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Systematic Review

Building Information Modeling for Infrastructure Lifecycle Management: A Systematic Review of Interoperability, Asset Management, and Digital Twins

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Featured Application

This review provides a structured basis for designing and evaluating BIM-oriented information environments for the operational management of existing infrastructure, with particular emphasis on interoperability, information continuity, integration with asset management systems, and the development of Digital Twins.

Abstract

The digital transformation of infrastructure management calls for a shift from BIM models developed primarily for design to information environments that can support inspection, maintenance, monitoring, and decision-making throughout the asset lifecycle. This paper presents a systematic review of the role of Building Information Modeling (BIM) and related technologies in civil infrastructure management. The review examines 97 primary studies selected from 531 records retrieved from Scopus and Web of Science. The searches used to build the corpus were last accessed on 16 August 2026; the common publication-year range is 2015–2026. Of the 97 included studies, 73 (75.3%) were published in 2022–2026. Bridges and roads account for 45 studies, while 77 address operation and maintenance, asset management or the full life cycle. In 65 studies, the dominant information-related role concerns interoperability and data modelling. The technology classification allows multiple labels per study and identifies Digital Twin/IoT/SHM in 49 studies and open standards/semantic interoperability in 47. These labels alone do not establish the operational maturity of the solutions. The comparison of cases distinguishes implemented functions from conceptual frameworks and identifies cases of one-way updating. The synthesis highlights gaps in semantic continuity, updating, governance and long-term operational validation. Study heterogeneity, sequential checking, unretrieved reports and the eligibility period limit the generalisability of the findings. The proposed pathway organises complementary capabilities without assuming a universal sequence or claiming measured improvements in maintenance.

Keywords: Building Information Modeling; BIM; infrastructure asset management; operation and maintenance; interoperability; openBIM; Digital Twin; GIS; lifecycle information management

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Academic Editor: Asterios Bakolas

Received: 10 September 2026
Revised: 23 October 2026
Accepted: 27 October 2026
Published: 30 October 2026

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1. Introduction

Civil infrastructure comprises long-lived systems in which information remains valuable after design and construction are complete. During operation, inspection, mainte-

nance, rehabilitation, and decommissioning, decisions depend on the ability to reconstruct an asset's condition, connect documents with geometry, integrate field observations and time-series data, and keep information produced by different organizations and software platforms consistent. In this context, Building Information Modeling (BIM) has gradually moved beyond design coordination and is increasingly viewed as a potential information backbone for lifecycle management [1]. Related research has also proposed a smart BIM framework for managing off-site construction logistics from a lifecycle perspective [2]. Existing reviews and synthesis papers have already highlighted BIM's potential for managing asset data, combining heterogeneous information, and integrating Digital Twin approaches [3–5]. In the building sector, reviews have examined BIM applications for smart buildings and their enabling technologies [6]. Research on BIM–life cycle assessment (LCA) integration highlights semantic interoperability barriers to supporting circular economy practices [7]. Information standardization has also been examined in relation to BIM for the seismic rehabilitation of buildings [8].

A three-dimensional model alone is not sufficient. Linear and distributed infrastructure requires spatial reference systems, domain-specific information schemas, links to GIS and management databases, update procedures, and mechanisms that preserve meaning during exchange. The literature also shows increasing convergence among BIM, openBIM/IFC, GIS, the Semantic Web, IoT, Structural Health Monitoring (SHM), reality capture, and Digital Twins. This convergence broadens the range of operational possibilities, but it also makes it harder to distinguish architectures mature enough for asset management from those that remain experimental demonstrators [9–12].

A second issue concerns the relationship between data availability and decision quality. BIM can organise inspection reports, damage information, sensor data and maintenance information. Linking these data to intervention priorities, risk, costs or maintenance strategies requires an explicit decision-making function. Distinguishing integrated information from demonstrated improvements in decision-making is therefore essential to assessing the practical contribution of digitalisation to asset management [13–16]. This systematic review addresses that gap by treating the role of BIM and its associated information systems in maintaining information continuity across infrastructure lifecycles as the unit of analysis, rather than focusing on any single technology. It examines how the literature links digital models, interoperability, operational data, Digital Twins, and decision support, while distinguishing demonstrated results from recurring limitations and future research directions. More specifically, the review addresses the following research questions:

- RQ1. How is the literature distributed by publication period, infrastructure domain, and lifecycle phase?
- RQ2. Which information roles, technologies, and standards characterize BIM applications for O&M and asset management?
- RQ3. How is BIM integrated with GIS, asset management systems, sensors, the Semantic Web, and Digital Twins?
- RQ4. What operational benefits are reported, and what barriers limit adoption at scale?
- RQ5. What research gaps emerge, and what development pathway can be inferred for future infrastructure information ecosystems?

The review makes three complementary contributions. The first is a systematic and quantitative mapping of 97 primary studies, organised by publication period, infrastructure domain and life cycle stage. The second is a classification framework based on the role of BIM and information management, the technologies and standards used, and the form of integration adopted. The third is a proposed pathway that links BIM/BrIM, open and semantic interoperability, operational data, digital twins and decision support, while distinguishing technological integration from demonstrated value for asset management.

2. Materials and Methods

2.1. Review Design

The review followed six stages: identification, deduplication, screening, full-text retrieval, eligibility assessment and data extraction. Reporting was aligned with PRISMA 2020 [17]. Explicit criteria relating to infrastructure and BIM/information management were used, together with a structured data extraction matrix. Supplementary Table S1 lists the 97 included records [9–16,18–106].

2.2. Information Sources and Search Strategy

The Scopus and Web of Science searches used for the review were last accessed on 16 August 2026. The review covers English-language publications from 2015–2026, including journal articles and conference or proceedings papers. The dataset for the common period contains 364 Scopus records and 167 Web of Science records, giving a total of 531 records before deduplication (Table 1). The searches combined terms relating to BIM, civil infrastructure, and the life cycle or asset management with terms relating to information management or interoperability. The full search strings and the procedure for selecting records by year are provided in Supplementary Section S2. GIS, Digital Twin, IoT and AI were analysed as enabling technologies without being required search terms.

Table 1. Literature search strategy.

Database	Search Field	Document Type	Language	Results
Scopus	TITLE-ABS-KEY: title, abstract and keywords	Article; Conference Paper	English	364
Web of Science	TS (Topic): title, abstract, author keywords and Keywords Plus	Article; Proceedings Paper	English	167
Total				531

Note: The full search strings, filters, access dates, and procedure for selecting records by publication year are provided in Supplementary Section S2.

