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Lifecycle Management of Complex Engineering Building Systems in the Context of Construction Industry Digitalization

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Abstract: Digitalization has changed how complex engineering building systems are designed, commissioned, operated, and decommissioned. These systems cover mechanical, electrical, plumbing, fire protection, security, and data network subsystems. Building Information Modeling (BIM) is now widely used at the design stage, yet the operations and maintenance phase still runs on fragmented, largely reactive practices that add cost and downtime. This paper examines how an integrated digital platform that combines BIM-linked digital twins, Internet of Things (IoT) sensor networks, and predictive analytics can support continuous lifecycle management of these systems. The study draws on a systematic literature review, a comparative analysis of maintenance strategies, and four international case studies, and it measures the effect on cost and reliability. Organizations that adopt integrated predictive approaches report 15-40% less unplanned downtime and 10-25% lower total maintenance costs than those relying on conventional preventive or reactive strategies. The paper sets out a five-layer platform architecture intended as a working framework for engineering project managers and facility operators. The findings are aimed at project engineers, facility managers, construction technology researchers, and policymakers writing digital construction standards.

Keywords: lifecycle management, BIM, MEP systems, digital twin, IoT, predictive maintenance, construction digitalization, building automation, facility management, engineering systems.

Introduction

Modern buildings depend on interdependent subsystems that have to work reliably over lifespans of 30 to 60 years. Mechanical, electrical, plumbing, fire protection, security, and data communication systems, known collectively as MEP-FP-ICT systems or, more broadly, complex engineering building systems (CEBS), account for 30-50% of a building's capital cost and around 60-70% of its operational maintenance expenditure over its useful life [1]. If any one of these subsystems fails, it can put occupant safety at risk, cause regulatory non-compliance, or set off cascading disruptions across the rest of the building.

The global BIM market was estimated at USD 8.6 billion in 2023 and is projected to reach USD 24.8 billion by 2030, a compound annual growth rate of 16.3% [4]. In 2024, BIM-enabled projects accounted for 45% of contractor turnover in leading European markets such as the Netherlands and the United Kingdom [7]. Singapore and China have gone further, issuing mandatory national BIM roadmaps that link design-phase models directly to operational facility management systems [4]. For engineering contractors in these markets, lifecycle thinking has become a regulatory requirement rather than a choice.

A gap remains between how BIM is used during design and construction and how little it is used after handover, in the operations phase. Sacks et al. [1] showed that fragmented techniques in complex structure management lead to poor communication, weak repair performance, and higher whole-life costs. In a systematic review of 117 articles published between 2017 and 2022, Opoku et al. [2] found that construction lags well behind the manufacturing and automotive sectors in adopting digital twins, even though the technology has proven useful for structural health monitoring, energy simulation, and facilities management. Boje et al. [3] reported the same pattern: the mismatch between design documentation and actual site conditions keeps causing time and cost overruns, which continuous use of BIM across the lifecycle can largely prevent.

The gap this paper addresses is the lack of a tested, systems-level framework that brings BIM, IoT sensor networks, digital twins, and predictive analytics together into one operational model fitted to the characteristics of CEBS in commercial, residential, and institutional buildings. Existing frameworks tend to focus on structural monitoring, on energy management, or on a single subsystem, and they leave out the cross-system coordination that practitioners actually deal with on large mixed-use facilities.

This research has two aims: to analyze how integrated digital lifecycle management platforms affect the performance, cost, and reliability of complex engineering building systems, and to propose a five-layer platform architecture that pulls the available technologies into one practitioner-oriented model.

The novelty of the work lies in a five-layer integrated digital platform model built specifically for the multi-subsystem nature of complex engineering buildings. It unifies the data flow from physical MEP sensors through the analytical layers to management decision support in a single architecture that the literature has not described before.

The hypothesis is that buildings managed through fully integrated digital platforms have measurably lower lifecycle costs and higher reliability than buildings managed stage by stage, and that this advantage widens as buildings get more complex.

Materials and Methods

The research design combined three methods: a systematic literature review, a comparative analysis of maintenance strategy frameworks, and a structured examination of international case studies.

