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Preface of the publisher

29th Journal für Facility Management: Science meets Practice

AI changes dramatically the way we do research and publish it. Also economic and social challenges change the way we work and live. Therefore, I am more than happy that the scientific community but also the editorial board and the reviewers support our journal over all these years. This community stands together and is convinced of the importance of a scientific journal for real estate and facility management based on high class international research and following strict rules for scientific quality assurance.

It was not always easy, a lot of hard work and sleepless nights, but the results prove that this is worth the efforts and that a high standards journal is needed by researchers but also by practitioners. For me especially the bridging of science and practise is important. Science develops great ideas, new methodologies and approaches. But they only come to life due to exchange with practice. When these ideas are known to practice, when they are taken up and used, then we develop innovation. Especially in times of change, solid, validated approaches are important. I know that several papers presented in this journal were taken up by industry and led to innovative user-centric services and products. This makes me very proud and fulfils the slogan “Science meets Practice” at its core.

I know this issue of the journal has some great insights and ideas for innovation. The papers cover topics from sustainability and life cycle management to urban facility management (FM) and the usage of AI to generate digital twins:

- Systematic Integration of ESG Criteria into Infrastructural Facility Management – Development of an Evaluation Framework
- A Lifecycle-Oriented Framework for Facility Management in 3D Concrete Printed Infrastructure
- Monitoring Urban Conditions through Computer Vision – New Possibilities for Data-driven Urban FM?

Sustainability and life cycle management are increasingly important in FM, especially due to international ESG legislation. The first paper focuses on the social dimension of sustainability, which is especially important in infrastructural FM while coordinating external service providers. The aim of this paper is to develop a standardized evaluation framework for the use of corporate and facility service providers based on recognized Global Reporting Initiative (GRI) framework. Therefore, the existing gefma ESG-KPI tool is extended to include weighted social criteria. The developed model is validated using data from real university buildings. The developed framework supports the structured collection and evaluation of operational sustainability information that can contribute to ESG reporting processes.

The second paper deals with the 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. A structured literature review combines ISO 41001 and EN 15221 with research on 3DCP durability, sensing, design and application as a digital twin while identifying five LOFM dimensions. These dimensions are translated into a quantitative framework for decision-making

that covers 3DCP condition, FM requirements, monitoring systems, deterioration, intervention, repair and lifecycle cost. The framework provides a practical pathway for translating 3DCP characteristics into decisions on access, inspection, monitoring, maintenance, digital handover and lifecycle cost.

The third paper explores how computer vision can transform urban condition monitoring through the analysis of street-level imagery and positions these methods as a technical foundation for dynamic digital twins. The study highlights data-driven methods – particularly image segmentation and deep learning models such as DeepLabv3+ – used to assess indicators such as greenery, cleanliness, or accessibility. The findings demonstrate computer vision's potential to generate high-frequency data that can feed dynamic digital twins, enabling continuous monitoring and immediate response strategies. Integrating these techniques into Urban FM supports more data-driven decision-making and adaptive management of the built environment.

At this point, I would like to express my sincere gratitude to all international researchers who submitted abstracts and papers for the double-blind peer-review process, with particular appreciation for our new colleagues from India, whose contributions enriched the submission process. More than 50% of the submissions were declined, reflecting the selectivity of the review process.

I would also like to thank the members of the Editorial Board and the Scientific Board for their valuable contributions, and dedicated work. They supported me throughout the review process, from the initial assessment of abstracts to the evaluation of full papers and provided authors with constructive feedback to support the further development of their work.

The selectivity of the review process, the expertise of the members of the Editorial and Scientific Boards, and the support of the participating universities contribute to maintaining the journal's scientific standards while fostering the practical relevance of its contributions. Our aim is to publish research that meets academic expectations and offers insights that practitioners can apply in their professional contexts.

My sincere thanks also go to my team, particularly Barbara Gurdet and Elisabeth Morillo-Napetschnig. Their personal commitment and dedicated work are essential to maintaining the journal's quality.

From Vienna, I wish you an enjoyable and insightful read, and I hope that the contributions in this issue will provide valuable perspectives for your research and professional practice.

I look forward to receiving further thought-provoking research for the next issue of the IFM Journal and to continuing our stimulating exchange at the 20th IFM Congress in 2027.

Grammar optimized with AI

Your

Alexander Redlein

Head of Editorial Board

To my family Barbara, Caroline Sidonie und Alexander David

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Science meets Practice: Sustainability & Lifecycle Management

Systematic Integration of ESG Criteria into Infrastructural Facility Management – Development of an Evaluation Framework

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Abstract:

Sustainability is increasingly important in facility management (FM). With a rising focus on Environmental, Social and Governance (ESG) regulatory requirements - especially EU Taxonomy, Corporate Sustainability Reporting Directive (CSRD), and associated European Sustainability Reporting Standards (ESRS) - companies must address sustainability both strategically and operationally in building operations. While existing ESG tools for monitoring building performance and collecting relevant KPIs focus on technical building management, the social dimension of sustainability, which is especially important in infrastructural FM while coordinating external service providers, remains underrepresented. The aim of this paper is to evaluate the relevance of ESG criteria for infrastructural FM and to develop a standardized evaluation framework for use by corporates and facility service providers. First, relevant ESG criteria for controlling, monitoring, and reporting sustainability in infrastructural FM are derived from the internationally recognized Global Reporting Initiative (GRI) framework. Next, the existing gefma ESG-KPI tool is extended to include these criteria by mapping ESG criteria to GRI categories. The criteria are moreover weighted using a scoring tool that rates them from “not fulfilled” to “best practice”. The developed model is validated using data from real university buildings and demonstrates that transparent measures to improve ESG performance can be systematically identified and implemented. The model can be used in any role, such as property management, FM, and FM service providers, enabling application across the various responsibilities within the context of ESG. The developed framework supports the structured collection and evaluation of operational sustainability information that can contribute to ESG reporting processes.

Keywords:

ESG integration, infrastructural facility management, KPI framework, GRI standards, sustainability reporting

1. Introduction

While sustainability is increasingly important in facility management (FM) (Jensen et al., 2024) and environmental, social, and governance (ESG) aspects become more important to FM, standardized approaches for integrating ESG criteria into operational FM processes are still underdeveloped (Santana Tovar et al., 2025). International guidelines and recent research suggest that formal evaluation and implementation models are required, particularly for practical use (International Facility Management Association, 2017; Jensen et al., 2024). Furthermore, regulatory requirements, such as the Corporate Sustainability Reporting Directive (CSRD) and the EU Taxonomy, require organizations to address sustainability both strategically and operationally in daily building operations (Gefma, 2023).

FM ensures the built environment functions through multidisciplinary technical, commercial, and infrastructural services (International Facility Management Association, 2017). Infrastructural FM (IFM) refers to service-oriented activities that support the daily operation and use of buildings, such as cleaning, security, catering, and waste management. (Wills and Díaz, 2022). Besides the economic importance of IFM, standardized procedures for the systematic capture and integration of ESG criteria into FM are missing and are mainly driven by client expectations (Ramantswana et al., 2026). Existing approaches predominantly address technical and energy-related aspects, while IFM services remain insufficiently considered (Nielsen et al., 2016; Okoro, 2023; Opoku and Lee, 2022). In particular, a practice-oriented framework is lacking for identifying and structuring relevant ESG criteria and integrating them into IFM operational processes (Michalski, 2024). As a result, potential improvements in ecological, social, and governance-related performance remain largely underutilized.

This paper aims to systematically integrate ESG criteria into IFM. Therefore, relevant ESG criteria for IFM services are identified, and a functional evaluation grid is derived on this basis. The existing GEFMA ESG-KPI tool, which primarily addresses ESG at building and portfolio level, is extended through GRI mapping and a five-point scoring logic tailored to outsourced, labor-intensive IFM services. The approach therefore operationalizes an established practitioner tool rather than creating a new assessment philosophy. The resulting framework is role-neutral and can be applied

by property managers, FM departments, and service providers alike, providing a shared evaluation language.