Scopus was queried using TITLE-ABS-KEY and Web of Science using TS. Restrictions on language (English) and document type were applied in both sources. Scopus records were selected from the exported data using the inclusive range 2015–2026; the Web of Science export also covers 2015–2026. The same temporal eligibility criterion applies to publications from both databases. Deduplication was based on DOIs and, when these were missing or compatible, normalised titles. Records with identical titles but different DOIs were retained as distinct bibliographic records pending assessment of the relationship between the publications.

2.3. Eligibility Criteria

Studies published in 2015–2026 were eligible if they made a substantial contribution relating to BIM, BrIM, openBIM or information modelling applied to civil infrastructure and linked to life cycle information management. The focus is on O&M, asset management, inspection, monitoring, maintenance, handover, interoperability and integration. Methodological studies, frameworks, platforms, prototypes and case studies were included when their information-related contribution could be verified in the full text. A preview or an abstract alone is insufficient for full-text assessment. Exclusions comprised studies confined to buildings without a relevant infrastructure case; studies of digital twins, SHM, or monitoring in which BIM/openBIM did not play a substantive information role; work without a meaningful connection to lifecycle management; and secondary publications or

reports that could not be treated as individual primary studies. Relevant reviews were retained as background material but were not counted in the primary corpus.

2.4. Study Selection and Full-Text Retrieval

The dataset for the common period (2015–2026) comprises 531 records. After the results were merged, 124 duplicates were removed, leaving 407 unique records for title and abstract screening. At this stage, 242 records were excluded and 165 reports were sought for full-text retrieval. Of these, 149 full texts were retrieved and assessed. Sixteen reports that appeared potentially relevant could not be obtained despite repeated attempts; they were recorded as 'reports not retrieved' and were not assigned a full-text eligibility decision. Of the 149 documents assessed, 52 were excluded: 26 because the domain or asset was not relevant; 8 because they were reviews or other secondary contributions; 6 because the infrastructure context or scope was insufficiently specific; 6 because they did not adequately address the lifecycle/O&M or the review focus; 2 because BIM/openBIM did not play a substantive role; 2 because they could not be treated as individual primary studies; 1 because the publication/full text was duplicated; and 1 because of another topic/scope mismatch. The final corpus therefore comprises 97 primary studies (Figure 1).

2.5. Data Extraction and Coding

For each of the 97 included studies, data were entered into a structured matrix covering the bibliographic reference, year, infrastructure domain, life cycle stage, role of BIM/information management, technologies and standards, explicitly stated country or geographical context, method, application case, data sources, exchange or integration arrangements, O&M/asset management function, main contribution, reported benefits and limitations or barriers. Coding was based on the available full texts and was then normalised into common categories for synthesis across studies. When the country of the case study was not stated, author affiliations were not used as a geographical proxy. Screening and data extraction were performed by one author and then checked by the other. Checking was sequential rather than based on two independent assessments. Neither inter-rater agreement statistics nor formal study-level risk-of-bias scores are available. Selected cases are compared descriptively by mechanism, demonstrated function, validation context and reported limitations; this comparison does not provide a validated quality score.

2.6. Synthesis and Analysis

Infrastructure domain, life cycle orientation and dominant information-related role are each assigned a single primary code per study. The dominant role reflects the proposed or verified contribution: exchange schemas and semantic mappings are coded as interoperability; an asset model serving as the central information container is coded as the main asset information model; operational links to external systems as integration; specifications and information governance as information requirements; and explicit assessments, priorities or intervention choices as decision support. The qualitative synthesis distinguishes proposed frameworks from implemented systems. A primary code does not exclude secondary capabilities. Six technology categories are coded non-exclusively in Supplementary Table S3.1, and their co-occurrences are reported in Supplementary Table S3.2. For these categories, 1 indicates coded presence and 0 indicates that the category was not coded for that study. Supplementary Table S3.3 reports totals for the dominant information roles. Decision support is classified separately as a dominant information role. For example, maintenance decisions in [13] are combined with systems integration, whereas the comparison of documents in [100] concerns adoption and governance rather than a demonstrated decision engine for maintenance. Research priorities combine descriptive distributions, limitations

reported in the sources and the authors' interpretation; these forms of evidence are distinguished (Table 2). Percentages for the corpus are calculated as $n/97 \times 100$ and rounded to one decimal place; the sum of the mutually exclusive categories may differ from 100.0% because of rounding. Technology groups overlap, so their percentages need not sum to 100%.

