information (SUP/BIM), revision interfaces, and taxonomies that connect captured data to planning information.
- **T4 Site and organizational readiness:** physical site preparation, safety regimes, organizational roles, work processes, and the integration of robotic outputs into management routines.

Each roadmap cell is assigned an evidence status derived from the field data (Section 3.1): **field demonstrated** (supported by routine or repeated field operations), **feasibility demonstrated** (constraints remain) or **proposed** (an identified requirement that has not yet been attempted). Under this classification, Levels L1–L3 contain field demonstrated and feasibility demonstrated cells, whereas Levels L4–L5 are predominantly feasibility demonstrated or proposed.

The levels and enabler tracks represent the authors' synthesis of the longitudinal single-site study. Table 2 defines the capability requirements for each level and track, while Table 3 summarizes the corresponding evidence status. The capability levels are distinguished by the primary constraint they address.

L0 [*Traditional practice*] represents traditional practice, characterized by manual notetaking, manual on-site inspections, and a static SUP. L1 [*Digital capture-human*] introduces human-operated digital data capture (e.g., helmet-mounted 360-degree cameras) combined with virtual inspection. L2 [*Routine robotic capture*] introduces robotic

data capture along pre-programmed routes, enabling off-hours operation and the use of multi-sensor payloads. L3 [*Persistent evidence layer*] establishes a persistent evidence layer in which observations from repeated inspection rounds are subdivided, catalogued, and, where applicable, referenced to BIM elements and SUP objects, thereby providing a structured basis for subsequent analysis. L4 [*Automated interpretation & revision proposals*] automates analysis of this evidence layer by generating progress metrics, detecting changes, and producing revision proposals, while retaining human approval of revisions.

Table 2. Roadmap for frequent robotic digitalization of construction sites, showing capability levels (L0–L5) across four enabler tracks.

Level	T1 Data Acquisition	T2 Data Refinement & Analysis	T3 Information Integration	T4 Site & Organizational Readiness
L0	Site conditions are observed and recorded manually.	Site conditions are assessed manually through physical inspection.	A static 2D SUP is maintained separately from the BIM and recorded observations.	Inspections require site access during working hours; methods are project specific.
L1	Human-carried 360-degree capture provides repeatable, spatially referenced data and can be performed by non-specialists.	Spatially referenced media support virtual inspection and manual comparison with the model.	An object-based 3D SUP complements BIM; changes are revised manually.	Capture, privacy, access, and review procedures are defined, and outputs are available within the planned review cycle.
L2	A UGV repeatedly completes pre-programmed routes with the required sensors, achieving target coverage and mission success, typically outside working hours.	Robot data enters the same review workflow as in L1; raw sensor data, timestamps, and poses are retained for subsequent processing.	Routes and reporting targets are maintained as explicit artefacts but are not yet generated from SUP/BIM information.	A safety regime, route and marker maintenance, recovery procedures, and clearly assigned technical coordination support routine operation.
L3	Robot routes are planned for construction activities and sensor coverage; sensor pose data are recorded.	Repeated inspections are aligned, partitioned into persistent spatial units, and stored with timestamps and provenance.	Evidence units maintain stable, machine-readable links to BIM elements and SUP areas.	Data is available within the decision cycle, with defined quality control and limited manual correction.
L4	Reliable inspections achieve the frequency, coverage, and mission success required by site changes and management needs.	Automated per-element progress or condition metrics, change detection, and targeted AI analysis generate traceable findings from the evidence layer.	A machine-readable interface expresses findings as proposed SUP/BIM revisions; human operators review and approve changes before they are written back.	Findings are routinely incorporated into management processes using agreed metrics, assigned responsibilities, and escalation procedures.
L5	Mission execution adapts safely to obstructions and anomalies, including targeted close-up inspection and, where useful, the combination of compatible objectives within a single mission.	Continuous evidence history supports automated prioritization, anomaly interpretation, and selection of the most valuable subsequent observations.	The SUP/BIM provides machine-readable routes, constraints, inspection targets, and reporting taxonomies; approved revisions automatically update planning information.	Robot routes, access requirements, markers, and resources are integrated into site planning, and robotic systems are managed as standard production resources.

Table 3. Field evidence mapped to the roadmap capability levels and enabler tracks. D = field demonstrated; F = feasibility demonstrated; P = Proposed.

