

A Lifecycle-Oriented Framework for Facility Management in 3D Concrete Printed Infrastructure

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Abstract:

The 3D concrete printing (3DCP) enables automated, formwork-free construction, but facility management (FM) requirements are rarely considered during asset design and handover. This creates a gap between how 3DCP structures are designed and printed and how they will be maintained throughout their service life. This study develops a Lifecycle-Oriented Facility Management (LOFM) framework to address this gap by integrating FM considerations into the design and printing stages of 3DCP. A structured literature review cross-maps ISO 41001 and EN 15221 with research on 3DCP durability, sensing, design, and digital-twin applications, identifying five LOFM dimensions: maintainability, durability, accessibility, adaptability, and digital integration. These dimensions are translated into a quantitative decision framework covering 3DCP condition, FM requirements, monitoring systems, deterioration, intervention, repair, and lifecycle cost. A parameterised daily-step Monte Carlo model is demonstrated over a synthetic 25-year service life using 5,000 paired simulations. Under the stated assumptions, LOFM produces a mean normalized lifecycle cost of 2.19, compared with 3.19 for conventional FM, representing a 31.3% reduction in the simulated normalized lifecycle cost under the baseline assumptions. The probability of at least one unplanned reactive repair is 0.52% under LOFM, compared with 10.24% under conventional FM. However, sensitivity analysis shows that the economic benefit is conditional on key assumptions; increasing sensor/platform cost five-fold reduces the simulated advantage to -2.0%. When change in Lifecycle Cost, $\Delta LCC > 0$, LOFM is economically favourable; when $\Delta LCC \leq 0$, the assumptions or LOFM provisions should be reassessed. The framework therefore provides a practical pathway for translating 3DCP characteristics into decisions on access, inspection, monitoring, maintenance, digital handover, and lifecycle cost. Given the limited availability of long-term, asset-level 3DCP data, these results are interpreted as scenario-based

estimates rather than field-validated predictions. Overall, LOFM provides a design-stage, testable framework for making 3DCP structures not only printable, but also maintainable and economically manageable throughout their lifecycle.

Keywords:

3D Concrete Printing, Facility Management, Lifecycle-Oriented Design, Digital Twin, Structural Health Monitoring

1. Introduction

The 3D concrete printing (3DCP) replaces formwork-based casting with automated, layer-wise deposition and has reported reductions in material waste, construction time, and labour relative to conventional practice (Aghajani Delavar et al., 2023; Heidelberg Materials, 2026). Yet research remains concentrated on printability, mix design, and as-built performance rather than operation and maintenance after handover. This creates a lifecycle gap because 3DCP's layered fabrication introduces service interfaces and orientation-dependent behaviour that can affect inspection, repair, and durability.

Layer-wise deposition produces measurable anisotropy, with reported compressive-strength retention of 59–85% and flexural-strength retention as low as 53% relative to cast concrete, depending on orientation (Sapata et al., 2025). Interlayer porosity and moisture-ingress pathways can further concentrate deterioration (Nodehi et al., 2022). These characteristics are predictable at design stage and therefore provide an opportunity to plan access and monitoring before they become maintenance liabilities. Conventional Facility Management (FM) primarily focuses on operating, maintaining, inspecting, and repairing an asset throughout its service life. In contrast, Lifecycle-Oriented Facility Management (LOFM) extends FM by incorporating maintainability, durability, accessibility, adaptability, and digital integration into design-stage decisions. The LOFM can help by shifting maintenance considerations from the post-construction stage to the design and printing stage. It can guide designers and contractors to plan service access, inspection provisions, durability-sensitive details, sensor locations, and digital handover in advance, potentially reducing difficult reactive repairs, downtime, and lifecycle costs.

This paper proposes a Lifecycle-Oriented Facility Management (LOFM) framework that treats maintainability, monitoring, durability, and adaptability as design requirements for 3DCP infrastructure. The scope covers low-to-mid-rise 3DCP assets with demonstrated construction precedents, including walls and utility/security cabins, pedestrian and cycling bridges, and modular public-realm elements. High-rise structural systems, vehicular-load bridges, and buried utility networks are excluded because current validation is insufficient. The framework is developed by cross-mapping facility-management standards with 3DCP design, durability, sensing, and digital-twin literature.