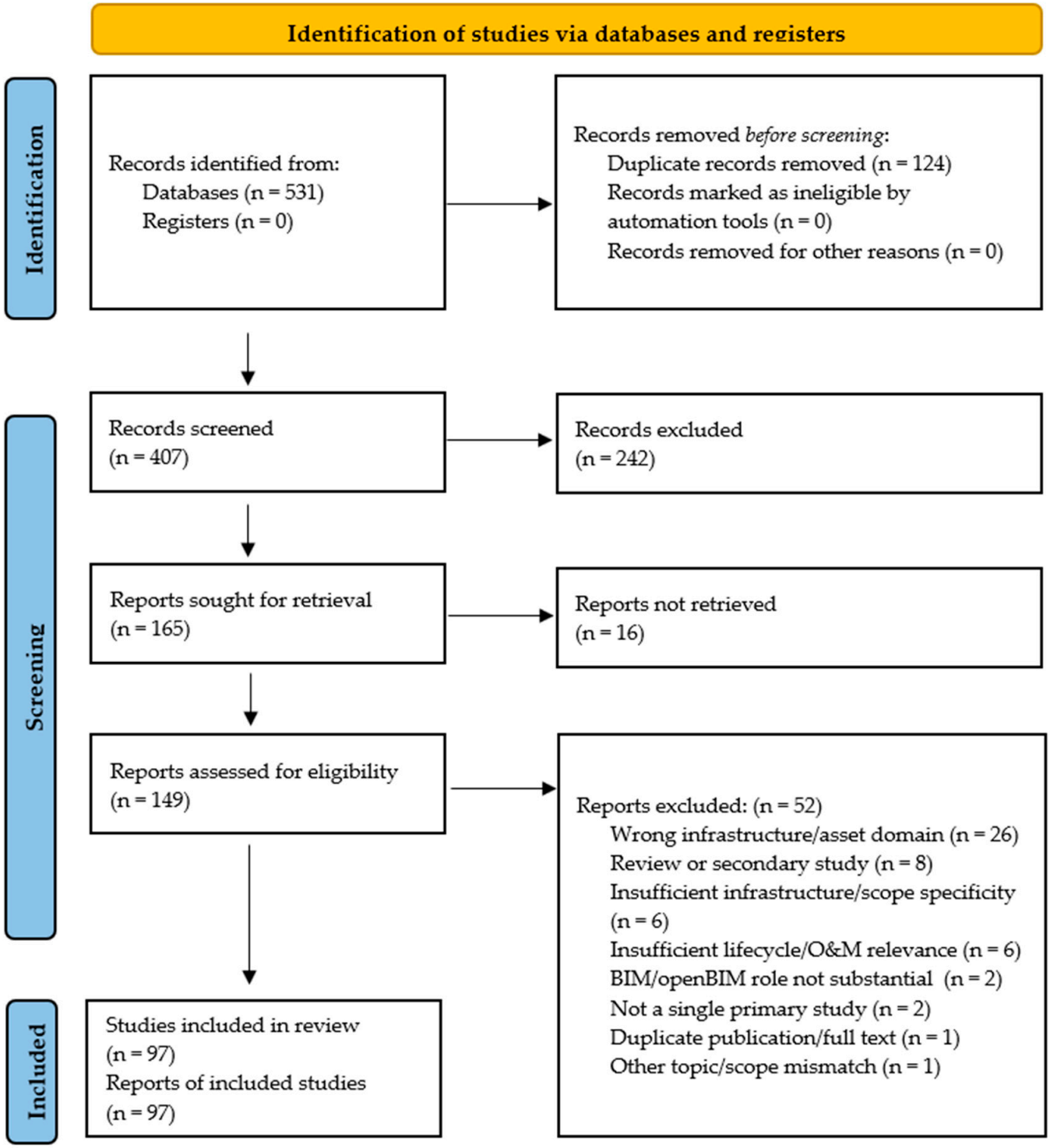


Figure 1. Study selection flow used in the review, based on the final counts in the screening log [17]. Arrows indicate the progression through the study selection process, including exclusions at the relevant stages.

Table 2. Operational definitions and coding rules used in the synthesis.

Variable/Category	Operational Definition	Coding Rule
Infrastructure type	Primary infrastructure asset addressed by the application.	One primary code only; use 'multi-infrastructure/general' when the contribution does not concern a single asset.
Lifecycle phase	Lifecycle phase targeted by the study's main contribution.	One primary code only, based on the stated objective, case study, and function.
Interoperability/data modelling	Data structuring, mapping, exchange, conversion, or semantic preservation.	Assigned when interoperability/data modeling is the dominant information contribution.
Core asset-information model	BIM/BrIM used primarily as a structured container for asset information.	Assigned when the main value lies in the information model and its operational use.
Integration layer	A link between BIM and GIS, AMS/BMS/PMS, sensors, databases, cloud platforms, or other systems.	Assigned when the integration architecture is the central contribution.
Information requirements	Definition, specification, or governance of required information.	Includes AIR/OIR/EIR/IDS and equivalent approaches when they are the main focus.
Decision support	Explicit use of data for assessment, prioritization, or maintenance choices.	Requires an explicit decision function; visualization or integration alone is not sufficient.
Technology clusters	Technologies and standards used within the same study.	Non-exclusive coding; one study may belong to several clusters.

3. Results

3.1. Study Selection and Corpus Composition

The selection process produced a final corpus of 97 primary studies from an initial 531 records. The duplication rate was 23.4% (124/531). After 407 unique records had been screened, 165 reports were sought in full text; 16 could not be retrieved. Of the 149 full texts assessed, 52 were excluded. The aggregated reasons were an irrelevant domain/asset ($n = 26$), a review or other secondary contribution ($n = 8$), insufficient infrastructure specificity/scope ($n = 6$), insufficient relevance to the lifecycle/O&M or to the review focus ($n = 6$), a non-substantive BIM/openBIM role ($n = 2$), a document that could not be treated as an individual primary study ($n = 2$), duplicate publication/full text ($n = 1$), and another topic/scope mismatch ($n = 1$). The remaining 97 studies form the analytical corpus.

3.2. Temporal Trends

The literature is heavily concentrated in the most recent years. Seventy-three of the 97 included studies (75.3%) were published between 2022 and 2026. Output peaked in 2025, with 30 studies (30.9%), followed by 2026 with 15 (15.5%), 2022 with 11 (11.3%), and 2023 with 10 (10.3%). The count for 2026 is partial and reflects the results retrieved as of the search date (16 August 2026). The corpus contains only six studies published before 2019. Within the limits of the search strategy, this pattern signals a recent acceleration of interest in connecting BIM, operational management, and data-driven technologies (Figure 2).