Level	T1 Data Acquisition	T2 Data Refinement & Analysis	T3 Information Integration	T4 Site & Organizational Readiness
L1	D—Repeatable human-carried 360-degree data capture was performed by non-specialist personnel.	D—Spatially referenced media supported virtual inspection and manual comparison with the model.	D—An object-based 3D SUP was used alongside the BIM and revised manually.	F—Capture and review procedures were implemented, but timely data availability remained constrained.
L2	D—Pre-programmed UGV inspection rounds were repeated over an extended period, although not during off-hours operation.	D—Robot-acquired data entered the same review workflow as in L1, while raw sensor data were retained.	F—Routes and reporting targets were maintained manually rather than generated from SUP/BIM information.	F—Routine operation was supported, but route and marker maintenance remained labor-intensive.
L3	F—Robot routes were coordinated with construction activities.	F—Inspection rounds were aligned, partitioned, and linked to BIM; versioning and provenance remain incomplete.	F—Evidence units were linked to BIM elements and SUP objects, but persistent machine-readable integration remains incomplete.	F—Automated processing proved feasible, but manual correction prevented routine delivery within the decision cycle.
L4	P—Routine operation at the required inspection frequency was not evaluated.	F—Geometric metrics and change detection were demonstrated; AI-assisted review was not evaluated.	P—No machine-readable interface for revision proposals or write-back was implemented.	P—Robotic findings were not evaluated as routine inputs to management processes.
L5	F—Adaptive route deviation and anomaly triggered inspection were demonstrated with predefined routes.	F—Anomaly detection demonstrated; automated observation prioritization not implemented.	P—SUP/BIM-derived mission generation, reporting, and planning updates were not implemented.	P—Robot routes and resources were not integrated into routine site planning.

L5 [Autonomous capture-to-planning] introduces autonomous capture-to-planning workflows in which routes are generated from the SUP/BIM, missions adapt during execution, multiple purposes are combined within a single inspection round, and approved revisions are automatically fed back into the planning information.

Levels L4 and L5 extend the L3 evidence layer with automated interpretation and decision-support capabilities. Table 2 presents the resulting roadmap matrix, in which each cell specifies the capabilities required on a given track to enable routine operation.

5. Field Evidence Mapped onto the Roadmap

This section maps the empirical field evidence onto the proposed roadmap. Table 3 summarizes the evidence status for each capability level across the four enabler tracks, indicating whether capabilities have been field demonstrated through routine or repeated field operations, feasibility demonstrated, or remain proposed.

Figure 4 illustrates one of the L5 capabilities investigated in this work: controlled route deviation for adaptive robotic inspection.

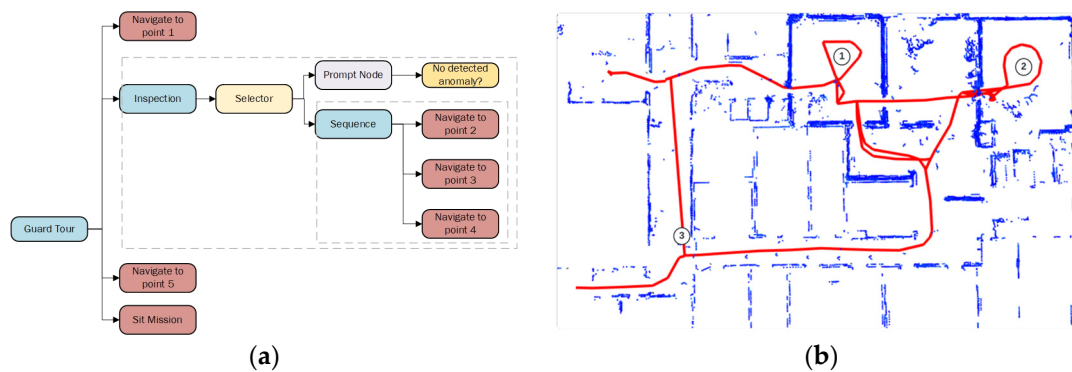


Figure 4. Controlled route deviation for adaptive data capture. (a) A behaviour tree diverts the robot from its standard route to a predefined inspection sequence when an anomaly is detected. (b) A recorded construction-site route (red line) with decision points, corresponding to the numbered nodes in the behavior tree, that enable predefined route deviations.

Overall, the field programme demonstrates that the lower capability levels (L1–L3) are supported by repeated field demonstrations, whereas the higher levels (L4–L5) remain only feasibility demonstrated or conceptual. The strongest evidence concerns repeatable data acquisition, SUP revision, and the establishment of a persistent evidence layer, while autonomous interpretation and planning require further development

6. Discussion

Tables 2 and 3 are consistent with the central hypothesis advanced in this paper: frequent robotic digitalization depends on a coordinated capture-to-planning chain rather than on data capture alone. The field evidence supports this hypothesis at the lower capability levels but does not establish it conclusively, because the higher-frequency operating regimes in which data acquisition might again become the dominant constraint (L4–L5) were not reached. Both human-operated and robotic data capture were shown to be feasible, whereas the principal unresolved capabilities relate to evidence management, information integration, and organizational adoption. Although the four enabler tracks may progress at different rates, routine attainment of any capability level requires that no critical constraint in any track prevents completion of the intended operational cycle.