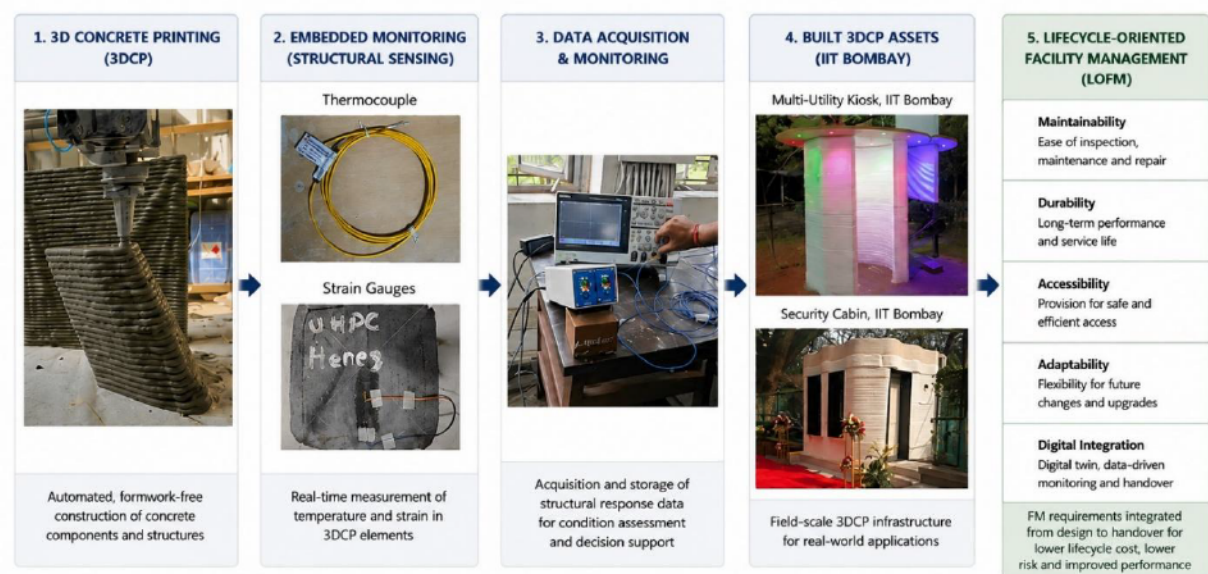


Figure 1. From 3D concrete printing and embedded monitoring to lifecycle-oriented facility management (LOFM).

The specific contributions of this study are threefold: (1) to develop a Lifecycle-Oriented Facility Management (LOFM) framework that links 3DCP-specific characteristics with facility-management requirements at the design and printing stages; (2) to translate these requirements into quantitative indicators covering anisotropy, embedded sensing, deterioration, intervention, and lifecycle cost; and (3) to demonstrate the decision framework through a reproducible stochastic lifecycle model and sensitivity analysis that identifies the conditions under which LOFM is economically advantageous.

2. Methodology

2.1 Review protocol and data sources

This study builds the LOFM framework through a structured literature review rather than new laboratory testing. Searches were run across Scopus, ScienceDirect, and Google Scholar using combinations of “3D concrete printing” / “3D printed concrete” with “durability”, “facility management”, “maintenance”, “structural health monitoring”, “embedded sensor”, and “digital twin”, supplemented by targeted searches for named built precedents (e.g. “3D printed bridge”). Sources were restricted to peer-reviewed journal articles and conference proceedings, and, for built-precedent data only, primary project reporting from the delivering organisations, since facility-level performance data for built 3DCP assets is not yet consistently reported in peer-reviewed form. Records were screened for relevance to one of three evidence types: (i) as-printed mechanical or durability performance, (ii) embedded/self-sensing cementitious composites applicable to 3DCP, and (iii) reported FM or maintenance outcomes of IoT/digital-twin monitoring in buildings generally, used as a benchmark. Sources addressing only mix design or printability without durability, sensing, or FM data were excluded. This produced the working corpus cited in the results, spanning material science, structural engineering, and FM/digital-twin practice literature. The review was targeted and thematic rather than an exhaustive PRISMA-protocol systematic review; it is best characterised as a structured narrative synthesis, and Section 5 identifies this as a limitation.

Evidence maturity for LOFM parameters

Available evidence is uneven across the five LOFM dimensions. Built 3DCP precedents provide feasibility evidence for construction and, in selected cases, embedded monitoring, but longitudinal facility-level maintenance records, intervention histories, and 3DCP-specific lifecycle-cost datasets are not consistently reported. The framework therefore uses field/build evidence where available, literature-derived performance evidence for material and sensing mechanisms, and explicit scenario assumptions where operational FM data are unavailable as shown in Table 1.

Table 1. Evidence maturity and modelling treatment for the five LOFM dimensions. Field/build evidence is used as feasibility evidence where available; missing longitudinal FM data are not inferred and are instead represented as explicit modelling assumptions.

<i>LOFM dimension</i>	<i>Available evidence</i>	<i>Data maturity</i>	<i>Treatment in this study</i>
Maintainability	3DCP toolpath/design freedom enables service cavities and inspection provisions; no longitudinal 3DCP FM work-order dataset.	Low–medium	Design requirement; access/intervention represented parametrically.
Durability	Measured anisotropy and interlayer deterioration mechanisms from 3DCP laboratory literature.	Medium	Literature-derived bounds; stochastic deterioration model.
Accessibility	Built 3DCP precedents demonstrate different monitoring/access provisions; Shanghai bridge includes embedded monitoring.	Medium	Physical-access advantage treated as an explicit scenario assumption.
Adaptability	Geometric/modular flexibility is demonstrated; no reviewed built precedent reports in-service reconfiguration.	Low	Design principle and testable hypothesis; not treated as measured benefit.
Digital integration	Embedded/self-sensing cementitious composites and selected 3DCP monitoring precedents; digital-twin FM benefits mainly benchmarked from conventional buildings.	Medium	Sensor sensitivity and platform cost modelled; maintenance benefit remains hypothesis-level.

This evidence structure is important for interpreting the quantitative results: the model demonstrates how the LOFM framework can translate FM assumptions into lifecycle decisions, but it does not claim that the assumed intervention rates, access differential, sensor costs, or deterioration process have been validated over a 25-year operating period.