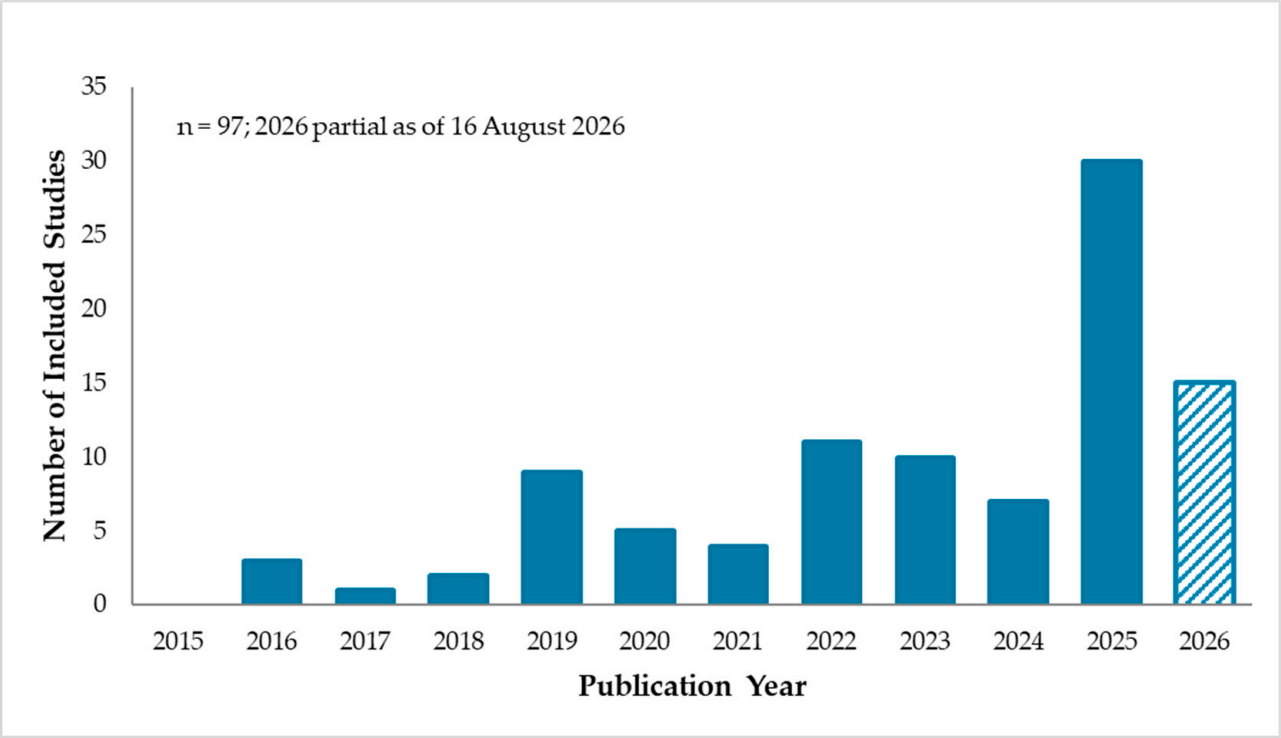


Figure 2. Annual distribution of the studies included in the systematic review ($n = 97$). The count for 2026 is partial, as the searches used to compile the final corpus were last accessed on 16 August 2026.

3.3. Infrastructure Domains

Bridges are the most widely studied domain, with 26 contributions (26.8%), followed by roads and highways with 19 (19.6%) and railways with 13 (13.4%). A further 18 studies (18.6%) address several infrastructure categories or propose general approaches. Tunnels and underground works account for seven studies (7.2%); airports, ports/maritime works, and water infrastructure for four each (4.1%); and utility tunnels for two (2.1%). The evidence base is therefore weighted toward bridges and roads, 45 of the 97 studies (46.4%) (Figure 3, Table 3).

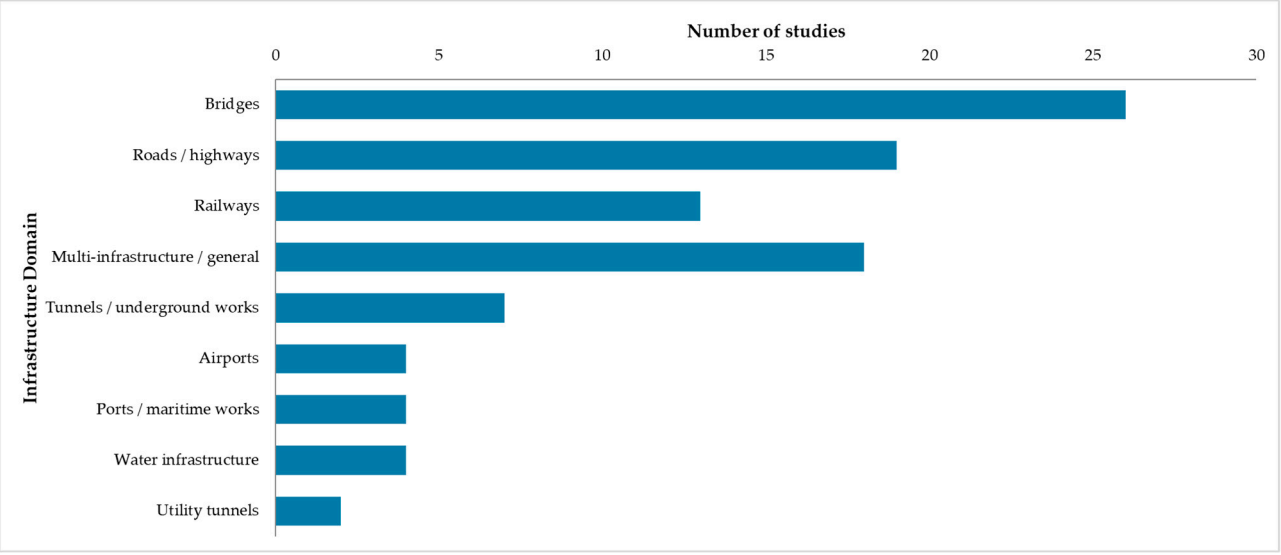


Figure 3. Distribution of included studies by infrastructure domain.

Table 3. Distribution of studies by infrastructure domain.

Infrastructure Domain	*n*	%
Bridges	26	26.8
Roads/highways	19	19.6
Multi-infrastructure/general	18	18.6
Railways	13	13.4
Tunnels/underground works	7	7.2
Airports	4	4.1
Ports/maritime works	4	4.1
Water infrastructure	4	4.1
Utility tunnel	2	2.1

3.4. Lifecycle Orientation

Fifty-four studies (55.7%) focus primarily on operations, maintenance, or asset management, while 23 (23.7%) explicitly address the entire lifecycle. Together, these two categories account for 77 studies (79.4%). Eleven studies (11.3%) are mainly oriented toward design/construction, five (5.2%) toward the handover-O&M transition, one (1.0%) toward end-of-life/deconstruction, one (1.0%) toward construction/rehabilitation, and two (2.1%) adopt a multiple or general orientation. By sector, 15 of the 19 road studies focus on O&M/asset management; among bridge studies, 15 focus on O&M and eight take a whole-lifecycle view; among rail studies, seven of 13 adopt a whole-lifecycle perspective (Figure 4).