The paper is organized as follows: Section 2 outlines the theoretical background on ESG in the real estate and FM context, the relevant regulatory framework, the role of IFM, and the GRI standards as a reference framework for ESG reporting. Section 3 describes the methodological development of the evaluation framework, including the selection of criteria, the mapping to GRI standards, and the scoring logic. Section 4 applies the framework to an empirical case study at a public building. Section 5 discusses the results, the contribution of the framework, and its limitations. The paper concludes with a summary and an outlook on potential future research directions.

2. Theoretical background

ESG assesses sustainability performance across environmental, social, and governance dimensions, including resource use, working conditions, and organizational accountability (Helmold et al., 2024). As facility managers play a key role in the daily delivery of facility services, FM directly influences the ESG performance of an organization. While environmental aspects have traditionally dominated sustainability initiatives, increasing attention is being brought to social and governance issues that arise from operational service delivery and outsourced facility services (Jensen et al., 2024).

The growing relevance of ESG is reinforced by European regulations such as the CSRD and the EU Taxonomy, which require structured sustainability reporting (Kirchhoff et al., 2024). The EU Omnibus Simplification Package aims to simplify sustainability reporting, due diligence requirements, and reduce administrative burdens (EU Commission, 2025). Despite evolving regulations, structured ESG assessments remain relevant for IFM operations.

FM covers technical, commercial, and infrastructural services that support building operations and core organizational processes (Hirschner et al., 2018). Existing ESG assessment approaches primarily focus on technical FM, particularly on energy efficiency, emissions, and building performance. In contrast, infrastructural FM (IFM) includes service-oriented activities such as cleaning, security, catering, waste

management, and outdoor maintenance (GEFMA e.V. Deutscher Verband für Facility Management, 2004).

As IFM services are often outsourced, occupational health and safety, working conditions, supplier management, and compliance are key sustainability aspects (Hirschner et al., 2018; Kaiser et al., 2025).

Despite the growing importance of sustainability in IFM, existing assessment approaches remain fragmented and predominantly address individual service areas rather than IFM as an integrated management domain. In cleaning services, current approaches primarily focus on life cycle assessment (LCA) or hygiene monitoring (Fontana, 2024; Fontana, 2026). Research on catering mainly addresses environmental impacts, food waste, and sustainable procurement (Huang, 2025; Takacs and Borrion, 2020). Studies on gardening and outdoor maintenance focus on ecosystem services, life cycle thinking, and multi-criteria decision analysis (Jato-Espino et al., 2023; Romanovska et al., 2023). Thus, standardized assessment frameworks that systematically integrate ESG aspects across the full spectrum of IFM services are missing.

To facilitate the transfer of the framework to the ESRS context, the identified GRI Standards were additionally related to the corresponding ESRS topics. This mapping is intended for orientation only and does not represent a formal ESRS compliance assessment. The GRI Standards are sustainability reporting standards that provide a structured framework for ESG reporting (Global Reporting Initiative, 2021). For IFM, the most relevant standards relate to energy, emissions, and waste (GRI 302, 305, 306), occupational health and safety, and employment (GRI 401, 403, 404), as well as supplier assessment, anti-corruption, and compliance (GRI 205, 308, 414, 419). These standards form the basis for selecting and structuring the ESG criteria developed in this paper. The GRI Standards were selected as the primary reference framework because they provide an established structure for identifying and categorizing sustainability impacts relevant to the operational delivery of IFM services. The ESRS, in contrast, provide the European regulatory framework for sustainability reporting under the CSRD. To establish a link to this regulatory context, the identified GRI-based criteria were mapped to corresponding ESRS topics (Table

1). This mapping is indicative and does not establish equivalence between individual GRI disclosures and ESRS data points or demonstrate full ESRS compliance.

Table 1: Relevant GRI standards IFM (own representation, based on GRI, 2021)

<i>ESG Criterion</i>	<i>Relevant GRI Standards</i>	<i>ESRS Criterion</i>
E–Resources and emissions	GRI 302, GRI 303, GRI 305, GRI 306	E1
S–Occupational safety	GRI 403	S1
S–Working conditions	GRI 401, GRI 404	S1, S2
G–Supply-chain control	GRI 308, GRI 414	S2
G–Compliance	GRI 205, GRI 419; GRI 2	G1

The framework does not cover all ESRS disclosure requirements or data points. It focuses on sustainability criteria that are relevant and operationally assessable within the six IFM service areas; therefore, additional ESRS-specific requirements may need to be addressed separately when using the framework to support regulatory reporting.

Despite its international recognition, the application of GRI in the building sector has limitations, as not all sector-specific aspects are covered and practical interpretation may vary (Kaiser et al., 2025; May et al., 2022). Moreover, the risk of greenwashing highlights the need to ensure that ESG measures result in measurable improvements rather than mere formal compliance.

3. Development of the ESG evaluation framework

The ESG evaluation framework is developed in three steps, as shown in Figure 1.

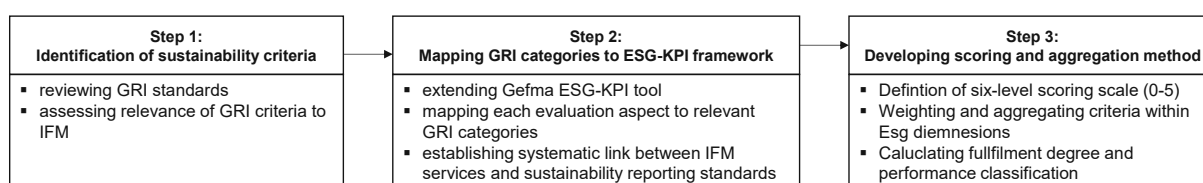


Figure 1: Process of framework development (own representation, 2026).

First, relevant sustainability criteria were identified based on the GRI standards. Second, these criteria were integrated into the existing GEFMA ESG-KPI tool and

linked to relevant GRI categories. Third, a standardized scoring and aggregation methodology was developed to evaluate ESG performance across IFM service areas.

The framework follows a hierarchical structure, translating overarching ESG dimensions into specific evaluation criteria for individual IFM service areas (Table 2).

The evaluation criteria were selected according to the following principles:

1. relevance to sustainability-oriented IFM and
2. empirical measurability based on available operational proof.

Criteria were included only if they could be meaningfully assessed through documented processes, operational practices, or measurable indicators. Less relevant or non-evaluable aspects were excluded or consolidated. The environmental dimension focuses on resource consumption, including chemicals, machinery, and operational products. The social dimension addresses human and organizational aspects of IFM service delivery, including subcontractor management. The governance dimension covers compliance, documentation, transparency, control mechanisms, and supplier management.

To translate general sustainability requirements into measurable operational indicators, the identified ESG criteria were assigned to the relevant IFM service areas.

The framework considers six major IFM service areas:

- security and reception services,
- catering services,
- waste and disposal management,
- outdoor and green-space maintenance,
- winter and caretaker services, and
- cleaning services.

This operationalization ensures that sustainability performance is assessed not at an abstract organizational level but at the level of individual FM processes and responsibilities. Consequently, each criterion can be evaluated based on service-specific evidence and operational practices.

To ensure compatibility with established sustainability reporting practices, the operationalized ESG criteria were mapped to relevant GRI Standards. The mapping

establishes traceability between operational FM activities and internationally recognized sustainability disclosure categories.