2.2 Framework-mapping technique

The five LOFM dimensions—maintainability, durability, accessibility, adaptability, and digital integration—were derived by cross-mapping ISO 41001:2018 and EN 15221 with recurring 3DCP technical themes. The FM standards provide the service and management scope, while the 3DCP literature identifies issues such as interlayer bonding and porosity, service routing, geometric flexibility, and sensor integration. The intersection of these categories was converted into testable design implications; for example, service-routing requirements translate into pre-provisioned service corridors. The mapping is deductive and qualitative, while the quantitative synthesis reports metrics from the cited sources rather than new measurements.

2.3 Scope of embedded sensing and digital-twin integration

In the proposed LOFM framework, embedded sensing refers to sensors integrated within the structural element during fabrication, rather than sensors retrofitted after construction. The intended measurements are structural condition indicators primarily strain, interlayer crack initiation, and, where applicable, moisture ingress at print-layer interfaces. These data are envisaged to link with the as-printed BIM model through a lightweight digital-twin representation to support condition-based FM decisions. General building-automation IoT applications, including HVAC, lighting, and occupancy monitoring, are outside the scope of the present study. We have also clarified that conventional-building IoT/digital-twin literature cited in the manuscript is used only as benchmark evidence for the potential value of condition-based monitoring and is not presented as measured maintenance performance from 3DCP assets.

2.4 Quantitative parameters and governing equations

To move the framework beyond descriptive tabulation, four quantities are defined here and used consistently in Section 3. Each is a standard, citable formulation from the structural-engineering, sensing, or facility-management literature, populated with the ranges reported in the sources reviewed above.

The anisotropy index (AI) expresses the orientation-dependent strength loss characteristic of 3DCP as a single dimensionless ratio:

$$AI = \sigma(\min) / \sigma(\text{cast}) \quad (1)$$

where $\sigma(\min)$ is the minimum reported strength across print orientations and $\sigma(\text{cast})$ is the equivalent cast-concrete baseline. From Table 1, $AI(\text{compressive}) = 0.59$ and $AI(\text{flexural}) = 0.53$ (Sapata et al., 2025). AI is treated as an orientation-dependent design knockdown rather than a fixed material constant.

The piezoresistive sensitivity of an embedded self-sensing cementitious sensor is expressed by the gage factor (GF), the standard measure used to characterise the sensors reviewed in Section 2.3:

$$GF = (\Delta R / R_0) / \varepsilon \quad (2)$$

where ΔR is the change in resistance, R_0 the unstrained baseline resistance, and ε the applied strain. Wang and Aslani (2023) report $GF = 318$ for the printed-sensor form and 527 for the bulk cast form.

At the asset level, total cost of ownership (TCO) is decomposed following standard FM practice:

$$TCO = C(\text{acq}) + C(\text{inst}) + C(\text{op}) + C(\text{maint}) + C(\text{down}) + C(\text{cons}) + C(\text{comp}) + C(\text{energy}) + C(\text{disp}) - V(\text{resale}) \quad (3)$$

The terms represent acquisition, installation, operation, maintenance, downtime, consumables, compliance, energy, and disposal, net of resale value. Equation (4) gives the discounted lifecycle cost over n years.

$$LCC = I + \sum [C(t) / (1 + r)^t], \text{ for } t = 1 \text{ to } n \quad (4)$$

The standard formulations are used in Section 3.6 to translate literature-reported monitoring effects into a bounded TCO sensitivity.

3. Results

3.1 Quantitative Synthesis

Table 2 synthesises quantitative metrics reported in the reviewed literature against the five LOFM dimensions, contrasting conventional practice with 3DCP or digital-twin-enabled practice. Values are taken from the cited sources.

Table 2: Literature-derived quantitative synthesis of 3DCP and digital-twin/FM performance metrics, organised by LOFM dimension. Values are taken from the cited peer-reviewed, industry, or technical sources, as applicable.

<i>Dimension</i>	<i>Metric</i>	<i>Conventional practice</i>	<i>3DCP / digital-twin-enabled practice</i>	<i>Source</i>
Durability	Compressive strength retention vs. cast concrete, by print orientation	100% (baseline, cast)	59–85%	Sapata et al., 2025
Durability	Flexural strength retention vs. cast concrete	100% (baseline)	53–75%	Sapata et al., 2025
Durability	Splitting tensile strength retention	100% (baseline)	~90%	Sapata et al., 2025
Material efficiency	Construction material waste	3–8% of project cost lost to waste	30–90% reduction in material waste	Cosmos 3D, 2025; Heidelberg Materials, 2026
Programme	Construction time	Baseline	50–70% reduction	Aghajani Delavar et al., 2023
Programme	Labour cost	Baseline	50–80% reduction	Aghajani Delavar et al., 2023
Lifecycle cost	Operations & maintenance share of total cost of ownership	65–80% of TCO	Not yet reported for 3DCP; LOFM targets this share via monitoring	Expansive Solutions, 2026
Digital integration	Maintenance cost, digital-twin/IoT-enabled buildings	Baseline	10–45% reduction	IoT For All, 2026; Matterport, 2025
Digital integration	Unplanned downtime, digital-twin-enabled buildings	Baseline	Up to 45% reduction	IoT For All, 2026; SAMEX EAM, 2026
Digital integration	Embedded piezoresistive gage factor	n/a	318 (printed-sensor form) / 527 (bulk cast form)	Wang and Aslani, 2023

Maintainability is the dimension most directly shaped by 3DCP's layered fabrication process. Because material is deposited by a nozzle following a toolpath rather than poured into a mould, cavities for services and inspection access can be defined at the design stage rather than cut into finished concrete, the basis for the embedded service-corridor and sensor-cavity interventions proposed in the original conference abstract. Industry FM benchmarks indicate that operations and maintenance can constitute a substantial proportion of total cost of 65–80% of an asset's total cost of ownership (Expansive Solutions, 2026). If even a fraction of that load shifts from reactive, invasive repair to planned, corridor-accessed intervention, lifecycle economics improve independently of upfront construction savings.