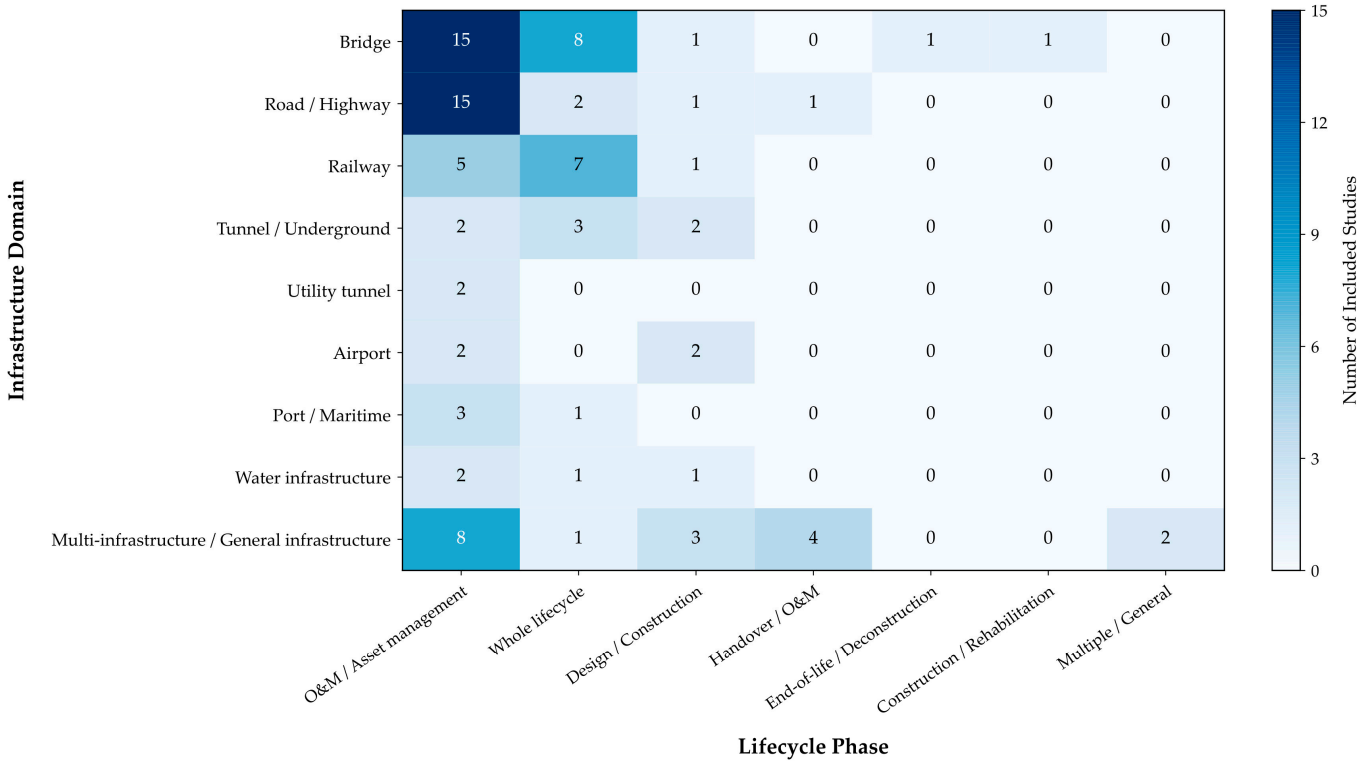


Figure 4. Distribution of lifecycle orientation across infrastructure domains ($n = 97$).

3.5. Information Roles and Technology Clusters

Interoperability and data modeling are the dominant information role in 65 studies (67.0%). These are followed by applications in which BIM serves as a core asset information model (12 studies; 12.4%), as an integration layer (9; 9.3%), studies centered on information requirements/governance (6; 6.2%), and studies in which decision support is the dominant role (5; 5.2%). This finding suggests that the field is concerned less with geometric modeling alone than with the ability to exchange, connect, and reuse infrastructure information across heterogeneous systems (Figure 5, Table 4).

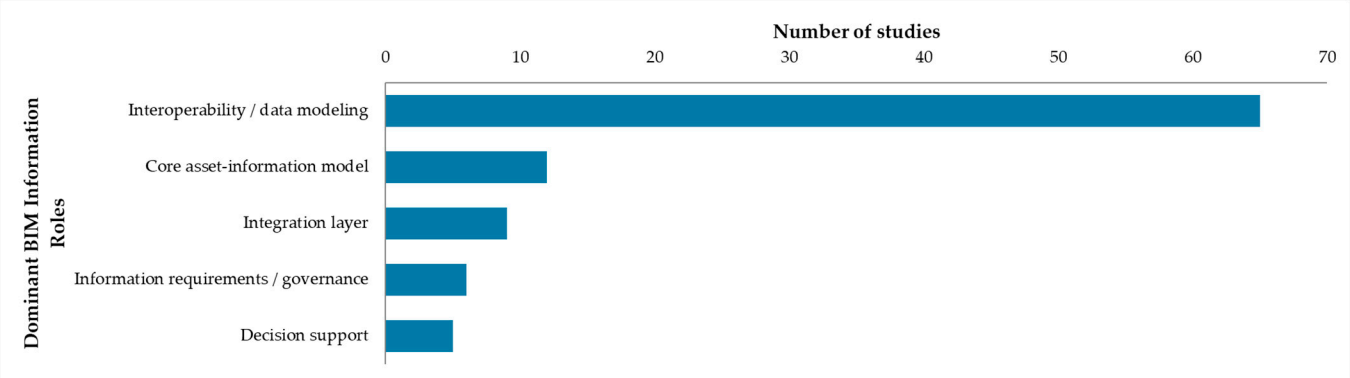


Figure 5. Distribution of dominant information roles assigned to the included studies ($n = 97$).

Table 4. Distribution of dominant information roles. Each study has one primary role; the categories are mutually exclusive.

Dominant Information Role	*n*	% of Corpus
Interoperability/data modelling	65	67.0%
Core asset-information model	12	12.4%
Integration layer	9	9.3%
Information requirements	6	6.2%
Decision support	5	5.2%

The non-exclusive coding of technology clusters supports this interpretation. Percentages are calculated on the 97 included studies; a study may be assigned to more than one cluster. Digital Twin/IoT/SHM appears in 49 studies (50.5%), while 47 studies (48.5%) use open standards or semantic interoperability mechanisms, including IFC/openBIM, ontologies, Linked Data, ICDD, CDE, COBie, ISO 19650 [107], or BCF. Thirty-five studies (36.1%) integrate BIM with asset management systems or web/cloud platforms; 26 (26.8%) use reality capture or automated inspection techniques; and 24 (24.7%) address BIM-GIS integration. Information requirements/governance are explicit in 10 studies (10.3%) (Figure 6, Table 5), whereas decision support or maintenance prioritization is coded separately as the dominant role in only five (5.2%) (Figure 5, Table 4). Dominant role counts and technology frequencies describe different variables. The 65 studies with interoperability/data modelling as their dominant role should not be equated with the 47 studies coded for open standards/semantic interoperability. Likewise, the Digital Twin/IoT/SHM count of 49 identifies studies within a combined technology group; it does not quantify validated operational Digital Twins or demonstrated maintenance benefits. Co-occurrences include Digital Twin/IoT/SHM with asset management integration in 25 studies and with reality capture/inspection in 21 (Supplementary Table S3.2).