The mapping used a content-based approach. Each evaluation criterion was assigned to the GRI Standards that best represent the sustainability impact addressed. Where individual IFM activities influence multiple sustainability dimensions, multiple GRI references were applied. For example, mobility within security and reception services was linked to GRI 302 (Energy) due to fuel and energy consumption and to GRI 305 (Emissions) due to associated greenhouse gas emissions. The use of cleaning products was linked to GRI 301 (Materials) and GRI 306 (Waste), reflecting resource consumption and disposal impacts. Occupational safety criteria across all IFM services were mapped to GRI 403 (Occupational Health and Safety). Supplier-related governance aspects were connected to GRI 308 (Supplier Environmental Assessment) and GRI 414 (Supplier Social Assessment), reflecting the relevance of subcontractor management in IFM service provision. Governance-related criteria, including compliance, documentation, transparency, and subcontractor management, were primarily linked to GRI 2 (General Disclosures), GRI 308 (Supplier Environmental Assessment), and GRI 414 (Supplier Social Assessment). Documentation was explicitly considered as a governance criterion because the availability of verifiable records, procedures, and monitoring mechanisms is essential for demonstrating the implementation and traceability of sustainability practices in operational FM. The evaluation criteria developed in this study are operational indicators designed to assess the implementation and documentation of sustainability practices in IFM services. They are not intended to replace ESRS disclosure requirements or their associated data points. The GRI mapping provides a first orientation for connecting operational evidence to sustainability reporting topics, while a detailed alignment with applicable ESRS disclosure requirements remains a task for future development.

Table 2 presents the mapping between IFM service areas, ESG criteria, and relevant GRI Standards.

Table 2: Operationalization of ESG criteria for IFM service areas and mapping to GRI Standards (own representation, 2026).

<i>IFM service area</i>	<i>ESG dimension</i>	<i>(ESG)-Evaluation criterion</i>	<i>Relevant GRI Standards</i>
Security and reception	Environmental	Mobility	GRI 302 Energy; GRI 305 Emissions
	Social	Occupational safety	GRI 403 Occupational Health and Safety
	Social	Qualifications	GRI 404 Training and Education
	Social	Working conditions	GRI 401 Employment
	Governance	Compliance & Transparency	GRI 2 General Disclosures
	Governance	Documentation	GRI 2 General Disclosures
Catering	Environmental	Food origin	GRI 204 Procurement Practices; GRI 308 Supplier Environmental Assessment
	Environmental	Waste management	GRI 306 Waste
	Social	Occupational safety	GRI 403 Occupational Health and Safety
	Social	Employee qualification	GRI 404 Training and Education
	Social	Nutritional diversity	GRI 416 Customer Health and Safety
	Governance	Hygiene management	GRI 416 Customer Health and Safety
	Governance	Supply-chain transparency	GRI 308 Supplier Environmental Assessment; GRI 414 Supplier Social Assessment
	Governance	Reporting	GRI 2 General Disclosures
Waste and disposal management	Environmental	Recycling rate	GRI 306 Waste
	Environmental	Hazardous-substance management	GRI 306 Waste

	Environmental	Waste management	GRI 306 Waste
	Social	Occupational safety	GRI 403 Occupational Health and Safety
	Social	User information	GRI 306 Waste
	Governance	Documentation	GRI 2 General Disclosures
	Governance	Compliance	GRI 2 General Disclosures
Outdoor and green-space maintenance	Environmental	Biodiversity	GRI 304 Biodiversity
	Environmental	Chemical use	GRI 301 Materials; GRI 306 Waste
	Environmental	Machinery use	GRI 302 Energy
	Social	Occupation safety	GRI 403 Occupational Health and Safety
	Governance	Documentation	GRI 2 General Disclosures
	Governance	Compliance	GRI 2 General Disclosures
Winter and caretaker	Environmental	De-icing and cleaning materials	GRI 301 Materials
	Environmental	Material efficiency	GRI 301 Materials
	Environmental	Resource efficiency	GRI 302 Energy; GRI 303 Water and Effluents
	Social	Occupation safety	GRI 403 Occupational Health and Safety
	Social	Working conditions	GRI 401 Employment; GRI 403 Occupational Health and Safety
	Governance	Documentation	GRI 2 General Disclosures
	Governance	Liability management	GRI 2 General Disclosures
Cleaning	Environmental	Cleaning products	GRI 301 Materials; GRI 306 Waste
	Environmental	Resource intensity	GRI 302 Energy

	Environmental	Emission impacts	GRI 305 Emissions
	Social	Working conditions	GRI 401 Employment; GRI 403 Occupational Health and Safety
	Social	Qualifications	GRI 404 Training and Education
	Governance	Documentation	GRI 2 General Disclosures
	Governance	Compliance	GRI 2 General Disclosures
	Governance	Subcontractor management	GRI 308 Supplier Environmental Assessment; GRI 414 Supplier Social Assessment

The integration of GRI references differentiates the developed framework from generic sustainability assessment approaches by linking operational FM practices with established sustainability reporting structures. However, the mapping does not imply direct compliance with regulatory reporting frameworks such as CSRD or the European Sustainability Reporting Standards (ESRS). Instead, it provides a structured foundation for improving the traceability and potential reuse of operational FM information within sustainability reporting processes.

The evaluation framework uses a six-point ordinal rating scale ranging from 0 to 5. Points are assigned based on the quality, completeness, and verifiability of the available documentation. A score of 0 indicates a lack of documentation or non-fulfillment. Scores between 1 and 2 indicate limited implementation, in which intentions regarding sustainability are present, but operational evidence remains insufficient. A rating of 3 indicates measures that have been implemented with partial documentation. Ratings of 4 and 5 indicate advanced stages of implementation characterized by documented processes, measurable results, and established control mechanisms. Table 3 shows the scoring scale.

Table 3: Scoring scale for the evaluation of ESG criteria (own representation, 2026).

Score	Meaning	Rationale
0	Not fulfilled	No evidence or corresponding information available

1	Insufficient	Criterion mentioned only as general intention
2	Partially fulfilled	Initial approaches identifiable, limited operational evidence
3	Fulfilled	Measures implemented, but documentation remains incomplete
4	Above average	Clearly documented processes, responsibilities, or measurable data available
5	Best practice	Comprehensive documentation, measurable outcomes, and established governance structures

The evaluation approach follows the principle: higher scores require not only the existence of sustainability measures but also their active implementation, documentation, and verifiability.

For aggregation, the individual scores are first combined within each ESG dimension, resulting in separate values for the ESG performance. These dimension-specific values are compared to a predefined target value, which represents the expected performance level when all criteria are met and is rated as a 4. A target value of 4 represents advanced implementation without assuming maximum maturity for all criteria. The overall degree of fulfillment is calculated as the ratio of achieved scores to target scores, as shown on the following form.

$$\text{Degree of fulfillment} = \frac{\sum \text{achieved scores}}{\sum \text{target scores}} * 100$$

To account for realistic limitations of operational sustainability implementation and avoid interpreting maximum maturity as a universal expectation, the framework applies the following performance classification:

- ≥80%: very good performance,
- 60–79%: good performance,
- 40–59%: potential for improvement identified,
- <40%: critical area requiring priority action.

The classification represents a maturity-oriented benchmarking approach rather than an absolute sustainability assessment. It is intended to identify strengths, improvement opportunities, and governance priorities.

4. Results

The evaluation of the developed tool is conducted through a case study of buildings owned by a public-sector institution in Hesse, Germany. For confidentiality reasons, the case study organization is anonymized. The empirical data basis consists of the following sources:

- (i) a structured interview with the head of the FM department, addressing all six investigated IFM service areas; conducted on 23rd April 2026, 11:30-13:00
- (ii) sustainability-related information reported in the sustainability report (2022–2023) of the organization
- (iii) energy and resource consumption data from the energy and resource report, covering the period 2014–2024
- (iv) publicly available information on sustainable mobility measures published by the organization.