3.2 Durability

Durability is where 3DCP currently trades efficiency for risk. Table 2's compressive-strength figures, 85% of cast-concrete strength when load runs parallel to the printed layers, falling to 59% when applied perpendicular to the top plane (Sapata et al., 2025) show that anisotropy, formalised as the A_I in Equation (1), is a first-order design constraint. Interlayer zones are also identified as preferential paths for moisture ingress and crack propagation (Nodehi et al., 2022; Sapata et al., 2025). Because these weak zones are geometrically predictable, targeted instrumentation can focus monitoring on the interfaces most relevant to deterioration.

3.3 Accessibility

Maintenance accessibility concerns both physical access for inspection/repair and access to the performance data needed to plan it. Current 3DCP practice already varies in how it handles this: the Shanghai pedestrian bridge was delivered with an embedded real-time monitoring system reporting vibrating-wire stress and strain data from construction onward (ArchDaily, 2018), whereas smaller 3DCP demonstrators, including the security cabin shown in Figure 1, generally represent lower-instrumentation implementations. The LOFM proposes that this instrumentation-for-accessibility decision be made systematically at design stage according to asset criticality and expected service life, rather than being left to whether a project happens to have a research partner willing to install sensors.

3.4 Adaptability

Adaptability, the capacity to reconfigure or extend a structure over its service life, benefits from the same toolpath-level design freedom that enables service corridors. Modular, interlocking wall segments printed with defined joint geometries can, in

principle, be replaced or reconfigured without demolishing adjoining sections, in the same way that topology-optimised 3DCP designs already achieve material savings of up to 50–70% relative to conventional formwork-based sections. No built precedent in the reviewed literature yet demonstrates in-service reconfiguration of a 3DCP wall system; this dimension is a design principle supported by demonstrated geometric flexibility rather than a measured outcome, and is flagged in Section 5 as a priority for future work.

3.5 Digital integration

Digital integration is the dimension for which the clearest quantitative benchmark evidence is available, although that evidence is derived primarily from conventional buildings rather than 3DCP assets. Digital-twin-enabled predictive maintenance in buildings generally is associated with 10–45% reductions in maintenance cost and up to 45% reductions in unplanned downtime, alongside 10–20% extensions in asset service life (IoT For All, 2026; SAMEX EAM, 2026; Matterport, 2025). Embedded piezoresistive cementitious sensors printed directly into structural elements have demonstrated gage factors of 318 in printed-sensor form and 527 in bulk cast form, both capable of detecting crack formation in reinforced concrete beams under flexural loading (Wang and Aslani, 2023). LOFM hypothesizes that pairing this print-integrated sensing with a lightweight digital twin could provide a pathway toward comparable benchmark maintenance benefits while avoiding retrofit sensor-installation costs; this combination has not yet been measured on a completed 3DCP asset and remains the paper's central proposition for future validation. The evidence therefore supports the framework as a testable hypothesis, while the maintenance percentages remain benchmark values from conventional buildings rather than measured 3DCP outcomes and require field validation before adoption.

3.6 Illustrative parametric synthesis

Equations (3)–(4) and the literature ranges in Table 2 provide a bounded parametric estimate of the potential TCO effect of condition-based monitoring; it is not a measured LOFM outcome.

If $C(OM,conv)$ is the conventional operations-and-maintenance cost, LOFM reduces it according to Equation (5).

$$C(OM,LOFM) = C(OM,conv) \times (1 - r(DT)) \quad (5)$$

where $r(DT)$ is the fractional maintenance-cost reduction attributed to digital-twin/IoT monitoring, reported as 0.10–0.45. Using $f(OM)=0.65–0.80$ gives Equation (6).

$$\Delta TCO (\%) = f(OM) \times r(DT) \quad (6)$$

Under the stated assumptions, the lower and upper bounds are $0.65 \times 0.10 = 6.5\%$ and $0.80 \times 0.45 = 36.0\%$, respectively. Thus, the literature-based sensitivity bound is approximately 6.5–36% on total TCO reduction attributable to the assumed reduction in operations-and-maintenance expenditure. It excludes sensor-network cost because no built 3DCP asset provides a measured value. Section 4 therefore tests the interaction of monitoring, access, deterioration, and repair costs using a synthetic lifecycle model.

4. Numerical Simulation Case Study: Monte Carlo Lifecycle Cost Analysis

4.1 Purpose and scope

Section 3.6 derived a literature-based sensitivity bound on LOFM's potential TCO impact (6.5–36%). That bound cannot capture service-life interactions such as continuous versus periodic detection, service-corridor access, and delayed-failure risk. A Monte Carlo model therefore compares LOFM with conventional FM under a common stochastic degradation path. The case is synthetic because field degradation time-series and maintenance-cost datasets for 3DCP are unavailable; literature-derived parameters and modelling assumptions are distinguished in Table 3.