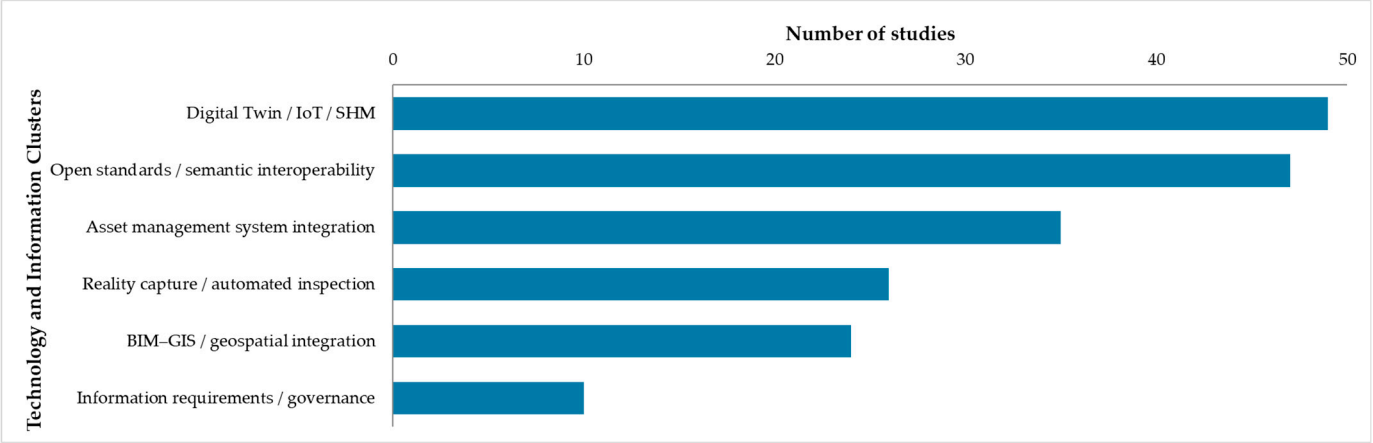


Figure 6. Frequencies of the six non-exclusive technology and information groups (n = 97). A study may belong to more than one group; decision support as a dominant role is reported separately in Figure 5.

Table 5. Frequencies of non-exclusive technology and information groups.

Cluster	*n*	% of Corpus
Digital Twin/IoT/SHM	49	50.5
Open standards and semantic interoperability	47	48.5
Integration with asset management systems	35	36.1
Reality capture/automated inspection	26	26.8
BIM-GIS/geospatial integration	24	24.7
Information requirements and governance	10	10.3

3.6. Observed Integration Configurations

The studies show several recurring integration configurations. In rail systems, BIM is linked to GIS to locate assets and make O&M data queryable; IFC allows geometry and attributes to be separated and transferred into geospatial environments [10,18,20]. In the road domain, asset location and identification are prerequisites for connecting AMS, BIM, GIS, and field data [9,12,77]. For bridges, integration extends to inspections, point clouds, UAVs, SHM, and Digital Twins, with increasing attention to continuity among geometric representation, asset condition, and decision models [13,35,45,47,48,75].

A second group of studies uses the Semantic Web and ontologies to address the limitations of file-based exchange. ICDD, RDF/OWL, Linked Data, and domain ontologies can link BIM objects to damage, inspections, management databases, or asset management concepts without necessarily imposing a single monolithic schema [23,28,88,105]. In ports, COBie has been adapted to manage maintenance data, while semantic alignment and cross-domain transformation approaches are emerging in water systems and linear infrastructure [51,82].

Finally, the most recent studies tend to incorporate dynamic data. The Cavour Canal aqueduct case brings together metric survey data, an information model, IoT sensors, and a cloud database to turn a static representation into an updated digital shadow [33]. Similarly, platforms for bridges and railways integrate sensors, dashboards, GIS, and BIM models to support monitoring, resilience, and operational management [16,45,48,89].

Table 6 compares ten included studies by information mechanism, implemented function, and validation limitations. For bridge O&M, IFC/GIS exchange requires mappings that preserve object identity and the meaning of defects across platforms; point-cloud and

monitoring workflows must instead connect observations to an asset model and an explicit decision method. Gao et al. [45] use a pilot bridge and customized defect representations; Matrone et al. [33] demonstrate one-way updating of a digital shadow. Mohammadi et al. [13] propose formal prioritization and budget-constrained intervention choices for a bridge. These mechanisms address different operational questions. The conceptual BIM-PMS framework [15] and planned CEMBOX components [104] must be distinguished from functions already demonstrated. None of these examples alone establishes longitudinal maintenance effectiveness across an entire network.

Table 6. Comparison of selected studies by information mechanism, implementation status and validation limitations. The cases show differences and do not rank study quality.

Study	Mechanism/Function	Implementation Status and Validation Limitations
[45] Gao et al.	Pilot BIM–GIS bridge and defect information	Pilot demonstrated; customized JSON representation limits the generality of exchange.
[33] Matrone et al.	Survey/HBIM linked to aqueduct sensors	One-way digital shadow; reliable alert thresholds still require validation.
[48] Rico-Thirion et al.	Object identity and event-driven semantic interaction	Feasibility demonstrated on a bridge and in controlled scenarios; automation and scalability limitations.
[13] Mohammadi et al.	TLS-derived BrIM, condition information, and budget-constrained intervention choices	Demonstration on one bridge; no longitudinal comparison of outcomes across the entire network.
[15] Utami et al.	Conceptual BIM–PMS framework for prediction and decision-making	Implementation and field validation identified as future work.
[104] CEMBOX	Management, inspection, and monitoring services	Implemented services distinguished from planning under development and future predictive components.
[28] Zabin et al.	Water asset information based on IFC, ontologies, and rules	Plant case and expert evaluation; sustained production operation not demonstrated.
[38] Bosurgi et al.	BIM-based attention indicators for road barrier inspection priorities	Verification on 10 km of Italian highway; sustained network-wide effects not demonstrated.
[88] Hagedorn et al.	Linked information containers and inspection data	Structured semantic exchange; transferability requires validation on additional assets/operators.
[90] Lee et al.	BIM and 3D GIS for utility tunnel operations	Real-world scenarios and user evaluation; distinct from measured, sustained maintenance effects.

3.7. Reported Benefits

The qualitative synthesis groups the reported benefits into four broad categories. The first is access to information: the model acts as a spatial interface for locating components, documents, defects, and maintenance activities [27,31,90]. The second is reduced fragmentation, achieved by linking BIM with GIS, AMS/BMS/PMS, databases, or information containers [12,15,88]. The third is automation, including Scan-to-BIM reconstruction, point-cloud segmentation, UAV-based damage mapping, and the transfer of inspection data [24,32,47,76]. The fourth is operational support, including monitoring, maintenance planning, condition assessment, and, in a smaller number of studies, explicit decision sup-

port [13,30,38]. These categories summarize reported functions and outcomes, rather than pooled estimates of effectiveness or independently verified maintenance savings.