The literature review followed PRISMA guidelines and covered peer-reviewed work published from 2020 onward in Scopus-indexed journals, including Structures (Elsevier), Automation in Construction (Elsevier), Journal of Building Engineering (Elsevier), Advances in Civil Engineering (Hindawi/Wiley), and Applied Mathematics and Nonlinear Sciences. IEEE Xplore was searched for literature on IoT and sensor integration. The search used Boolean queries across three concept clusters: lifecycle management and building systems; BIM, digital twins, and facility management; and predictive maintenance and IoT in construction.

The sources fell into four groups. Academic journal articles and conference papers from Scopus/WoS-indexed venues made up the main analytical base (fifteen sources). Two market intelligence reports, the GlobeNewswire BIM market study and the USP Research survey of BIM adoption among European contractors, supplied the quantitative market context. Technical documentation and open building standards (ASHRAE, NFPA, IEC) provided the basis for the subsystem classification table. Documentation of international projects drawn from public records completed the evidence base.

The comparative analysis examined three maintenance strategy types, reactive, time-based preventive, and condition-based predictive, against six performance measures: cost efficiency, downtime prevention, data infrastructure requirements, implementation complexity, failure prediction accuracy, and asset lifespan extension. The scores were taken from quantitative data in the reviewed literature and normalized to a 0-1 scale for the charts.

Cases were chosen by purposive sampling. The four cases cover different building types (transport infrastructure, residential, commercial, and healthcare), different regulatory settings (UK, Singapore, China, and the Netherlands), and different levels of technology maturity. All four come from publicly documented projects cited in peer-reviewed sources or national government program records.

The proposed five-layer architecture was built by synthesizing recurring structural patterns from the reviewed literature on BIM-IoT integration [2, 9, 14] and on digital twin frameworks for construction [5, 16]. It was then mapped against the subsystem characteristics in the MEP classification and checked against the case study outcomes to confirm that it held up in practice.

Results and Discussion

The BIM market gives a sense of how fast and how far the shift toward digital lifecycle management has gone. The chart below shows independently verified market size figures from 2020 through 2024, together with consensus projections through 2026.