4.2 Degradation, sensing, and decision model

The true (unobserved) interlayer strain at a representative monitored zone is modelled as a drift-diffusion process with superimposed discrete shocks, representing gradual environmental/load cycling plus episodic crack-initiation events at the interlayer interface (Nodehi et al., 2022; Sapata et al., 2025):

$$\varepsilon(t) = a \cdot t + W(t) + \sum J_i \text{ (for shock times } \tau_i \leq t) \quad (7)$$

where a is the assumed drift rate, $W(t)$ is environmental noise, and J_i are exponential jumps at Poisson-distributed times. In the baseline simulation, LOFM is assumed to observe the monitored state continuously and triggers planned intervention at $\varepsilon(\text{crit}, \text{planned})$, subject to the dispatch lag. In the baseline simulation, conventional FM is assumed to observe the state only at five-year inspection dates and triggers reactive repair if $\varepsilon(\text{crit}, \text{failure})$ is crossed between inspections.

4.3 Cost model

Each repair resets the local degradation to zero and incurs a cost with a fixed (mobilisation/access) component and a variable component that scales convexly with the severity of degradation addressed, reflecting the compounding secondary damage (moisture ingress, crack propagation) associated with delayed intervention discussed in Section 3.2:

$$C(\text{repair}) = C(\text{fixed}) + C(\text{var}) \cdot s^p \quad (8)$$

where s is the strain addressed at the time of repair and $p > 1$ is a convexity exponent. Reactive (unplanned) repairs incur an additional emergency-response premium:

$$C(\text{reactive}) = C(\text{repair}) \times r, \quad r \sim \text{Uniform}[3, 5] \quad (9)$$

The premium is sampled from Uniform[3,5]. LOFM uses a lower fixed access cost to represent pre-provisioned service corridors, while conventional repair requires cut-in access. The 2.3× ratio is an explicit sensitivity-tested assumption informed by concrete coring/GPR service costs, not a measured 3DCP repair constant.

For independent verification, the stochastic process is discretized at one-day steps, $\Delta t = 1/365$ year. Brownian increments use $10\sqrt{\Delta t}$ Z microstrain and shock arrivals follow a Poisson process at 0.30 events/year.

The reference implementation specifies $C(\text{var})=0.25$ normalized cost units, annual sensor/platform cost of 0.01 normalized units, and baseline seed 20260808; these are modelling assumptions tested through sensitivity analysis.

Repair severity is normalized as $s = \epsilon/150$, giving:

$$C(\text{repair}) = C(\text{fixed}) + 0.25 \cdot s^p$$

The five-day LOFM dispatch lag is represented explicitly: when observed strain crosses the planned-intervention threshold, intervention is scheduled and the local state is reset after five simulated days unless the latent state reaches the failure threshold first, in which case a reactive event is recorded.

Parameters are classified as (i) literature-informed or physically motivated bounds, and (ii) explicit modelling assumptions required to make the synthetic case computationally complete. No parameter is presented as a field-calibrated 3DCP maintenance constant unless supported by the cited literature. The normalized cost coefficients are modelling assumptions and are therefore interpreted through sensitivity analysis rather than as measured economic quantities.

4.4 Simulation design and parameterisation

Table 3 lists all parameters used. Each replicate draws one realisation of Equation (7) and evaluates both maintenance strategies against the same realisation (common random numbers), so the comparison isolates the effect of strategy rather than random differences between draws.

Table 3: Simulation parameters for the stochastic lifecycle model. Literature-derived/literature-informed quantities are distinguished from explicit modelling assumptions. The reference implementation adds a daily time step, $C(\text{var})$, and a fixed random seed so that the baseline audit is reproducible.

<i>Parameter</i>	<i>Value</i>	<i>Basis</i>
Anisotropy index, AI (compressive)	0.59	Literature — Sapata et al., 2025
Gage factor, GF (printed sensor)	318	Literature — Wang and Aslani, 2023
Service-life horizon	25 years	Literature-informed — ISO 15686-5 medium-design-life category
Degradation drift rate, a	15 microstrain/yr	Explicit modelling assumption; no 3DCP-specific longitudinal dataset available
Environmental noise (annual s.d.)	10 microstrain	Explicit modelling assumption; no 3DCP-specific longitudinal dataset available
Shock (crack-jump) rate	0.30 events/yr	Explicit modelling assumption; no 3DCP-specific longitudinal dataset available
Shock magnitude (mean)	50 microstrain	Explicit modelling assumption; no 3DCP-specific longitudinal dataset available
Planned-intervention threshold	150 microstrain	Literature-informed modelling threshold; adopted as a representative first-crack-scale strain rather than a validated 3DCP intervention threshold (~79–200 microstrain; USPTO 11,325,863; USPTO 9,440,881)
Failure threshold	450 microstrain	Representative modelling threshold bounded by reported concrete strain-development ranges; not a validated 3DCP failure threshold.
Sensor measurement noise	3 microstrain (absolute)	Literature — $\pm 0.1\%$ FS on 3000-microstrain range, ST4 embedment gauge (Sensel Measurement, 2026)
LOFM detection/dispatch lag	5 days	Assumed; no published SLA benchmark
Conventional inspection interval	5 years	Literature — IIBEC/ASTM E2270 recommended facade-inspection interval (IIBEC, 2025)