3.8. Barriers and Limitations

The reported limitations show that technical maturity remains uneven. Several studies present a framework, prototype, or single case and require validation across larger networks, organizations, or time spans [15,19,21,23]. Interoperability continues to be constrained by incomplete infrastructure schemas, semantic or geometric mismatches, and transformations among IFC, GIS, and proprietary systems [10,26,77,96]. In Digital Twin applications, continuous two-way updating among the model, sensors, and management systems is not always built in and may require additional architecture [33,48].

Organizational barriers are also reported. Technology alone does not define Asset Information Requirements or align organizational goals with the information needed [14,91,103]. In existing systems, data quality, legacy systems, established procedures, digitalization costs, and skills can all limit scalability [22,25,75,95].

4. Discussion

RQ1. The corpus contains 73 of 97 studies published in 2022–2026; the count for 2026 is partial as of 16 August 2026. Bridges account for 26 studies, roads/highways for 19, and railways for 13. O&M/asset management is the dominant lifecycle orientation in 54 studies, while 23 address the whole lifecycle. The eligibility period is 2015–2026, whereas the included studies were published in 2016–2026 (Sections 3.2–3.4).

RQ2. Interoperability/data modeling is the dominant role in 65 studies. The overlapping technology clusters include 49 studies coded for Digital Twin/IoT/SHM and 47 for open/semantic interoperability. The five studies assigned a primary decision-support role do not capture all secondary decision-support functions. Relative frequencies are calculated using 97 as the denominator and do not measure standards adoption or Digital Twin maturity (Section 3.5).

RQ3. The synthesis identifies BIM–GIS exchange, links to asset management databases, semantic connections among distributed sources, and integration of inspection or sensor data. These configurations can occur together; their contribution depends on the functions demonstrated and the information preserved (Section 3.6).

RQ4. Reported benefits include access to asset information, reduced fragmentation, automation, and support for operational activities. Specific evidence includes pilot integrations, one-way updates using sensor data, and formal intervention choices [13,33,45]. Heterogeneous validation and conceptual contributions [15] limit inferences about sustained performance or network-wide cost savings (Sections 3.7 and 3.8). Reported barriers include semantic and geometric mismatches, incomplete exchange schemas, difficulties in maintaining model–sensor updates, unclear information requirements, legacy systems, data quality issues, digitalization costs, and skills gaps (Section 3.8).

RQ5. The synthesis suggests priorities for operational validation, semantic continuity, updating, governance, decision-support functions, and broader sectoral coverage. The proposed pathway organizes these capabilities into an interpretive framework; the corpus does not establish a universal or longitudinally validated development sequence (Sections 4.2 and 4.7).

4.1. From BIM as a Model to BIM as an Information Infrastructure

The review's main finding is the predominance of interoperability/data modeling: 65 of the 97 studies were assigned to this category. This changes the conventional interpretation of BIM for infrastructure. The central research question is no longer simply 'how should

the asset be modeled?' but rather 'how can the asset's information remain usable as the lifecycle phase, software, organization, and level of detail change?' Studies on rail openBIM, GeoBIM, and asset management systems show that even a formally rich representation can lose operational value if properties, classifications, spatial references, or relationships are lost during transfer [10,12,20,77].

This points to a conceptual distinction between a model and an information infrastructure. A model represents the asset. An information infrastructure also encompasses persistent identities, exchange rules, requirements, versions, links to documents and time-dependent data, responsibilities, and query services. Approaches such as cMod, ICDD, and Linked Data are significant precisely because they attempt to make explicit aspects that a static BIM model cannot adequately represent: history, links among sources, distributed semantics, and updating [19,23,88].

4.2. From BIM to the Digital Twin: Interoperability and Operational Data Integration

The distribution of clusters and the selected applications suggest complementary capabilities: BIM/BrIM provides the asset structure; IFC/openBIM, GIS, or semantic technologies enable interoperability; sensors, SHM, point clouds, UAVs, and management systems add observations of real-world condition; and analytical or decision-support functions apply this information for operational purposes. These capabilities are evident in studies that integrate GIS and BIM for bridge O&M, in Scan-to-BIM-to-Sim frameworks, and in platforms built around identity, semantics, and interaction [45,47,48]. This grouping reflects an interpretation of the applications reviewed. It does not establish that every application follows the same stages or that these constitute a necessary chronological sequence.

It would be an oversimplification, however, to regard every BIM + IoT integration as a mature Digital Twin. Some studies use the term for environments that remain largely updated visualizations or one-way integrations. Others explicitly address synchronization, real-time exchange, or links to management systems. The review therefore suggests assessing twin maturity in terms of the functions actually demonstrated: persistent identification, updating, bidirectionality, semantics, analytical capability, and decision support, rather than relying on the technology label alone [33,34,44,89,104].

The six dimensions in Table 7 define observable questions, not a cumulative maturity score. A capability should be recorded as described, demonstrated, not reported, or not applicable, with a precise reference to the source. Persistent identification and semantic mapping concern information continuity; updating concerns observed mechanisms for updating information; bidirectionality requires an explicit return flow; analytical capability requires a specified method and an evaluated result; and decision support requires alternatives, criteria, or constraints linked to a choice. The examples in Tables 6 and 7 illustrate these boundaries. A one-way digital shadow [33] does not demonstrate feedback to the physical system, and a conceptual decision-support component [15] does not equate to field validation. This is a descriptive framework for examining cases, not a retrospective score for all 97 studies.

For example, one-way updating in [33] does not demonstrate a return flow, whereas the formal prioritization and intervention methods in [13] document a decision-making function. The field validation planned in [15] must be distinguished from functions already demonstrated on a real asset.

Table 7. Observable dimensions of digital twin capabilities, with application examples.

Dimension	Observable Evidence
Persistent identity	Identifiers linking objects and external records, including their treatment during revisions or replacements. Example: object–record links in [48]; preservation during asset replacement requires separate evidence.
Updating	Source, frequency, and mechanism of data updates, with an update actually performed. Example: one-way sensor–HBIM updating in [33]; the frequency must be reported in the source.
Bidirectionality	Flow direction and an explicit return mechanism; distinguish software exchange from feedback to the physical or operational system. Example: one-way updating in [33] does not demonstrate operational feedback.
Semantics	Mappings of classes, properties, and relationships, with checks that operational meaning is preserved. Example: IFC/ontology mappings in [28,88]; exchange alone does not establish preservation of all semantics.
Analysis	Specified analytical methods and evaluated results; distinguish visualization, diagnosis, and prediction. Example: prioritization/condition methods in [13]; predictive validation in [15] remains future work.
Decision support	Explicit alternatives, criteria, and constraints, and how results inform maintenance choices. Example: budget-constrained interventions in [13]; conceptual component in [15].