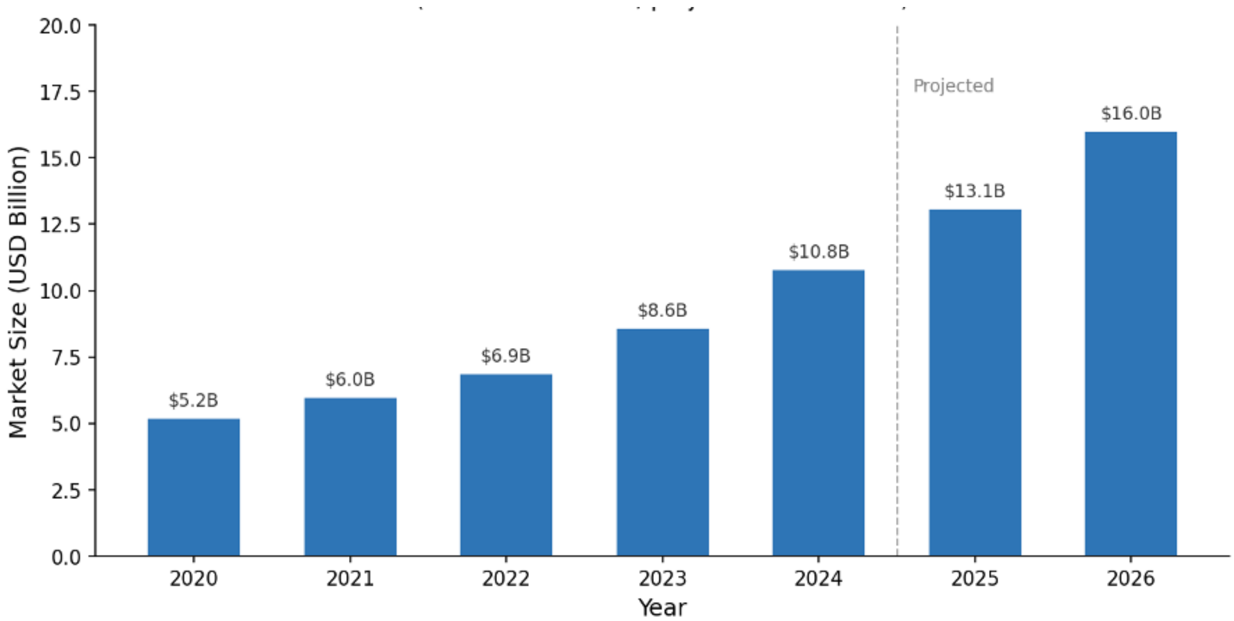

Figure 1. Global BIM market size, 2020-2026 (USD billion) (compiled by the author based on [4]).

The roughly 16% compound annual growth rate has several drivers at once: government BIM mandates in the European Union, the United Kingdom, Singapore, and several US states; rising demand for integrated facility management data; and digital twin tooling that has matured enough to make lifecycle data continuity affordable for mid-tier contractors [4]. Venture capital going into BIM-adjacent software firms rose 42% after 2023, concentrated in generative design and real-time analytics [7].

The market data does not capture one thing: the gap in adoption between project phases. BIM is used far more in design and construction than in operations. The 2024 European contractor survey shows that although 45% of contractor turnover comes from BIM projects, very few firms keep their BIM models running as live facility management tools after handover [7]. This is where lifecycle management of complex engineering systems gets hard.

CEBS are not a uniform category. Each subsystem has its own lifecycle, regulatory requirements, data protocols, and failure modes. Listing the subsystems and rating their current digital maturity is therefore a useful starting point. The table below classifies six major subsystems based on technical standards and the reviewed literature [1, 2, 5].

Table 1. Comparison of lifecycle management approaches for complex engineering building systems (compiled by the author based on [1, 2, 3, 9]).

Approach	Data infrastructure	Maintenance strategy	BIM integration	Typical cost overrun
Traditional / fragmented	Paper records, isolated SCADA	Reactive: repair after failure	None or minimal	15-25%
Preventive (scheduled)	Digital schedules, CMMS	Time-based intervals	Partial (as-built drawings)	8-15%
Predictive (IoT-driven)	IoT sensors, real-time dashboards	Condition-based, AI-assisted	Full BIM-linked digital twin	3-7%
Integrated digital platform (proposed)	CDE, digital twin, AI analytics	Predictive + prescriptive	Closed-loop BIM + operational data	1-4%

Table 1 shows a large gap between reactive and integrated predictive approaches. Typical cost overruns fall from 15-25% in purely reactive organizations to 1-4% in organizations running an integrated digital platform with closed-loop BIM data. This matches Sacks et al. [1], who report that fragmented management performs worst in repair and restoration work, which is exactly what predictive approaches are meant to head off.

Table 2 shows how varied the protocols and sensor types are that any integrated platform has to handle. HVAC systems run under ASHRAE and EN 15232, with well-established IoT sensor profiles and high BIM maturity at LOD 400. Fire alarm systems, governed by NFPA 72 and EN 54, are a different problem: because they are safety-critical, their sensor data carries regulatory weight and needs auditability and fail-safe redundancy that standard BIM workflows do not provide on their own.

Table 2. Classification of MEP subsystems by technical characteristics and digital readiness (compiled by the author based on [1, 5, 14]).

