

# INVESTIGATING THE USE OF DIGITAL TWINS IN CONSTRUCTION MANAGEMENT AND MONITORING

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## Abstract

Digital twins (DTs)—virtual representations of physical assets that are continuously synchronized with real-world data—are gaining traction across the architecture, engineering, and construction (AEC) industry. This paper investigates how DTs are being used for construction management and monitoring, synthesizes capabilities and limitations as of 2022, and proposes a practical reference framework for deployment on real projects. We examine core DT functions (progress tracking, safety, quality, cost and schedule control, and sustainability), data architectures spanning BIM, IoT, and cloud/edge computing, and analytics approaches from rules-based alerts to machine learning. A mid-scale building project scenario illustrates the framework. We also define a set of measurable key performance indicators (KPIs) and an evaluation protocol to quantify benefits. Findings suggest DTs can reduce schedule variance, rework, and safety incidents while improving transparency and decision-making, provided that data governance, interoperability, and change management are addressed. The paper concludes with a roadmap and research agenda focused on standards alignment, human-in-the-loop analytics, and lifecycle integration from construction to operations.

**Keywords:** Digital Twin, BIM, Construction Management, Progress Monitoring, IoT, 4D/5D, Safety, Quality, Predictive Analytics, AEC, Interoperability

## 1. Introduction

Construction projects are complex, data-rich, and risk-prone. Managers must coordinate multidisciplinary teams, track evolving site conditions, and make time-critical decisions under uncertainty. Digital twins (DTs) promise to unify design intent (e.g., BIM), live field data (e.g., sensors, drones, and mobile apps), and predictive analytics into a continuously updated project “single source of truth.” As of **2022**, many AEC organizations are moving beyond pilots to targeted deployments for progress tracking, safety oversight, and quality control. Yet challenges remain—especially interoperability, data governance, organizational adoption, and demonstrable ROI.

**Objective.** This research synthesizes 2022 practices and proposes a deployable framework for DT-enabled construction management and monitoring, including a realistic evaluation protocol.

### Research questions (RQs).

- **RQ1:** What construction management functions benefit most from DTs as of 2022?
- **RQ2:** What reference architecture enables scalable, secure, and interoperable DT deployments on active sites?
- **RQ3:** Which KPIs and methods best quantify DT value in schedule, cost, safety, quality, and sustainability?

### Contributions.

1. A function-architecture mapping for construction DTs; 2) a practical deployment framework with data pipelines and governance model; 3) a case scenario illustrating implementation; 4) a measurement protocol and KPIs; 5) a 12-month roadmap for organizations at different maturity levels.

## 2. Background and Definitions

**Digital Twin (DT).** A virtual representation of a physical asset or process that is kept in near-real-time synchronicity via data flows and is used for monitoring, simulation, and decision support.

### Related Concepts.

- **BIM (Building Information Modeling):** Geometric + semantic model; the backbone for DT visualization and alignment of IDs.
- **4D/5D BIM:** Integration of time (4D) and cost (5D) with the model for planning and control.
- **Common Data Environment (CDE):** A shared repository for project information and model coordination.
- **IoT/Reality Capture:** Sensors (environmental, structural), RFID/RTLS, computer vision from fixed cameras and UAVs, laser scanning.

**Why now?** Falling sensor costs, maturing cloud/edge stacks, and site digitization enable DTs that are operationally viable during the construction phase—not only in operations and maintenance.

### 3. Literature-Informed Capability Map

Capability	Construction Management Use	Typical Data/Input	Outputs/Decisions
Progress Monitoring	Compare actual vs. plan; earned value; delay root-cause	4D schedule, tokens/IDs, from site cameras/UAVs, manual updates	model % complete by WBS/trade, variance, look-ahead adjustments
Safety Oversight	Hazard identification, restricted zones, PPE compliance	Camera analytics, sensors, RTLS, geofencing	proximity Alerts, stop-work triggers, near-miss analytics
Quality Control	Tolerance checks; documentation traceability	Laser scans/photogrammetry vs. BIM; checklists, NCR logs	Deviation maps, NCR assignments, rework forecasting
Cost Control	5D linkages, automated quantities, change impacts	5D BIM, procurement records, progress data	Cost variance, cash-flow curves, forecast at completion
Sustainability	Fuel use, waste tracking, carbon	Equipment material logs	telematics, delivery KPIs, GHG dashboards, waste sustainability compliance

### 4. Reference Architecture for Construction DT (2022)

#### A. Layers

- Physical/Field:** Sensors (temperature, humidity, vibration), mobile apps, RFID/RTLS, cameras/UAVs, equipment telematics.
- Edge Compute:** Local gateway for buffering, basic analytics, bandwidth optimization, and safety interlocks.
- Connectivity:** 4G/5G + Wi-Fi mesh; MQTT/AMQP for telemetry; TLS/HTTPS for API exchange.
- Data Integration & CDE:** Time-series DB for telemetry; object storage for imagery/point clouds; graph/relational DB for BIM semantics; model server (IFC/BCF, open APIs).
- Twin Core:** State estimation, alignment service (mapping sensor streams to BIM element IDs), versioned 4D/5D states, rules engine.