Environmental Dimension

In security and reception services, mobility was rated 3, reflecting that employee arrivals are dominated by car and public transport, added by active cycling-promotion measures (e.g. bicycle service stations) and a bicycle-friendly-employer certification. A mobility concept is still under development and mobility is not organizationally anchored within FM. In catering, food origin was rated 1 and waste management 2: sustainability criteria are applied selectively, but a systematic regional or organic procurement is missing. Waste and disposal management scored rather strongly: recycling rate 3, hazardous-substance management 5 (fully organized storage, labeling, digital recording and training), and general waste management 4 (separation systems in place, though user information gaps remain). In outdoor and green-space maintenance, biodiversity scored 4 (green roofs, planted areas and land-use projects already implemented), while chemical use and machinery use both scored 0 due to a lack of available data, and tree care scored 3 (managed via a tree cadaster, though details for externally contracted work remain unclear). In winter and caretaker services,

de-icing/cleaning scored 3, material efficiency 2 (limited steering capacity due to external service delivery), and resource efficiency 4, reflecting extensive energy-efficiency measures at the Friedberg site (hydraulic balancing of heating systems, valve replacement, intelligent control systems). Cleaning services scored consistently high, with ecological products (5), reduced resource intensity through lower cleaning frequency (4, approx. 30% savings) and moderate emission impact (3). Table 4 shows the scoring results of the environmental dimension

Table 4: Scoring results environmental dimension (own survey, 2026). Sum of scores: 46

<i>IFM Service Area</i>	<i>Criterion</i>	<i>Score (0–5)</i>
Security & reception	Mobility	3
Catering	Food origin	1
	Waste management	2
Waste & disposal management	Recycling rate	3
	Hazardous-substance management	5
	Waste management	4
Outdoor & green-space maintenance	Biodiversity	4
	Chemical use	0
	Machinery use	0
	Tree care	3
Winter & caretaker	De-icing / cleaning agents	3
	Material efficiency	2
	Resource efficiency	4
Cleaning	Products used	5
	Resource intensity	4
	Emission impact	3

Social Dimension

Occupational safety was rated 5 in security and reception (in-depth training, personal protective equipment and risk assessments) and 5 in outdoor maintenance, while qualification and working-conditions scores in most service areas ranged between 2 and 3, showing regulated working hours and ergonomic checks but only partial documentation (especially in terms of working hours documentation). Customer/visitor interaction (security) and staff qualification/nutritional diversity (catering) each scored 0. The reason therefor is a lack of available information, proving data gaps particularly where services are fully outsourced. Waste management scored moderately on occupational safety (4) and user information (2), reflecting continued difficulties with waste separation in shared areas. Comfort quality in outdoor areas scored 4, supported by seating, shading and sports/leisure facilities.

Table 5: Scoring results social dimension (own survey, 2026). Sum of scores: 41

<i>IFM Service Area</i>	<i>Criterion</i>	<i>Score (0–5)</i>
Security & reception	Occupational safety	5
	Qualifications	3
	Working conditions	3
	Customer/visitor interaction	0
Catering	Occupational safety	3
	Staff qualification	0
	Nutritional diversity	0
Waste & disposal management	Occupational safety	4
	User information	2
Outdoor & green-space maintenance	Occupational safety	5
	Amenity quality	4
Winter & caretaker	Occupational safety	4
	Working conditions	2

Cleaning	Working conditions	3
	Qualifications	3

Governance Dimension

Governance scores (see Table 6) were highest in security and reception (documentation 5, transparency 4, compliance 3, supported by contractual performance records, inspections, and regular reporting and in cleaning services (documentation 5, compliance 4, subcontractor management 3). Catering again scored weakest across the board (hygiene management 0, reporting 0, supply-chain transparency 1), consistent with the fully externalized delivery model and the absence of systematic supplier controls. Waste management scored consistently well (documentation and compliance both 4), while outdoor maintenance scored lower on documentation (2) because of only partial documentation (e.g., incomplete tree-cadaster data).

Table 6: Scoring results governance dimension (own survey, 2026). Sum of scores: 45

<i>IFM Service Area</i>	<i>Criterion</i>	<i>Score (0–5)</i>
Security & reception	Compliance	3
	Transparency	4
	Documentation	5
Catering	Hygiene management	0
	Supply-chain transparency	1
	Reporting	0
Waste & disposal management	Documentation	4
	Compliance	4
Outdoor & green-space maintenance	Documentation	2
	Compliance	3
Winter & caretaker	Documentation	3

	Liability management	4
Cleaning	Documentation	5
	Compliance	4
	Subcontractor management	3

Aggregation of the individual scores resulted in 46 points for the environmental dimension, 41 for the social dimension, and 45 for the governance dimension, corresponding to an overall fulfillment degree of 71.74% (Table 7). While this indicates solid sustainability performance, the largest gap between actual and target values was observed in the social dimension (19 points), highlighting catering and, to a lower extent, winter/caretaker services as priority areas for improvement.

Table 7: Aggregated ESG fulfillment: actual versus target values (own survey, 2026).

<i>ESG Dimension</i>	<i>Actual score</i>	<i>Target score</i>
Environmental (E)	46	64
Social (S)	41	60
Governance (G)	45	60
Total fulfilment	132	184

5. Conclusion

This paper developed and tested an ESG evaluation framework for IFM by integrating GRI-based criteria into the GEFMA ESG-KPI tool and applying a transparent scoring logic. The tool was tested through a case study. Application to public buildings shows that structured sustainability evaluation in IFM is feasible. Combining criteria helps identify strengths (e.g., cleaning and waste management) and weaknesses (e.g., catering) that might otherwise remain hidden. However, the value of the framework depends on data quality and includes a degree of subjectivity.

Future work should focus on three areas: validating the framework across more case studies and building types, integrating it with digital building models and automated

data collection (e.g., BIM, IoT sensors) to reduce manual effort, and regularly updating the criteria to reflect changing regulations. Overall, the study shows that a standardized evaluation framework can help operationalize ESG requirements in FM by supporting systematic assessment and reporting of ESG-related information.

6. Discussion

The case study shows that the evaluation framework allows structured assessment of sustainability in varied IFM service areas. In-house managed services (cleaning, waste management, security) achieved higher ESG scores, while fully outsourced catering scored lowest, especially in governance. This highlights that social and governance risks in outsourced services are harder to assess than technical or energy parameters, and existing ESG tools do not capture this gap.

The framework extends the GEFMA ESG-KPI tool by integrating IFM-specific criteria, GRI references, and a transparent scoring approach. Limitations include subjective selection and weighting of criteria, dependence on data quality and completeness, and the need for ongoing updates as regulations change. The study is based on a single case, limiting generalizability, and uses data from different reporting periods, preventing a uniform temporal assessment.

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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.

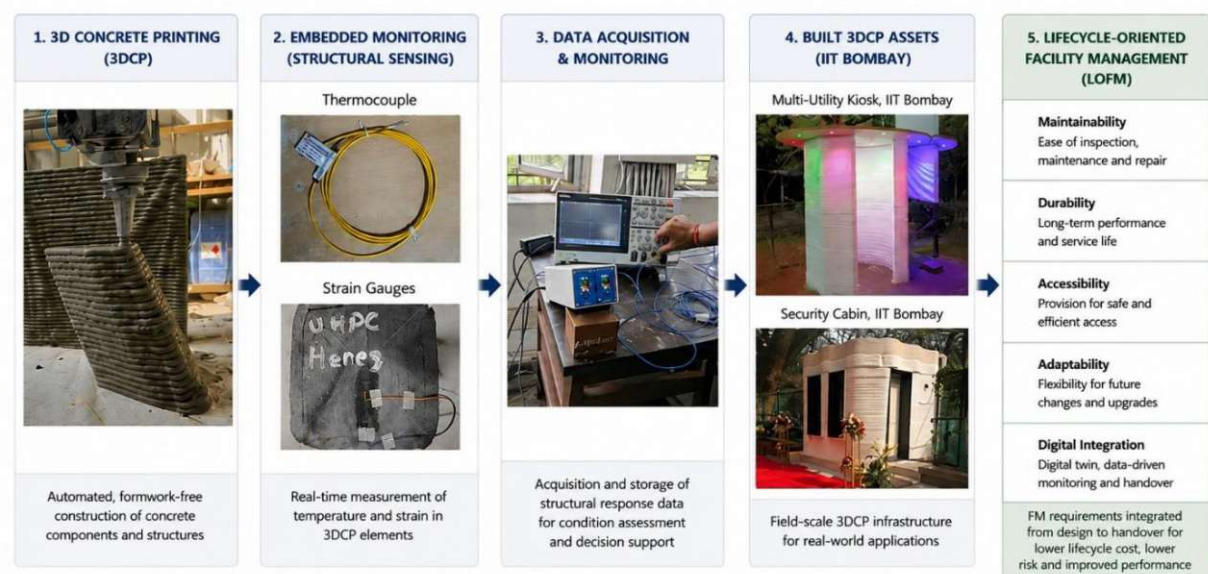


Figure 1. From 3D concrete printing and embedded monitoring to lifecycle-oriented facility management (LOFM).