6.1. What Currently Limits Frequency

Within T1, repeated human-operated and robotic data capture was field demonstrated. However, routine operation continues to depend on maintained routes, robust localization, integrated sensor pose estimation, and measurable levels of coverage and mission success. These requirements define the transition from routine robotic data capture at L2 to reliable and scalable data acquisition at L3–L4.

T2 currently represents the principal constraint in the capture-to-planning chain. Repeated observations must be aligned, spatially indexed, versioned, and made available within the relevant management decision cycle. The field-developed data refinement pipeline established key elements of this structure; however, manual position correction and incomplete support for persistence and provenance management continue to constrain routine operation. Automated metrics and change detection appear promising, whereas targeted AI-assisted review and continuous prioritization remain only feasibility demonstrated or proposed.

T3 and T4 determine whether observed findings are translated into planning and management actions. Machine-readable links between the evidence layer and the SUP/BIM were only feasibility demonstrated, while revision proposals, automated write-back mechanisms, BIM-derived mission generation, and reporting taxonomies remain

proposed capabilities. Similarly, management routines, agreed performance metrics, assigned responsibilities, and site-planning procedures for robotic operations were not evaluated as part of routine practice.

Overall, the dominant constraint shifts from latency and route maintenance at L1–L2, through integrated sensor pose estimation and data alignment at L3, to trusted interpretation, planning interfaces, and organizational adoption at L4–L5.

6.2. Implications

For tool vendors, a priority is to support the L3 evidence layer as a first-class capability. Repeated observations should be spatially indexed, versioned, traceable, and accessible to multiple downstream applications. In addition, open interfaces are needed to support automated data ingestion, revision proposals, approval workflows, and write-back mechanisms, with processing performance sufficient to meet the requirements of the intended management decision cycle.

For BIM and information standards, the principal requirement is bidirectional machine readability. SUP/BIM environments should provide machine-readable routes, operational constraints, inspection targets, and reporting taxonomies to robotic systems while also receiving traceable findings and approved revisions in return. This extends the role of BIM and SUP beyond human interpretation and coordination towards direct support for robotic mission execution, reporting, and planning.

For construction management practice, the required frequency of robotic digitalization should be defined relative to the site's rate of change and the requirements of management decision-making. Target levels for coverage, mission success, capture-to-availability latency, and acceptable manual effort should be specified explicitly. Robotic findings should be integrated into established review, coordination, and escalation processes. Similarly, robot access requirements, inspection routes, site markings, and supporting resources should be incorporated into site planning and operational management.

For robotics research, the roadmap highlights several priorities, including robust localization, integrated sensor poses estimation, coverage-aware sensing, adaptive data capture, and reliable recovery. However, further advances in robotic platform capabilities are unlikely to translate into operational value unless the evidence management, information integration, and organizational readiness tracks are sufficiently mature to convert captured data into actionable planning information.

The proposed roadmap has implications for different stakeholder groups. Small and medium-sized contractors may benefit from focusing initially on lower capability levels based on standardized digital capture and commercially available services. Large contractors are better positioned to invest in integrated BIM–robot workflows and organizational processes supporting higher capability levels. Equipment and software vendors play a key role in enabling higher levels of automation through standardized interfaces, machine-readable information structures, and interoperable data exchange mechanisms.

6.3. Relation to Prior Work

Prior research has demonstrated many individual components of the capture-to-planning chain, including robotic reality capture [6], BIM-based progress monitoring and scan-to-BIM comparison [9,23], multi-source assessment of as-built conditions [24], digital twin information systems [33], and BIM-derived robot navigation [27]. The roadmap proposed in this paper connects these capabilities through four enabler tracks and explicitly identifies the level of evidence supporting each capability level.

A key distinction of the proposed roadmap is the introduction of a persistent evidence layer positioned between repeated observation and selective interpretation. This layer enables the same traceable evidence to support progress assessment, safety review, SUP revision, and digital twin updating without requiring each application to reconstruct, duplicate, or overwrite the underlying observations. The concept is closely related to the integrated project information stores proposed by Sacks et al. for closed-loop digital twin development, in which automatically acquired data are incorporated into a shared project information environment [33]. Whether evidence retention governed by evidentiary value constitutes a distinct conceptual contribution or is more appropriately understood as a retention-and-access framework layered on top of an integrated information store remains an open question.

The roadmap further extends the role of the SUP by positioning it as a bidirectional interface that both receives approved revisions and provides machine-readable planning information for robotic operation. The staged, constraint-based structure of the roadmap complements existing frameworks for construction technology implementation and digital maturity assessment [11,32]. It also explains why deployments that combine L2 robotic data capture with L1 manual information consumption can succeed as technology demonstrations yet struggle to evolve into frequent, sustainable operational processes. In such cases, advances in data acquisition are not matched by corresponding progress in evidence management, information integration, and organizational readiness, resulting in constraints that limit overall system performance.