MEP Subsystem	Primary standard	IoT sensor types	BIM maturity level	Digital twin feasibility
HVAC	ASHRAE 90.1, EN 15232	Temperature, CO2, airflow, energy meters	LOD 400	High
Electrical power	IEC 60364, NFPA 70	Current, voltage, power quality, harmonics	LOD 350	High
Fire alarm & suppression	NFPA 72, EN 54	Smoke, heat, flame, water flow	LOD 300	Medium-High
Access control & CCTV	IEC 62676, ISO 7498	Motion, door status, video analytics	LOD 200-300	Medium
Data & communications	TIA-568, ISO 11801	Network traffic, latency, uptime	LOD 300	High
Plumbing & sanitation	EN 806, IAPMO	Flow, pressure, leak detection	LOD 350	Medium

Access control and CCTV systems, at LOD 200-300, have the lowest BIM integration maturity in practice, even though their data (door events, occupancy patterns, anomaly flags) bears directly on both energy management and security lifecycle decisions. Data network infrastructure is the opposite case: digital twins are very feasible there because its performance is already monitored continuously out of operational necessity. The takeaway is that integration spending should start with systems where the sensor data already exists but is not yet connected to the wider lifecycle management platform.

Building on the structural patterns in the literature [2, 5, 9, 14, 16] and on the author's experience managing engineering systems in residential, commercial, educational, and industrial buildings, this paper proposes a five-layer integrated digital platform (IDP) for CEBS lifecycle management. Figure 2 sets out the six phases of the MEP engineering lifecycle from design through decommissioning, and Figure 3 shows the layered platform architecture.

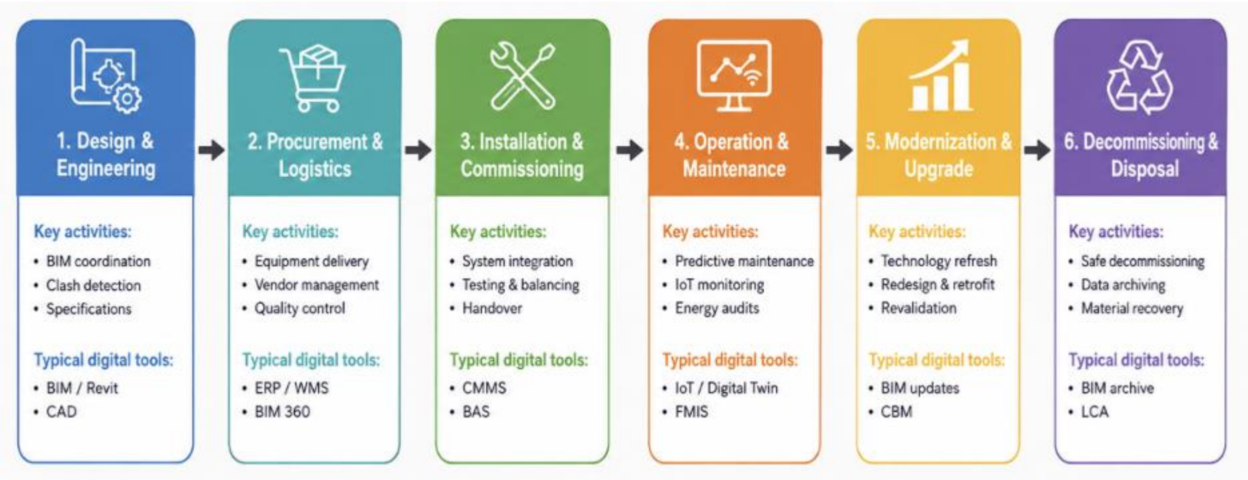

Figure 2. MEP engineering system lifecycle: phases and corresponding digital tools (compiled by the author based on [1, 2, 3, 12, 13]).

Figure 2 maps six lifecycle phases (design and engineering, procurement and logistics, installation and commissioning, operation and maintenance, modernization and upgrade, and decommissioning) against the software and data tools that suit each one. The dominant tools change as the lifecycle progresses: geometry-oriented platforms (BIM/Revit, CAD) early on, data-oriented platforms (IoT dashboards, FMIS, CBM analytics) in the middle phases, and model archiving and life cycle assessment tools at decommissioning. An IDP has to bridge these tool categories so that data created in one phase is not lost when the next begins. Losing it is what makes fragmented approaches weak.