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:

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

where $\sigma(min)$ is the minimum reported strength across print orientations and $\sigma(cast)$ is the equivalent cast-concrete baseline. From Table 1, $AI(compressive) = 0.59$ and $AI(flexural) = 0.53$ (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:

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

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 AI 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 $s = \varepsilon/150$, 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, $C(\text{var})$	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.

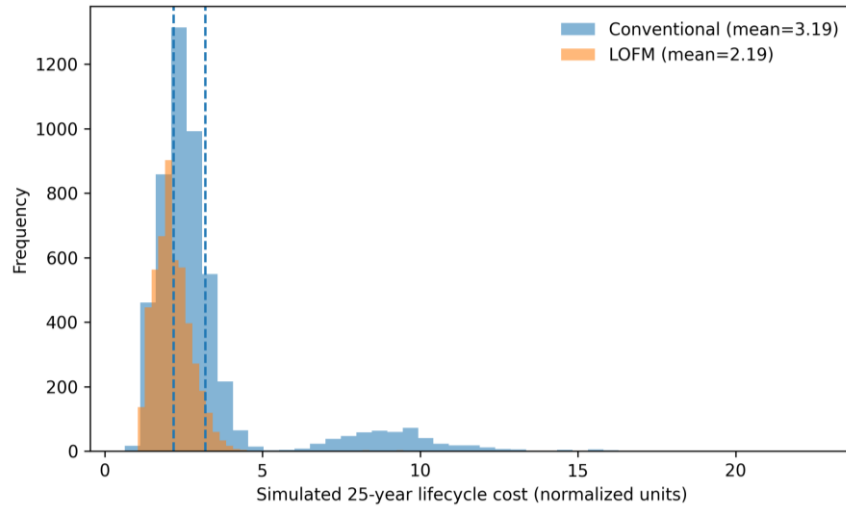


Figure 2. Independent-audit lifecycle-cost distributions from the fully specified reference implementation.

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.

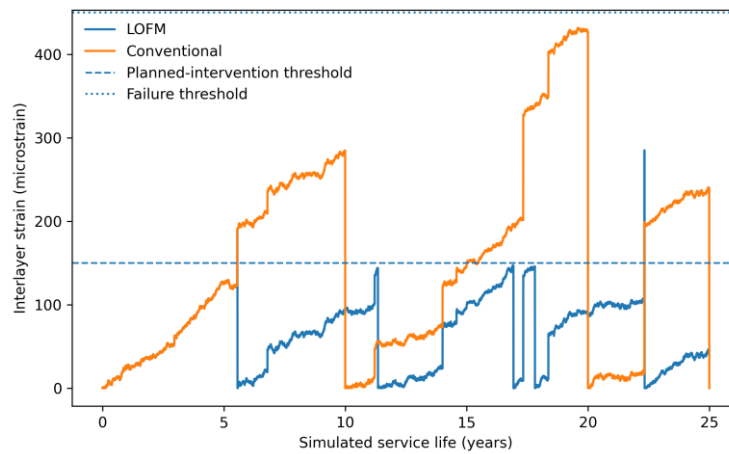


Figure 3. Representative daily-step degradation path generated by the independent reference implementation.

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

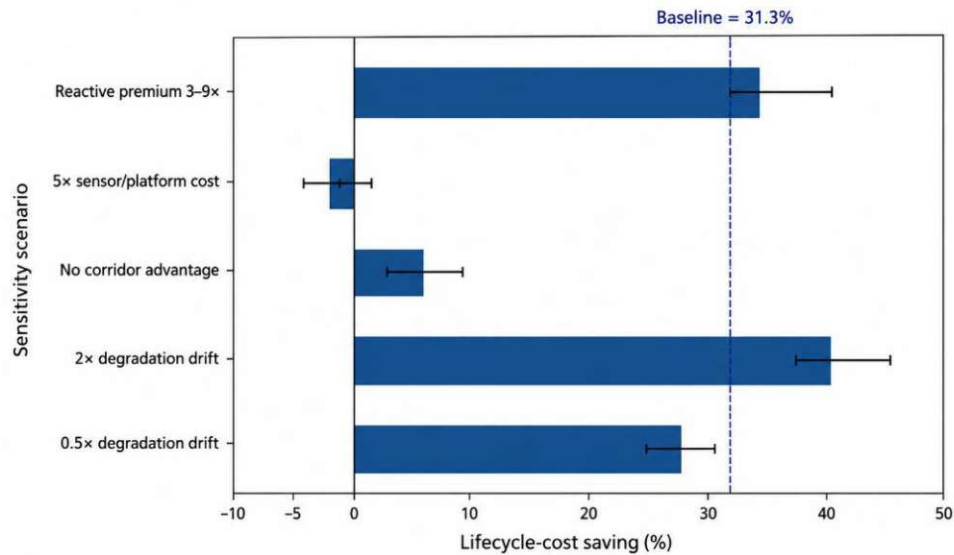


Figure 4. Independent-audit sensitivity analysis; error bars are 95% bootstrap confidence intervals.

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.

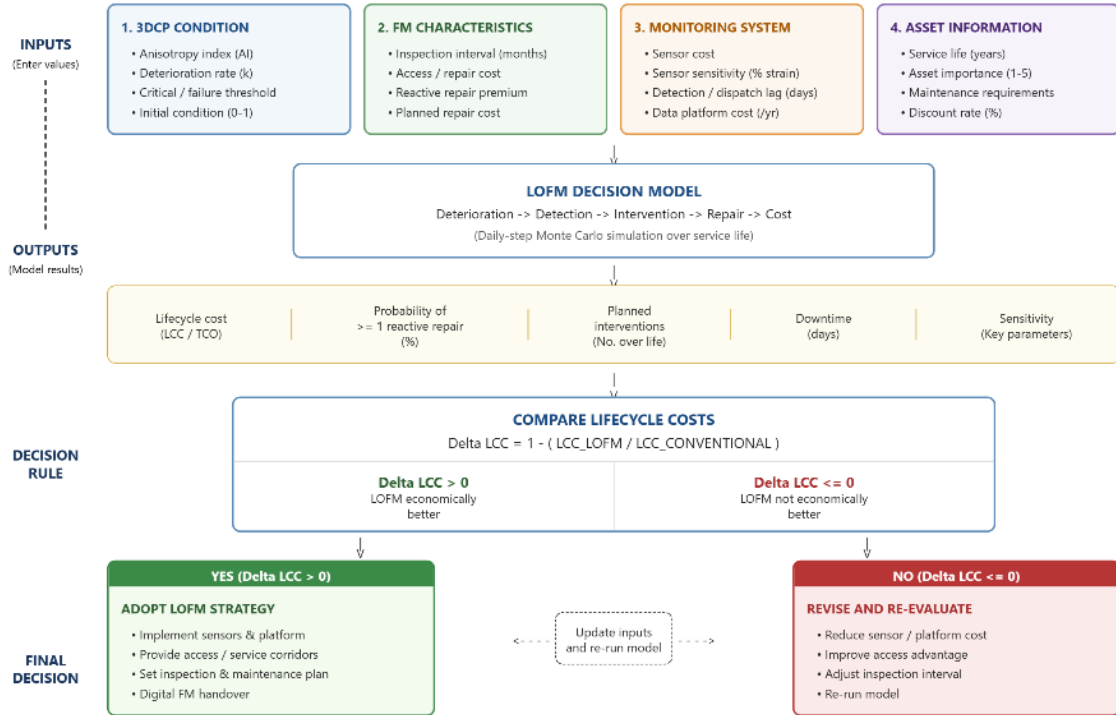


Figure 5. LOFM-based decision framework for lifecycle facility management of 3D-printed concrete structures.