Reactive : planned cost premium	Uniform[3, 5]×	Literature — eWorkOrders, 2026 (U.S. DoE)
Fixed repair cost — LOFM (corridor access)	0.15 (normalized)	Assumed baseline; ratio to conventional informed by coring-service cost data
Fixed repair cost — conventional (cut-in access)	0.35 (normalized)	Literature-informed ratio (~2.3×) — concrete coring/GPR-scan minimum service charge (naijaconstruct.com, 2026)
Variable-cost convexity exponent, p	1.5	Assumed modelling choice; qualitatively consistent with eWorkOrders, 2026
Annualised sensor/platform cost	0.01/yr (0.25 over horizon)	Assumed; order-of-magnitude bounded by SHM upfront-cost literature (Encardio, 2024)
Monte Carlo replicates	5,000 (paired, common random numbers)	—
Simulation time step	1 day ($\Delta t = 1/365$ yr)	Reference implementation
Variable repair-cost coefficient, C(var)	0.25 normalized	Explicitly specified for reproducibility
Baseline random-number seed	20260808	Reference implementation

The reference implementation used 5,000 paired Monte Carlo replicates with the same stochastic degradation realization for both strategies. Mean normalized 25-year lifecycle cost was 2.19 for LOFM and 3.19 for conventional FM, giving a 31.3% ratio-of-means saving (95% bootstrap CI: 30.2–32.3%).

The 2.5th–97.5th percentile range of simulated lifecycle cost was 1.18–3.51 for LOFM and 1.40–10.03 for conventional FM. The conventional strategy retains a pronounced right tail because delayed detection can produce reactive repairs with a 3–5× emergency premium. The simulated incidence of at least one unplanned reactive event was 10.24% for conventional FM and 0.52% for LOFM. LOFM generated 4.10 planned interventions per replicate on average, compared with 2.76 planned conventional interventions.

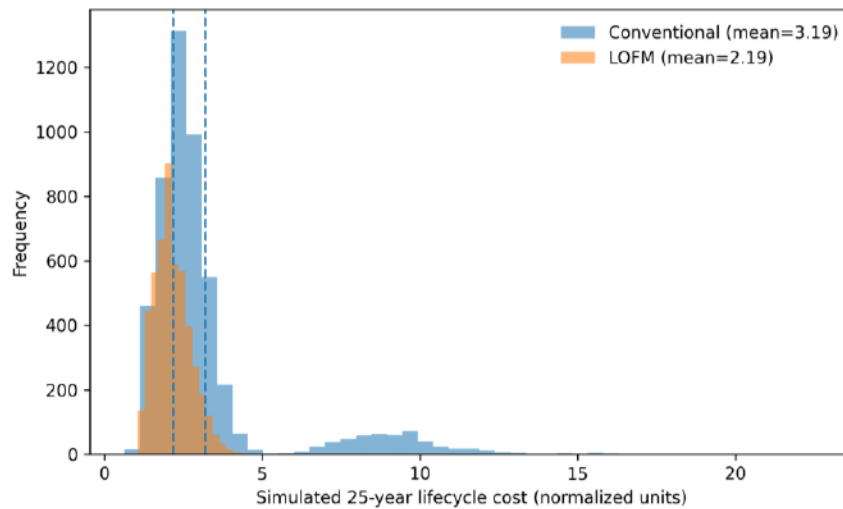


Figure 2. Independent-audit lifecycle-cost distributions from the fully specified reference implementation.

Figure 3 shows a representative daily-step realization. LOFM detects the planned-intervention threshold continuously and schedules intervention, whereas conventional FM is constrained to five-year inspection dates and can accumulate greater degradation before intervention.

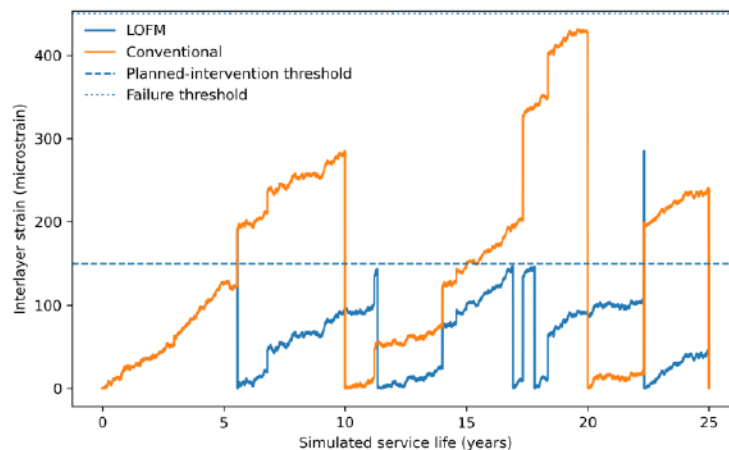


Figure 3. Representative daily-step degradation path generated by the independent reference implementation.

The results in Sections 4.5–4.6 are outputs of the synthetic stochastic model described in Section 4.4. They are not measurements from an operating 3DCP facility and should not be interpreted as empirical maintenance-cost savings.