6. **Analytics & Apps:** Progress analytics, safety AI, quality deviation detection, dashboards, what-if simulations.
7. **Access & Security:** Role-based access control (RBAC), SSO, audit logs, data retention policies.

## B. Interoperability Best Practices

- Use **IFC/BCF** for geometry and issues; open IDs for element tracking.
- Maintain a **Digital Thread** of documents, RFIs, changes, and approvals.
- Implement **schema mapping** between WBS, cost codes, and model elements.

## 5. Data Pipeline and Model Alignment

1. **Model Preparation:** Clean BIM; assign unique IDs; federate disciplines; link 4D/5D.
2. **Sensor & Vision Ingestion:** Standardize telemetry (MQTT topics); automate camera/UAV upload with metadata.
3. **Reality-to-BIM Alignment:**
  - **Scan-to-BIM** for as-built geometry alignment.
  - **CV-to-WBS** mapping (detect rebar, formwork, MEP runs) and associate to model elements.
4. **State Synchronization:** Maintain a digital state vector for each element: {installed?, date, quality score, % complete, responsible trade}.
5. **Feedback Loops:** Alerts to field apps; issue creation (BCF); updated look-ahead schedules.

## 6. Methods for Monitoring and Analytics

### Progress:

- Rules: If element state changes to *installed*, update % complete for parent WBS; compute SPI/CPI.
- CV approach: Object detection/segmentation on imagery; probabilistic confidence fused with manual confirmations.

### Safety:

- Zone-based geofencing; PPE detection as advisory (human-in-the-loop review); near-miss clustering.

### Quality:

- Point-cloud vs. BIM deviation heatmaps; tolerance thresholds (e.g.,  $\pm 10$  mm for MEP hanger elevation).

**Predictive:**

- Gradient-boosting/temporal models for delay/rework risk from leading indicators (crew sizes, inspection backlog, weather).

**7. Case Scenario: Mid-Rise Healthcare Building**

**Context.** A 10-story, 48,000 m<sup>2</sup> hospital project with 24-month schedule.

**DT Deployment.**

- **Scope:** Structural shell, facade, and MEP rough-in.
- **Inputs:** Federated BIM with 4D/5D; fixed cameras + weekly UAV flights; BLE beacons for zone entry; equipment telematics; weekly laser scans for critical areas.
- **Workflow:** Automated progress estimates feed weekly coordination; quality deviations create NCRs; safety zones trigger alerts for crane swings.

**Illustrative Outcomes.**

- Schedule variance reduced by ~15% in critical trades due to early detection of out-of-sequence work.
- Rework on MEP racks decreased due to 10 mm tolerance checks pre-pour.
- Documented reduction in near-miss incidents after geofence alerts (leading indicators improved).

**8. Measurement Protocol and KPIs**

**Design.** Pre-post or A/B design across work packages. Minimum 3-month baseline.

**Core KPIs.**

- **Schedule:** SPI, % tasks on-time, look-ahead adherence, average delay days.
- **Cost/Quality:** CPI, rework hours, NCR closure time, defect density.
- **Safety:** TRIR (recordable incident rate), near-miss rate, unauthorized zone entries.
- **Sustainability:** Fuel per operating hour, waste diversion %, delivery consolidation ratio.
- **Adoption:** Data freshness (median ingestion latency), user active days, issue resolution SLA.

**Statistical Approach.** Difference-in-differences vs. comparable packages; control for crew size, weather, and design changes; report effect sizes and confidence intervals.

## 9. Governance, Risk, and Ethics

- **Data Privacy:** Clear signage; worker consent where required; anonymize video analytics; retain only metadata needed.
- **Model Accountability:** Keep human-in-the-loop for safety decisions; document model performance and bias tests.
- **Change Management:** Training for superintendents/foremen; integrate with existing CDE and PM tools to minimize duplicate entry.
- **Cybersecurity:** RBAC, least privilege, encrypted transit/storage, incident response plan.

## 10. Implementation Roadmap (12 Months, 2022 Baseline)

**Quarter 1:** Business case; select pilot scopes; prepare BIM (ID hygiene); procure sensors; define KPIs and governance.

**Quarter 2:** Stand up CDE and data pipeline; integrate 4D/5D; deploy cameras/UAV workflows; build dashboards; initiate training.

**Quarter 3:** Add point-cloud QA; roll out safety geofences; start predictive risk models; run first A/B evaluation.

**Quarter 4:** Scale to additional trades; optimize edge processing; formalize SOPs; publish ROI with KPI deltas and lessons learned.

## 11. Conclusion

Digital twins represent a transformative advancement in construction management and monitoring. Their ability to provide real-time insights, predictive analysis, and efficient lifecycle management makes them a cornerstone of future smart construction practices. While challenges such as cost and interoperability remain, ongoing research and technological innovation are expected to accelerate their adoption across the global construction industry.

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