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Science meets Practice: Urban FM

Monitoring Urban Conditions through Computer Vision – New Possibilities for Data-driven Urban FM?

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Abstract:

Rapid urbanization demands new approaches for the continuous monitoring of urban conditions to ensure smooth operation and liveable cities – key goals of successful Urban Facility Management (FM). Traditional inspection methods offer limited scalability and low temporal resolution. This paper explores how computer vision can transform urban condition monitoring through the analysis of street-level imagery, and positions these methods as a technical foundation for dynamic digital twins that continuously capture and analyze urban conditions rather than serving merely as static, formal scale models. Based on a systematic review of recent studies, it highlights data-driven methods – particularly image segmentation and deep learning models such as DeepLabv3+ – used to assess indicators such as greenery, cleanliness, or accessibility. The findings demonstrate computer vision's potential to generate high-frequency data that can feed dynamic digital twins, enabling continuous monitoring and immediate response strategies. Integrating these techniques into Urban FM supports more data-driven decision-making and adaptive management of the built environment.

Key words:

Urban Facility Management, Dynamic Digital Twins, Computer Vision, Image Segmentation

1. Introduction

With accelerating global urbanization increasing the demand for effective urban monitoring (Hurbean et al., 2021; Amer et al., 2025), the established link between urban environment quality and people's well-being (Vallebuena et al., 2023) underscores this urgency.

Traditional methodologies for assessing urban conditions, ranging from infrastructure quality and walkability to socio-economic vitality, have historically relied on labor-intensive field observations, surveys, and census data (Amer et al., 2025). However, these approaches are often constrained by low update frequency, which hinders the ability to capture the dynamic nature of cities (Amer et al., 2025). To overcome these limitations, the field of urban studies has increasingly integrated big data and machine learning (ML), transforming the way researchers quantify both the tangible and intangible aspects of the built environment. A pivotal advancement in this domain is the utilization of Street View Imagery (SVI), provided by platforms such as Google Street View, Baidu Total View, and Tencent Street View (Cinnamon and Jahiu, 2021). Unlike sensing from an aerial perspective, SVI offers a high-resolution, pedestrian-level point of view that reflects how people experience the city (Cinnamon and Jahiu, 2021). Researchers utilize these 360-degree panoramas as an economical alternative for "virtual audits," enabling the large-scale extraction of detailed features such as greenery, building facades, and sidewalk accessibility (Chowdhury et al., 2024).

Beyond their academic relevance, these methods carry direct operational value for Urban FM. Automated detection of urban decay indicators such as graffiti, potholes, and broken windows (Vallebuena, 2023) can trigger targeted maintenance dispatch instead of relying on citizen complaints or periodic manual inspection rounds. Continuous assessment of street greenery through indices such as the Green View Index or the Street Greenery Comprehensive Evaluation Indicator (Wang et al., 2024) can inform the prioritization of green maintenance and irrigation schedules, while sanitation-focused models that detect garbage and road surface conditions (Wang, 2022) support demand-responsive cleaning routes rather than fixed schedules. Perceived safety and walkability indices (Costa et al., 2023; Fantous and Bennedjai, 2026) can likewise feed into infrastructure investment decisions on lighting, cycling infrastructure, or pedestrian zones. Once refreshed continuously, such indicators can be embedded in dynamic digital twins of urban infrastructure, moving Urban FM

practice from periodic, reactive inspection toward continuous, condition-based operations.

Despite this rapid progress, the fast-evolving field lacks up-to-date, comprehensive overviews of recent computer vision applications for urban monitoring. This paper addresses this gap by synthesizing recent advancements to provide a current state-of-the-art overview for data-driven urban assessment.

This paper addresses this by asking the following research questions:

1. Where and when have studies on urban qualities using computer vision been published?
2. Which models and training datasets have been used in studies so far?
3. Which urban conditions and qualities have already been studied using computer vision methods?

2. Methodology

In Phase 1 of the review process, studies were selected based on specific inclusion and exclusion criteria: publications from 2020 to 2026, written in English, and focused on urban environments, while excluding those with a primary emphasis on traffic (as an infrastructure domain outside the scope of the built environment). The search was conducted using Google Scholar as the primary database. A targeted search string was developed from predefined components: "urban quality" AND "computer vision" AND (observation OR monitoring). For data extraction, the software Publish or Perish queried the Google Scholar API with this string and the specified time frame, exporting the results to Microsoft Excel for processing. This yielded an initial result of 311 sources. Subsequent manual title screening based on relevance reduced the pool to 103 sources, followed by abstract screening, which further narrowed it to 54 studies. These were then differentiated by study type, identifying 46 case studies and 8

literature reviews. Finally, the case studies were categorized according to their geographical origin, year of publication, and associated keywords.

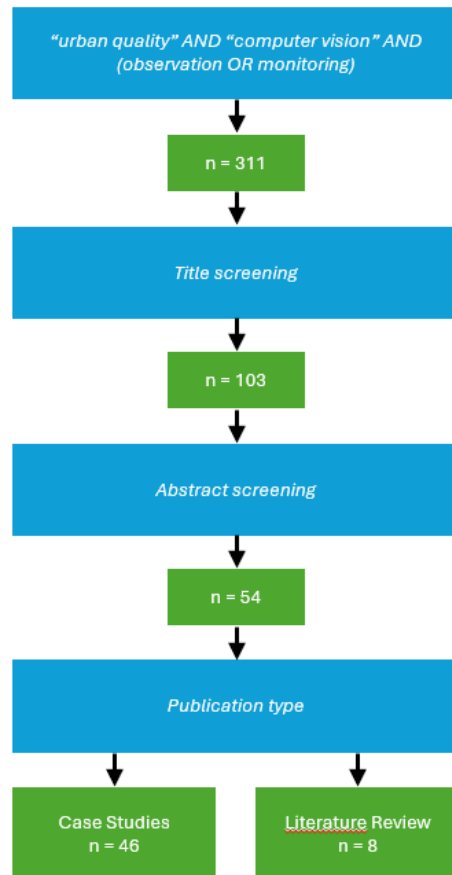


Figure 1: Flowchart of the Literature Search

Phase 2 involved an in-depth analysis of the 46 case studies identified in Phase 1. These were systematically categorized according to key dimensions: image sources, model training approaches, urban characteristics and examined urban qualities, as well as study design. This structured approach enabled a comprehensive mapping of methods and focus areas in computer vision applications for urban studies.

Phase 3 entailed a focused reading of the previously categorized and most relevant sources from Phase 2. This step enabled the extraction of detailed insights, arguments, and methods. Through this targeted analysis, key patterns and contributions were synthesized for the review's objectives.

3. Results

The final set of sources from Phase 1 includes 46 case studies and 8 literature reviews. The following analysis focuses on the case studies.

3.1 Geographical and Temporal Distribution of Publications

Approximately 89% of sources were published after 2022, with a peak in 2025, accounting for around 48% of the total publications. This distribution indicates a strong upward trend in research activity in recent years.