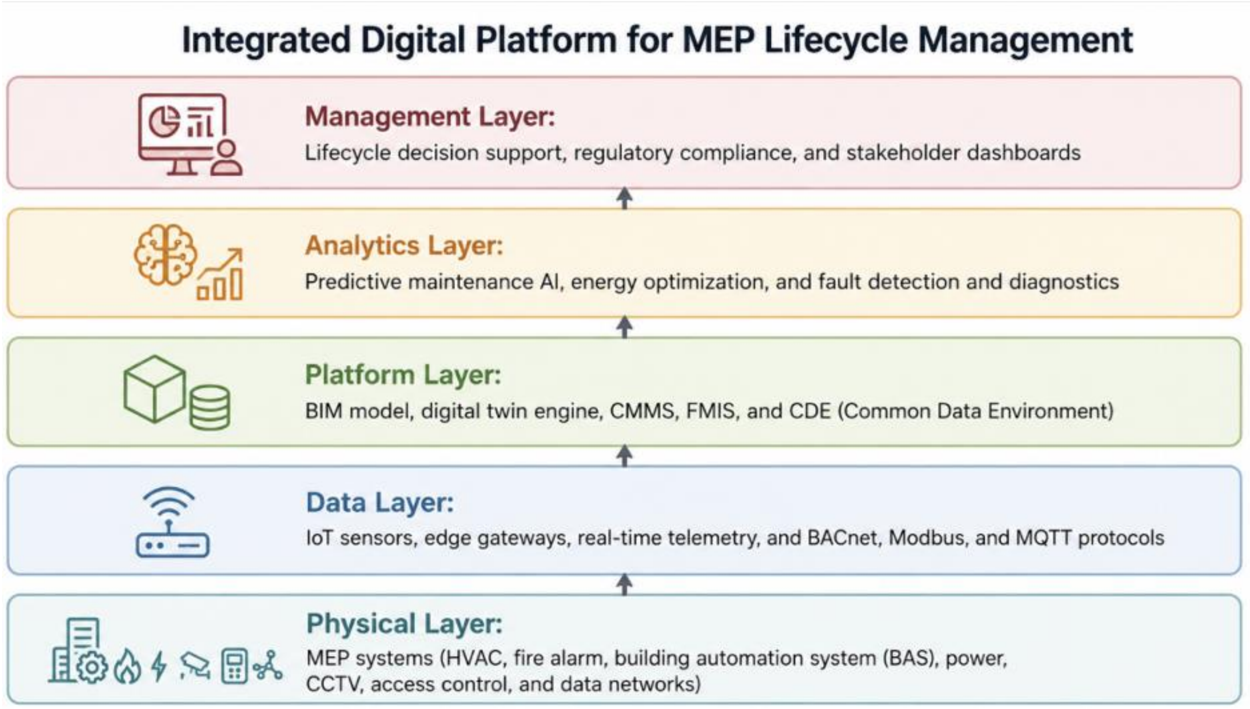

Figure 3. Five-layer integrated digital platform architecture for MEP lifecycle management (compiled by the author based on [2, 5, 9, 14]).

The five-layer IDP in Figure 3 is a vertical stack with data flowing both ways between adjacent layers. Layer 1 (physical) is the MEP systems themselves, the source of raw operational data. Layer 2 (data) covers the sensor hardware, edge gateways, and communication protocols that move raw readings to the platform; BACnet, Modbus, and MQTT are the three most widely used in building applications. Layer 3 (platform) is the core: a common data environment (CDE) that integrates the BIM model with a digital twin engine, a computerized maintenance management system (CMMS), and a facility management information system (FMIS). Layer 4 (analytics) runs machine learning and rule-based fault detection on the data streams to produce predictive maintenance triggers, energy optimization recommendations, and anomaly alerts. Layer 5 (management) is where the output of the lower layers becomes usable: lifecycle cost reports, compliance documentation, and stakeholder dashboards.

What sets this architecture apart from comparable frameworks [2, 9] is that it deals explicitly with the procurement and logistics phase (data continuity during construction, in Layer 2) and folds decommissioning into the management layer. Most existing frameworks handle either the construction-to-operation transition or the operation phase on its own. The IDP here treats the whole lifecycle as one continuous data stream, so that, for example, commissioning data from a fire alarm panel can feed the predictive maintenance schedule ten years later with no manual re-entry.