4.5 Baseline results

The 5,000 paired Monte Carlo simulations produced a mean normalized 25-year lifecycle cost of 2.19 for LOFM versus 3.19 for conventional FM, representing a 31.3% simulated cost reduction (95% bootstrap CI: 30.2–32.3%). LOFM also reduced the simulated probability of at least one unplanned reactive repair from 10.24% to 0.52%.

Although LOFM resulted in more planned interventions on average (4.10 vs. 2.76), earlier detection and lower access costs reduced the likelihood and severity of reactive repairs. These results are scenario-based model outputs, not field-validated measurements, and depend on the assumptions specified in Table 3.

4.6 Sensitivity and uncertainty analysis

Sensitivity analysis was repeated using 1,500 replicates per scenario. Six assumptions were varied individually while holding the remaining parameters at baseline values.

Table 4. Sensitivity of the independently audited lifecycle-cost saving to uncertain model assumptions.

<i>Scenario</i>	<i>LOFM saving (%)</i>	<i>95% bootstrap CI</i>	<i>Interpretation</i>
0.5× degradation drift	26.5	24.2–28.6	Saving remains positive
2× degradation drift	37.5	36.0–38.8	Saving increases under faster deterioration
No convexity ($p=1$)	18.9	17.3–20.6	Convex repair-cost escalation is important
No corridor-access advantage	5.0	2.4–7.8	Physical maintainability is a major contributor
5× sensor/platform cost	–2.0	–5.1–1.0	Advantage becomes indistinguishable from zero
Reactive premium 3–9×	30.5	28.5–32.3	Conclusion remains positive

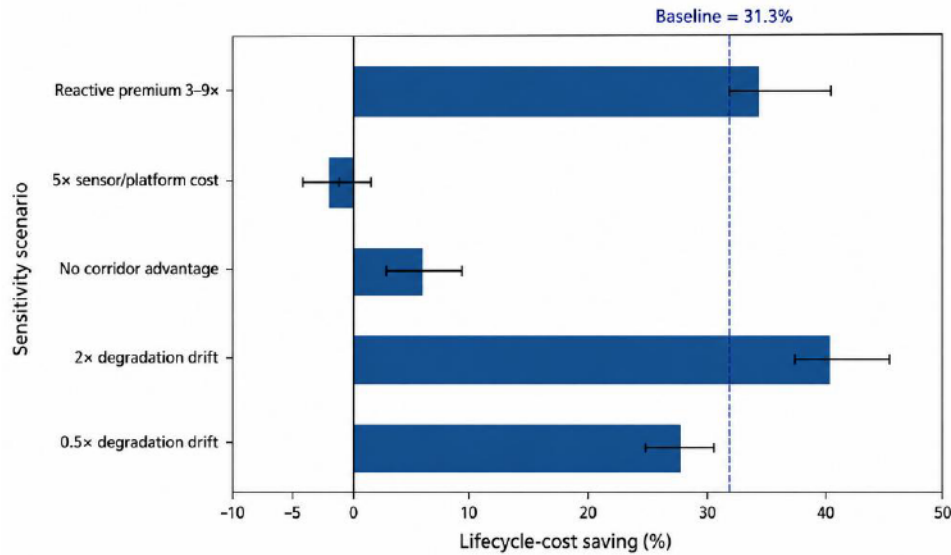


Figure 4. Independent-audit sensitivity analysis; error bars are 95% bootstrap confidence intervals.

The strongest stress case is five-fold sensor/platform cost: mean saving falls to –2.0% and the confidence interval crosses zero. The sensitivity analysis indicates that the economic case for LOFM depends strongly on the physical-access advantage created at the design stage; when this advantage is removed, the simulated lifecycle-cost saving decreases from 31.3% to 5.0%. Doubling or halving deterioration drift leaves saving positive, indicating greater sensitivity to sensing and access economics than to deterioration-rate uncertainty.

Sensor/platform cost is therefore the key economic variable tested. The five-fold cost case moves mean saving to –2.0%, with a confidence interval crossing zero. Because costs are normalized and uncalibrated, the study reports this stress condition rather than a universal currency break-even value.

The sensitivity analysis tests whether the primary comparison remains directionally robust under the most consequential modelling assumptions.

The economic break-even condition is defined as:

$$LCC_LOFM = LCC_conventional$$

LOFM is economically preferable when $\Delta LCC = 1 - (LCC_LOFM/LCC_conventional) > 0$. Because costs are normalized, this is a dimensionless break-even criterion rather than a currency threshold.

4.7 Limitations of the simulation

The simulation is a synthetic case study, not an empirical prediction. Degradation, shock rate, thresholds, repair-cost structure, sensor cost, and access differential are

assumptions or literature-informed bounds because no longitudinal 3DCP maintenance-cost dataset is available. The implementation is algorithmically specified, including daily discretization, dispatch lag, common-random-number pairing, seed, and bootstrap procedure, but remains uncalibrated to a real asset. Costs are normalized, so only relative strategy comparison is meaningful.

The drift-diffusion plus Poisson-shock model is a functional, unvalidated representation of interlayer deterioration chosen to reflect the mechanisms discussed in Section 3.2 rather than fitted to field data. Field instrumentation of a real 3DCP structure is the priority next step for replacing these assumptions with measured degradation and maintenance time series.