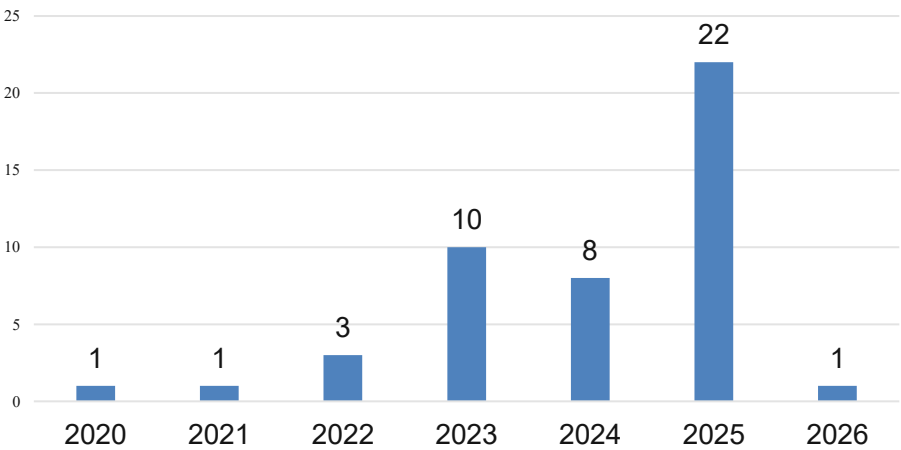


Table 1: Publication years of the examined case studies

The geographical distribution reveals the strong dominance of research conducted in China, accounting for approximately 52% of the publications.

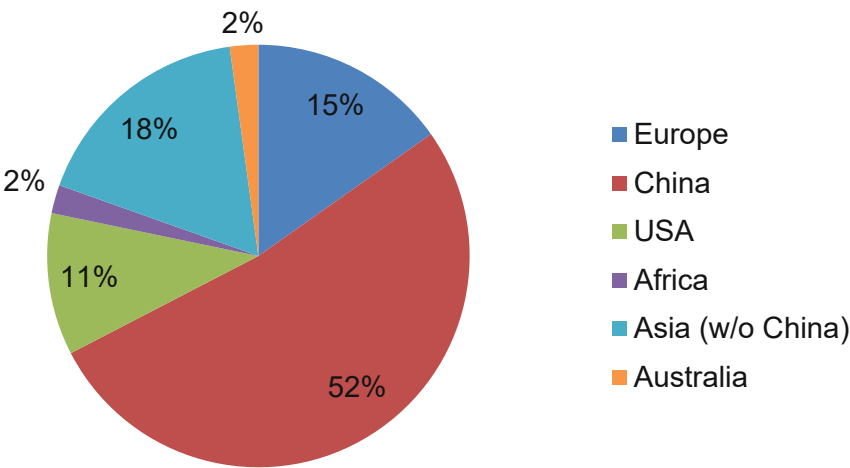


Table 2: Publication origins of the examined case studies

3.2 Keyword Clusters

Based on the identified keyword clusters, the literature review reveals a strong dominance of Google Street View–based approaches. This highlights the central role of street-level imagery for analyzing urban environments. Perception is the second

most prominent cluster, underlining the interest in subjective, human-centered dimensions such as perceived attractiveness and quality of urban space. In contrast, deep learning and semantic segmentation appear less frequently, suggesting that advanced AI-based methods are increasingly used but are not yet the standard across studies. Topics such as urban planning, visual quality, green space, and pedestrian-related aspects are represented to a moderate extent.

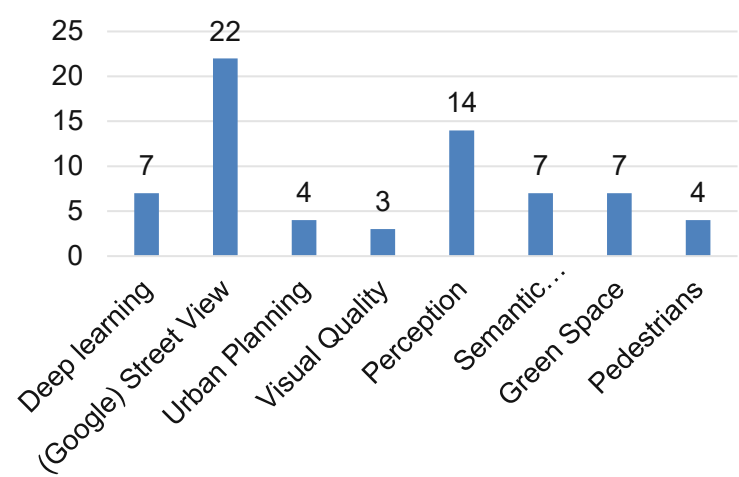


Table 3: Keyword clusters of the examined case studies

3.3 Data Sources for Testing the Models

By far the predominant data source was Baidu Street View Images, highlighting the platform's substantial relevance. Baidu Maps, the navigation and mapping service from the Chinese internet conglomerate Baidu and the primary equivalent to Google Maps, covers over 11 million kilometers of roadways nationwide (Xia et al., 2022). These findings align with the high number of Chinese sources identified in Phase 1.

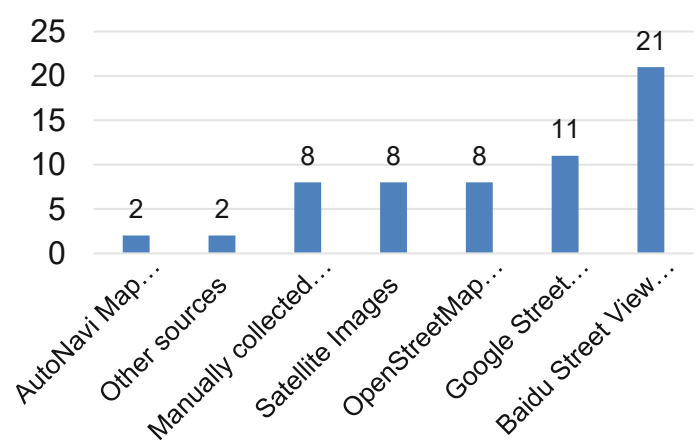


Table 4: Data sources for testing the models

3.4 Datasets for Training the Models

The analysis focused on established datasets used for training the computer vision models (excluding case studies without dataset mentions for a substantive overview). It reveals the distribution and significance of these datasets, with two primary ones standing out: ADE20K and MIT Place Pulse 2.0.

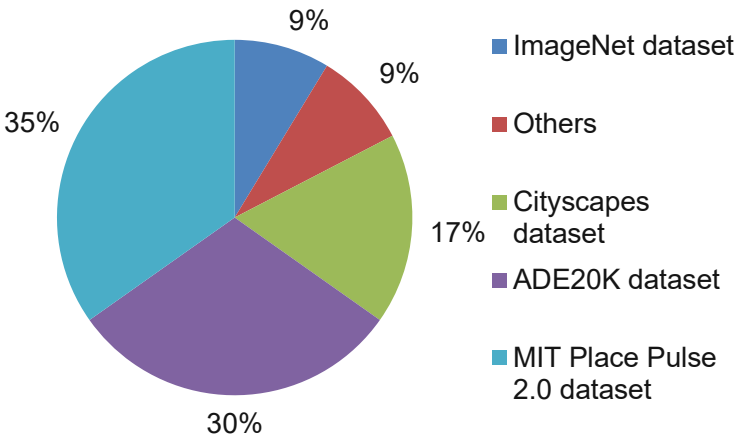


Table 5: Datasets for training the models

ADE20K (Zhou et al., 2019) originates from the MIT Computer Science and Artificial Intelligence Laboratory (CSAIL) and was released in 2016. This dataset comprises 25,000 images of complex everyday scenes, annotated with 3,169 distinct labels, with its primary objective being semantic segmentation.

MIT Place Pulse 2.0 (Dubey et al., 2016), from the MIT Media Lab and also released in 2016, is a crowdsourced dataset featuring 110,988 images from 56 cities, alongside 1,170,000 pairwise comparisons from 81,630 online volunteers across six perceptual attributes: safe, lively, boring, wealthy, depressing, and beautiful.