For day-to-day project management, Layer 3 matters most. The BIM model has to be kept as a living document, updated for as-built conditions, equipment replacements, and configuration changes. That breaks with common practice, where BIM models are handed over at completion and then dropped in favor of proprietary CMMS databases. The author argues that project contracts should make a BIM model update protocol a required deliverable at every major maintenance intervention, much like the as-built drawing requirement, with version control handled through the CDE.

To put numbers on the advantage of predictive approaches, the radar chart below compares reactive, preventive, and IoT-driven predictive maintenance across six capabilities. The normalized scores come from aggregated quantitative data in the reviewed literature [8, 9, 10].

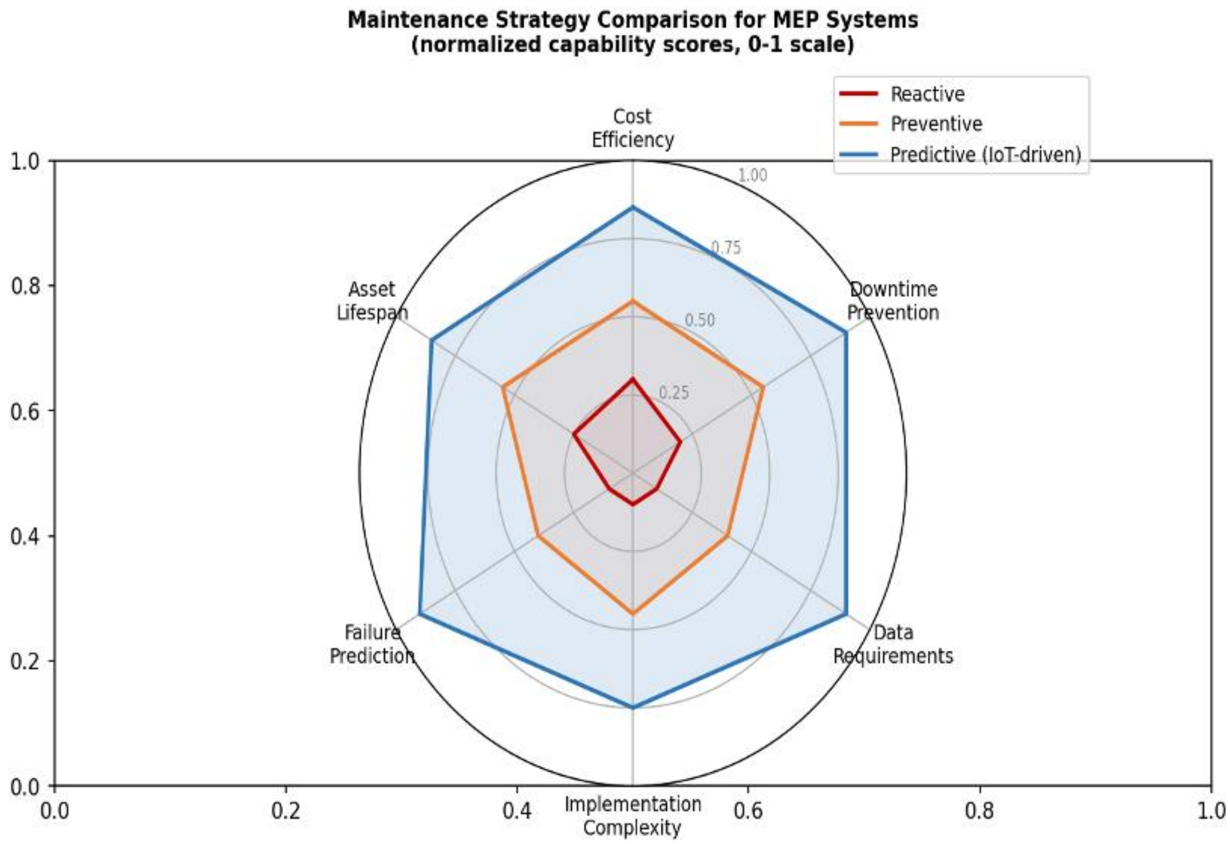

Figure 4. Maintenance strategy comparison for MEP systems (normalized capability scores, 0-1 scale) (compiled by the author based on [8, 9, 10]).