5. Discussion

5.1 What LOFM adds beyond BIM, SHM and digital-twin approaches

The BIM, structural health monitoring (SHM), and digital twins provide asset information, condition observations, and lifecycle data connections, respectively, but do not by themselves define a facility-management strategy for 3DCP. LOFM adds the decision layer: maintenance access, intervention pathways, replaceability, durability vulnerabilities, and digital handover are specified at design stage.

The literature synthesis and simulation support a bounded claim, not a general assertion that 3DCP is inherently more maintainable. The 31.3% simulated saving is conditional on the stated assumptions. Sensitivity analysis identifies sensor/platform cost and physical accessibility as priorities for future pilot measurement.

Field evidence should therefore be interpreted as feasibility evidence rather than lifecycle validation. For example, the reviewed Shanghai 3DCP pedestrian bridge demonstrates embedded real-time stress/strain monitoring, while smaller demonstrators such as the IIT Bombay security cabin illustrate the contrasting case of 3DCP assets delivered without equivalent instrumentation. This contrast supports the need for an explicit design-stage decision on monitoring and FM accessibility, but it does not provide the longitudinal maintenance-cost data required to calibrate the present model.

Key limitations are the targeted rather than exhaustive review, use of built precedents as feasibility evidence, and an uncalibrated stochastic deterioration and cost model. The numerical results should guide field-validation design rather than be interpreted as realized FM savings.

LOFM is best treated as a design brief and quantified hypothesis for instrumented 3DCP pilot projects. A longitudinal study of an instrumented bridge or cabin-scale demonstrator should measure sensor costs, degradation, interventions, and access costs against a conventional comparator.

The principal contribution of LOFM is therefore not the prediction of a universal lifecycle-cost saving, but the provision of a structured decision mechanism through which asset-specific monitoring, access, deterioration and intervention assumptions can be tested before construction.

6. Conclusion

The proposed LOFM framework provides a practical pathway for translating 3DCP characteristics into facility-management decisions. It takes key inputs related to 3DCP condition, FM characteristics, monitoring systems, and asset information and evaluates them through a lifecycle decision model covering deterioration, detection, intervention, repair, and cost. The resulting outputs—lifecycle cost, probability of reactive repair, planned interventions, downtime, and sensitivity to key parameters—support comparison between LOFM and conventional FM. When $\Delta LCC > 0$, LOFM is economically favourable and can guide the selection of monitoring, access, inspection, maintenance, and digital handover strategies. When $\Delta LCC \leq 0$, the assumptions or LOFM provisions should be reassessed and the model re-evaluated. Overall, the framework demonstrates how FM considerations can be incorporated into the design and printing stages of 3DCP, supporting more informed and lifecycle-oriented construction decisions as shown in Figure 5.

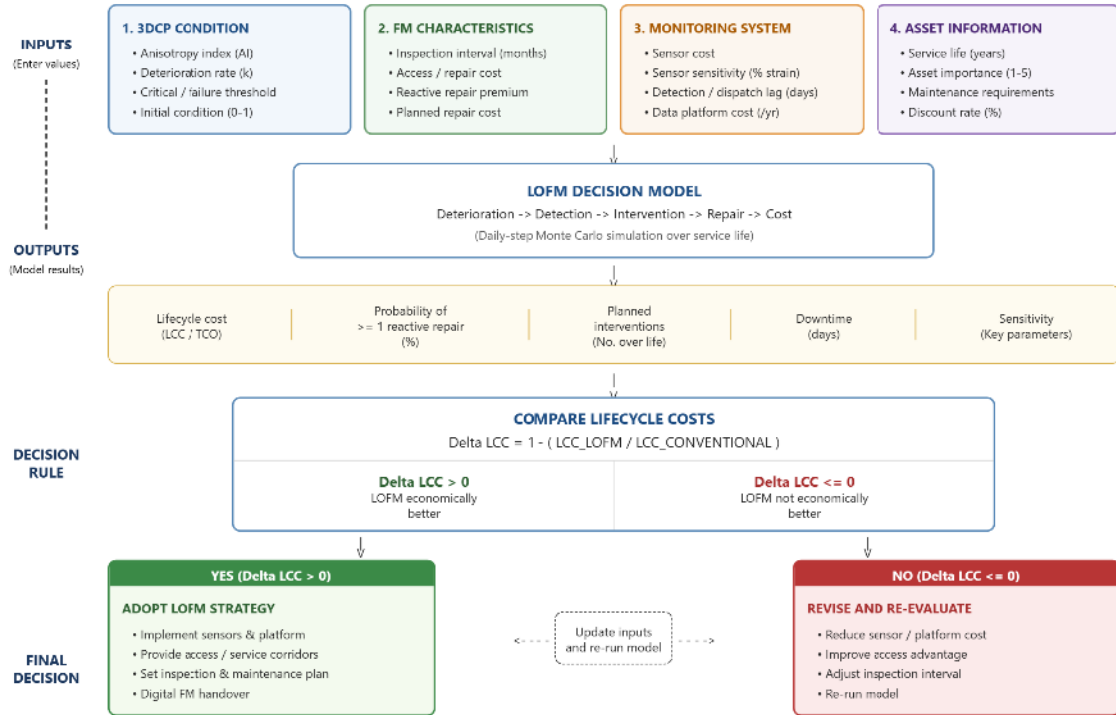


Figure 5. LOFM-based decision framework for lifecycle facility management of 3D-printed concrete structures.

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