3.5 Pre-trained Models

While datasets provide the raw training data for computer vision models, pre-trained models represent ready-to-use neural network architectures already trained on such data. The analysis examined the usage of pre-trained models (excluding case studies without concrete mentions for a substantive overview). DeepLabv3+ (Chen et al., 2018), released in 2018 as the fourth version of the DeepLab series from Google Inc., emerged as the most frequently adopted architecture, accounting for 31% of applications. The "Others" category includes various smaller models, each used in only a single instance across the reviewed literature.

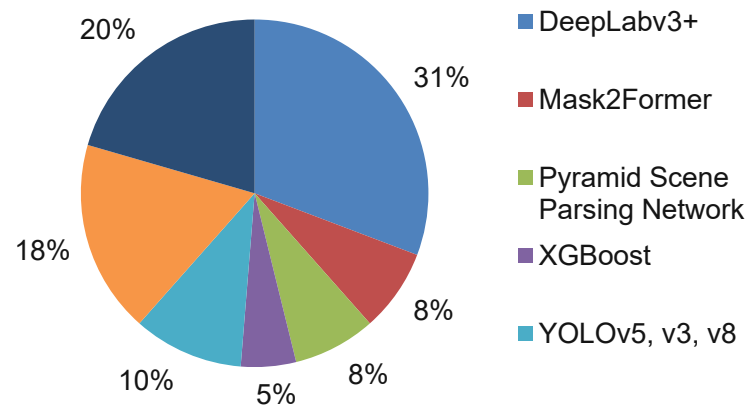


Table 6: Pre-trained models

3.6 Methods to Analyze Urban Conditions

The methodology and study design of the case studies revealed diverse approaches, with some models employing multiple methods to analyze urban conditions (categorized across all used techniques). Classification with implicit feature extraction was notable in certain models, which bypass explicit definitions of urban conditions and instead autonomously extract relevant features based on perceptual evaluations (labels). Image segmentation emerged as the most frequently utilized method, primarily because it assigns specific classes to every individual pixel. This granular approach enables a comprehensive and detailed quantitative analysis of represented classes and thus the relevant urban conditions.

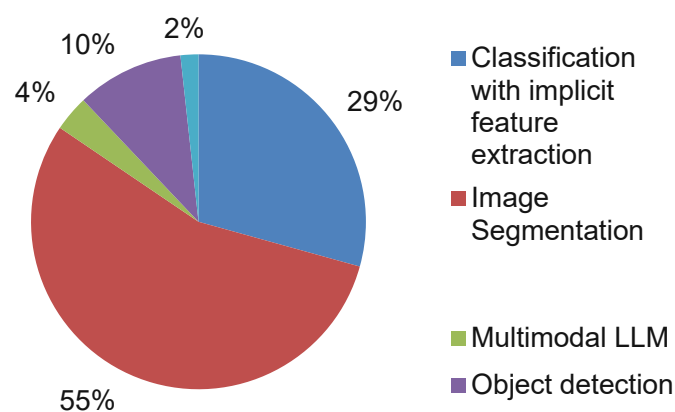


Table 7: Methods to analyze urban qualities

3.7 Urban Qualities and Indicators

The following analysis integrates the bibliographic data from the literature overview with the specific findings regarding urban qualities and indicators identified in the research datasets.

Urban Vitality and Social Perception: A significant cluster of research focuses on urban vitality and how it is perceived by citizens. Ma (2023) investigates urban vitality in Qingdao, utilizing perceptual emotion indicators such as "Safe," "Beautiful," "Depressing," "Lively," "Wealthy," and "Boring" to identify urban features. Similarly, Li et al. (2025) conduct a multi-level analysis in Hohhot, focusing on street vitality and the built environment. Their research stands out for its comprehensive use of specific indices, including the Population Density Index (PDI), Green View Index (GVI), and Street Cleanliness Index (SCI) to quantify urban conditions. In contrast, Chen et al. (2024) narrow their focus to "urban nature vitality" in San Francisco, primarily using basic physical indicators like buildings, sky, trees, and roads to understand how nature integrates into the urban fabric.

Visual Quality and Human Perception: Sottini et al. (2021) focus on how Flickr photo data can be used to assess the perceived quality of urban spaces, analyzing geotagged outdoor images. Based on the classification by Ewing and Handy (2009), their research also considers five key visual quality indicators such as visual enclosure, imageability, human scale, transparency, and complexity to interpret how urban form contributes to the public's perception of city spaces. Gönül and Durak (2025) apply these perceptual methods to a specific historical context, measuring change in historical city centers in Bursa City.

Environmental Qualities and Specialized Indicators: Several authors focus on specific environmental or functional urban qualities: Wang et al. (2024) developed the Street Greenery Comprehensive Evaluation Indicator (SGCEI) to identify priority greening areas in Beijing. This differs from the broader Green View Index used by Luo (2022). Fantous and Bennedjai (2026) examine urban walkability in Batna using specialized metrics like the Subjective Walking Preferences Index (SPI). Conversely, Costa et al. (2023) focus strictly on perceived safety for cycling in Berlin, using binary classifications of "safe" versus "unsafe." Vallebuena (2023) identifies urban decay by detecting specific objects like graffiti, potholes, and broken windows, while Wang

(2022) focuses on road sanitation quality, specifically detecting garbage and road surface conditions.

3.8 Similarities and Differences in Methodology

The primary similarity across these studies is the heavy reliance on Deep Learning and Computer Vision (e.g., SegNet, DeepLabv3+, Mask2Former) applied to Street View Imagery (Google, Baidu, or Mapillary). Many authors share the use of the MIT Place Pulse 2.0 dataset for training models to recognize human emotions related to urban space. The main difference lies in the granularity of indicators. While one group of authors (e.g., Ma) uses broad emotional labels to describe urban qualities, other authors (e.g., Fantous and Bennedjai) develop highly specific quantitative indices to provide actionable data for urban planning and maintenance.

4. Conclusion

This review synthesized 54 studies on computer vision applications for urban monitoring, differentiated into 46 case studies and 8 literature reviews. Approximately 89% of sources were published after 2022, peaking in 2025, and China dominates the field with 52% of publications. Keyword clusters highlight Google Street View–based approaches, while Baidu Street View led as the primary data source for model testing; training relied heavily on ADE20K and MIT Place Pulse 2.0, with image segmentation as the leading method.

Beyond these technical patterns, the review shows that computer vision has primarily been used to assess urban conditions and qualities, to measure specific environmental qualities such as greenery, walkability, and cycling safety, and to detect signs of urban decay and sanitation problems such as graffiti, potholes, broken windows, and litter. These studies range from broad, perception-based labels to highly specialized indices like the Street Cleanliness Index, the Street Greenery Comprehensive Evaluation Indicator, and the Subjective Walking Preferences Index, illustrating a shift from generic emotional ratings toward more actionable, planning-oriented indicators.

5. Discussion

For Urban FM, this shift is significant because it moves digital twins beyond their traditional role as static, formal-scale representations of the built environment toward dynamic digital twins that are continuously updated through image-based monitoring

and that can support immediate, condition-based response strategies. Indicators such as street cleanliness, greenery, and accessibility, once computed at scale and refreshed at high frequency, can feed directly into KPI-based FM dashboards, enabling prioritization of maintenance, cleaning, and infrastructure investment based on current rather than historic conditions. This reframes computer vision-based street-level analysis not merely as a research method, but as a candidate data layer for the continuous monitoring components of dynamic digital twins in Urban FM.

Despite these strengths in scalability, the heavy reliance on Chinese platforms and MIT-based perception datasets limits generalizability, particularly in data-scarce regions where urban form, infrastructure standards, and cultural perceptions of quality differ. The exclusion of traffic-focused studies from this review narrows its scope and may overlook integrated urban dynamics relevant to FM practice, such as the interaction between mobility infrastructure and pedestrian-level conditions. Future work should prioritize diverse, multi-scale data fusion, broader geographical representation, and richer indicators of urban change to capture both static urban conditions and dynamic transformations over time — a prerequisite for computer vision to mature into a reliable data source for dynamic digital twins in Urban FM.

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