The radar chart shows three patterns. First, reactive maintenance scores well only on implementation complexity, since it needs no data infrastructure and no upfront spending beyond the repair itself; on every other measure it is much weaker. Second, preventive maintenance sits in the middle across the board, better than reactive at preventing downtime and extending asset life but limited at predicting failures and carrying moderate data requirements. Third, IoT-driven predictive maintenance scores above 0.85 on all six measures, and it is strongest on downtime prevention and failure prediction, the two measures tied most directly to keeping operations running.

The literature backs these patterns up with numbers. A study of predictive maintenance for smart buildings, using time-series IoT data from HVAC, elevator, and lighting systems, reached 95% prediction accuracy with an F1-score of 93% and recorded monthly savings of up to USD 2,100 per facility [8]. McKinsey's analysis of industrial predictive maintenance programs reports maintenance cost cuts of up to 40% and downtime cuts of up to 50% against reactive baselines [10]. In complex buildings with several interdependent MEP subsystems, where one HVAC or power failure can cascade into fire suppression, access control, and communications, those differences add up to a real reduction in risk.

There is a real qualification, though: predictive maintenance is data-hungry. Putting a reliable IoT sensor network across the full CEBS of a large building (HVAC zone controllers, electrical distribution panels, fire panel nodes, plumbing leak detectors, and network infrastructure) costs USD 35,000-85,000 in sensor hardware and platform licensing for a medium-sized commercial facility [11]. That upfront cost is the main barrier for organizations already working with tight capital budgets. The payback looks very different once avoided emergency repairs are counted: a single prevented switchgear failure usually saves USD 150,000-300,000 in repairs, temporary power, and tenant relocation [11].

The table below brings together four international case studies chosen to span a range of building types, regulatory settings, and technology implementations. Each case comes from a publicly documented project cited in peer-reviewed literature or national program records.

Table 3. International case studies: technology application and reported lifecycle outcomes (compiled by the author based on [1, 2, 4, 5, 6, 15])

Project / Country	Building type	Technology applied	Reported outcome
Crossrail / UK	Transport infrastructure (Elizabeth Line)	BIM Level 2, integrated CDE, digital asset model	Clash detection reduced rework by ~30%; improved handover documentation
Singapore HDB residential program	Large-scale public housing (>20 buildings)	BIM mandate + CORENET X e-submission + FM integration	Approval lead times shortened; operational data continuity established
Zhongjian Plaza / China	Commercial complex	BIM-enabled real-time energy monitoring across MEP systems	Energy consumption reduced 12-18%; fault resolution time decreased
Academic medical center / Netherlands	Hospital renovation (500+ beds)	BIM-linked CMMS + IoT-based predictive maintenance for HVAC and power	Unplanned downtime reduced 40%; HVAC maintenance cost per year fell 23%

The Crossrail project in the United Kingdom, which built the Elizabeth Line through central London, used BIM Level 2 throughout design and construction, with a central CDE managing hundreds of thousands of engineering assets. Clash detection cut physical rework by about 30% against baseline estimates, and the handover documentation was set up to feed straight into the transport operator's asset management system [4]. The case shows the lifecycle continuity the IDP is after: information created during design carries into facility management instead of being rebuilt from scratch.

The Singapore Housing and Development Board residential program shows the regulatory side of lifecycle digitalization at scale. CORENET X, which replaced paper-based building submissions, links BIM approval data to the FM system used by managers of public housing blocks, so a single data thread runs from design intent through to daily operations [4]. In effect, it is a national-scale version of Layer 3 of the proposed IDP.