6.4. Limitations

The evidence base underpinning this study is limited to a single longitudinal renovation project, a single UGV quadrotor platform, and a single commercial construction management environment. Consequently, the findings may not transfer directly to greenfield construction projects, alternative robotic platforms, or different organizational contexts. In addition, the roadmap was synthesized by the authors and was not subjected to independent coding or external validation.

The evidence-status classification further constrains the claims that can be made. Levels L1–L2 are supported most strongly, although organizational readiness remained only feasibility demonstrated. L3 was field demonstrated primarily as a structural foundation; a durable, versioned, queryable evidence service with comprehensive provenance management and multi-user access was not developed. Levels L4–L5 remain largely feasibility demonstrated or proposed, as routine operation at management-driven inspection frequencies, validated AI-assisted review, automated revision write-back, organizational adoption, SUP/BIM-derived mission generation, and automated planning updates were not evaluated.

The roadmap should therefore be interpreted as a field-grounded set of testable claims rather than as a validated maturity model. Future research should evaluate the proposed capability levels and enabler tracks across multiple construction projects, organizational settings, and other robotic platforms such as wheeled UGVs and drones. In addition, quantitative thresholds should be established for key performance dimensions, including digitalization frequency, coverage, mission success, capture-to-availability latency, and manual effort. Ultimately, the value of frequent robotic digitalization should be assessed in terms of its ability to improve management decision-making and overall project performance.

7. Conclusions

This study proposes a six-level, four-track roadmap for frequent robotic digitalization of construction sites. The roadmap is based on the hypothesis that

achievable digitalization frequency depends on a coordinated capture-to-planning chain rather than on robotic data capture alone. The longitudinal field evidence is consistent with this hypothesis but does not establish it conclusively, as the upper capability levels (L4–L5) remain largely unevaluated. Accordingly, the roadmap should be interpreted as a field-grounded set of testable claims rather than as a validated maturity model.

- Human-operated and robotic data capture are feasible, but routine deployment remains constrained. Levels L1–L2 are supported most strongly with respect to data acquisition and review processes. However, processing latency, route and localization maintenance, and organizational readiness continue to limit routine operational use.
- The proposed persistent evidence layer provides a foundation for evidence-driven data management and retention. The field studies demonstrated capabilities for data alignment, spatial indexing, cataloguing, and BIM/SUP linking. However, capabilities such as durable versioning, provenance management, and delivery within the required management decision cycle remain incomplete.
- Automated interpretation and revision capabilities remain at the feasibility-demonstration stage. Geometric metrics and change detection were field demonstrated, whereas routine decision-driven data capture, targeted AI-assisted review, revision proposals, automated write-back, and organizational adoption remain at the feasibility-demonstration stage or are still proposed.
- Autonomous capture-to-planning requires bidirectional, machine-readable SUP/BIM information together with organizational and site readiness. Capabilities such as BIM-derived mission generation, reporting taxonomies, automated planning updates, and the routine integration of robotic access requirements and resources into site planning were not field demonstrated in the present study.
- The four enabler tracks may progress at different rates, but routine attainment of any capability level requires that no critical constraint in any track prevents completion of the intended operational cycle. Accordingly, performance expectations for digitalization frequency, coverage, mission success, capture-to-availability latency, and acceptable manual effort should be defined in relation to the site's rate of change and the requirements of management decision-making.

Future work should complete the development of persistent evidence management, validate automated review and revision interfaces, develop and evaluate bidirectional BIM–SUP robot interfaces, including lightweight data specifications and data exchange protocols, investigate SUP/BIM-derived dynamic route generation and closed-loop mission planning, evaluate organizational adoption, and further assess the roadmap across different construction sites and robotic platforms. Future research should also establish quantitative performance thresholds and practical implementation guidance for progressing between capability levels across different organizational contexts. Ultimately, the value of frequent capture-to-planning cycles should be assessed in terms of their ability to improve management decision-making and overall project performance.

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Data Availability Statement: The inspection datasets collected at the host site contain imagery of an active workplace and are subject to agreements with the host contractor and the General Data Protection Regulation (GDPR). Consequently, the datasets are available from the corresponding author upon reasonable request and subject to these constraints. The data refinement pipeline is also available from the corresponding author upon reasonable request. A curated release of the source code and an anonymized subset of the data is currently in preparation.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AprilTag	Fiducial marker used for robot localization and navigation
BIM	Building Information Model
CAD	Computer-Aided Design
GDPR	General Data Protection Regulation
IFC	Industry Foundation Classes
LiDAR	Light Detection and Ranging
SUP	Site Utilization Plan
UGV	Uncrewed Ground Vehicle
YOLOv8	You Only Look Once, Version 8 (object detection model)

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