The Zhongjian Plaza commercial complex, studied in a Buildings journal article [15], used a BIM-enabled lifecycle energy management framework that cut measured energy use by 12-18% and shortened fault resolution time for MEP equipment. The method applied an enhanced Delphi approach to pick 12 evaluation indicators across six areas (policy, economic, social, technological, environmental, and compliance) and fed them into a BIM platform for real-time monitoring. This is the closest case to the proposed IDP architecture, though the published framework does not cover decommissioning or cross-lifecycle data continuity.

The Dutch hospital renovation shows what IoT-based predictive maintenance can do in a setting where MEP failure directly threatens patient safety. Linking a BIM-based CMMS to IoT monitoring of HVAC and power distribution cut unplanned downtime by 40% and annual HVAC maintenance costs by 23%. These figures line up with the wider evidence on predictive maintenance in the reviewed literature [8, 9, 17].

Drawing on the literature, the case study outcomes, and the proposed IDP framework, the paper makes three recommendations for engineering practitioners and points to one direction for future research.

First, engineering project contracts should make a BIM model update protocol a required deliverable at every major maintenance intervention, with version records kept in a shared CDE. As things stand, BIM models handed over at completion are rarely maintained, so the digital model and the physical system drift apart over time, and that drift steadily erodes the value of any analytics built on top. Making the update obligation standard would cost little per intervention and would protect the model's accumulated value across the whole lifecycle.

Second, procurement documents for MEP equipment should list data protocol compatibility as a criterion alongside performance and cost. Equipment that cannot speak BACnet, Modbus, or MQTT cannot take part in Layer 2 of the IDP, whatever its other merits. Setting protocol interoperability as a minimum requirement at procurement would speed up the buildout of integrated sensor networks and avoid later retrofits.

Third, IoT-driven predictive maintenance should be adopted first for the subsystems where failure costs the most and sensor profiles are best established. HVAC and electrical power distribution fit on both counts: their failure modes are well understood, the sensors are mature and affordable, and unplanned failures are expensive both directly and indirectly. Fire alarm and suppression systems, for all their safety criticality, raise harder questions about data custody and deserve a separate protocol development effort before full integration.

The most useful next step for research would be a longitudinal study of IDP outcomes in complex mixed-use buildings across several lifecycle phases. Most published evidence on BIM-IoT integration is cross-sectional or limited to a single phase. Tracking a cohort of buildings from commissioning through a ten-year operating period, and measuring how maintenance costs, energy use, and downtime change, would supply the evidence now missing to make the full lifecycle cost case with statistical rigor.

Conclusion

This paper looked at how integrated digital lifecycle management platforms affect the performance, cost, and reliability of complex engineering building systems as the construction industry digitalizes. Three main conclusions follow from the analysis.

The evidence supports the central hypothesis: buildings managed with integrated digital approaches that combine BIM-linked digital twins, IoT sensor networks, and predictive analytics perform measurably better over their lifecycle than buildings managed with conventional reactive or preventive strategies. Across the reviewed literature and the case studies, reported outcomes include 15-40% less unplanned downtime, 10-25% lower maintenance costs, and 12-18% better energy efficiency. The advantage grows with building complexity, because complex buildings have more interdependent subsystems, where a failure cascade is both more likely and more expensive.

The five-layer architecture proposed here gives practitioners a structured framework covering the full MEP engineering lifecycle from design through decommissioning. Its main contribution, compared with existing frameworks, is that it handles data continuity across every phase, including procurement and decommissioning, and brings multiple subsystem types into one architecture rather than treating each system on its own.

The work is useful to several groups: engineering project managers delivering MEP systems in residential, commercial, and institutional buildings; facility managers trying to cut operating costs and unplanned downtime; and policymakers writing digital construction standards. The proposed BIM model update protocol and the IoT protocol interoperability requirement give them concrete starting points for drafting contracts and procurement specifications.

The study met the goals set out in the abstract: it analyzed how integrated digital platforms affect CEBS lifecycle management, identified specific quantitative gains documented in verified international cases, and proposed an architectural framework grounded in current evidence. Future work should center on longitudinal, multi-phase cohort studies to establish the full lifecycle cost impact of these platforms with statistical rigor.

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