4.3. Interoperability as Both a Technical and a Governance Challenge

The widespread use of IFC/openBIM and semantic technologies shows that open exchange is now a well-established priority. The studies nevertheless point to at least three distinct levels of interoperability. The first is geometric: objects and coordinates must be transformed correctly. The second is semantic: classes, properties, relationships, damage information, and operational meaning must be preserved. The third is organizational: stakeholders must determine what information is needed, who produces it, when it is validated, and which system is responsible for it. The first two levels dominate the literature; the third is less visible, as shown by the relatively small number of studies devoted to information requirements and governance [10,14,91,102,103].

This imbalance matters in practice. A technically interoperable workflow can still transfer information that is unnecessary, incomplete, or lacks clear ownership. Conversely, well-defined information requirements without robust exchange tools lead to manual processes. Mature asset information management therefore requires technical standards and governance to be aligned. IDS, AIR/OIR, and information management processes can provide the specification layer that connects organizational objectives to the data actually exchanged [14,21,91].

4.4. From Data Integration to Maintenance Value

A second key finding concerns the relationship between data integration and decision support. Five studies treat decision support or prioritization as the dominant role. This count does not include all secondary decision-support functions or explain why operational value may be difficult to achieve. Explanations involving standards, data quality, or organizational processes are therefore treated as source-specific barriers or research hypotheses, rather than causes inferred from the count.

Studies linking BrIM to decision support systems, Digital Twins to scheduled maintenance, or BIM to Pavement Management Systems show different levels of connection to maintenance planning [13,15,30]. Mohammadi et al. [13] demonstrate formal prioritization and intervention selection for a bridge, combining data integration, intervention criteria, and

budget constraints. Utami et al. [15] present a conceptual framework whose field validation remains future work. These examples demonstrate different levels of implementation and do not constitute a controlled comparison establishing which factors cause success or failure. The practical value of these applications depends on whether inspection records, sensor observations, and model-based information can support decisions on priorities, budgets, and the timing of interventions.

Future studies should therefore assess not only whether data can be exchanged, but also whether their use leads to measurable improvements in asset management. Relevant measures could include risk-based priority scores, condition-related performance indicators, reductions in diagnostic uncertainty, forecast accuracy, inspection and model-updating time, lifecycle costs, and the reliability of maintenance prioritization. Such measures would help trace a clearer path from data acquisition and integration to planning decisions and, ultimately, to intervention outcomes, risk reduction, and lifecycle optimization. This distinction is important because access to more data does not, by itself, result in better maintenance decisions.

4.5. Reality Capture, AI, and Updating As-Is Models

Reality capture and automation address a structural difficulty in managing existing infrastructure: the lack of reliable, up-to-date as-is models. Point-cloud reconstruction, semantic segmentation, UAV-based damage mapping, and GPR-to-IFC integration narrow the gap between physical condition and digital representation [24,32,35,73,76,79]. These approaches are especially relevant to bridges, roads, and railways, where scale, accessibility, and inspection frequency make manual updating costly.

Geometric automation alone, however, does not guarantee information quality. A recognized object must be classified, linked to a persistent identity, associated with a location, and placed within a structure compatible with the maintenance process. AI is therefore useful when it is part of a governed information pipeline, not when it produces an isolated output. Research should move beyond algorithmic accuracy alone and examine information traceability and the effect on decisions.

4.6. Differences Across Infrastructure Sectors

The predominance of bridges and roads influences the broader conclusions. For bridges, the combination of discrete assets, periodic inspections, SHM, and structural models encourages integration between BrIM and Digital Twins. At road-network scale, GIS, linear referencing, pavement management systems, and asset databases become more central. In railways, system complexity and long asset lives drive interest in lifecycle information management and cross-disciplinary interoperability. Ports, airports, water infrastructure, and utility tunnels offer promising cases, but the small number of studies limits generalizability [9,51,78,85,90,93].

4.7. Research Gaps and Research Agenda

The synthesis sets out seven priorities (Table 8). First, the field needs multi-asset, multi-year operational validation, not just proof-of-concept demonstrations. Second, infrastructure schemas and mappings need to be consolidated and tested for semantic loss and long-term compatibility. Third, Digital Twins should be assessed by their ability to synchronize dynamic data, not merely by the presence of sensors or dashboards. Fourth, information requirements and governance need to be built into technical architectures. Fifth, data must be linked to models of risk, cost, and maintenance priority. Sixth, the evidence base should be expanded to include more airports, ports, water infrastructure, and utilities. Seventh,

research should treat migration from legacy systems, data quality, cost, and skills as design variables rather than as problems external to the technology.

Table 8. Research priorities derived from descriptive findings in the corpus, barriers reported in the sources, and interpretive synthesis.

Gap	Evidence in the Corpus	Research Priority
Validation and scalability	Predominance of frameworks/platforms and numerous single cases	Multi-asset, longitudinal, and cross-operator validation using comparable KPIs
Interoperability and semantic completeness	65/97 studies centered on interoperability/data models	Stable infrastructure schemas, validated mappings, and semantic preservation
Operational synchronization	49/97 DT/IoT/SHM studies, but uneven real-time updating	Bidirectionality, temporal semantics, and robust live pipelines
Governance and requirements	Only 10/97 in the requirements/governance cluster	OIR/AIR/EIR/IDS linked to measurable O&M outcomes
Decision support	Only 5/97 with decision support as the dominant role	Prioritization based on risk, cost, condition, and lifecycle value
Sector imbalance	Bridges and roads dominate the corpus	Replication and validation in airports, ports, water infrastructure, and utilities
Legacy systems/data quality/costs	Recurring barriers in existing systems and data transformations	Migration strategies, quality metrics, and cost-benefit analysis

4.8. Limitations of the Review

This review has several limitations that should be considered when interpreting its findings. Sixteen potentially relevant reports could not be retrieved and were therefore not assessed in full text for eligibility, introducing a possible availability bias. The accessible corpus may underrepresent certain integration approaches, infrastructure contexts, implementation barriers, or unsuccessful applications. The direction and magnitude of this effect cannot be determined from abstracts or the included studies. The findings therefore describe accessible evidence and do not provide exhaustive coverage of infrastructure information management practices. In addition, the search covered English-language publications in Scopus and Web of Science, including conference and proceedings papers, but did not systematically include gray literature or other discipline-specific databases. Systematic backward and forward citation searching is not documented. Administrative reports, industry guidelines, and relevant studies indexed elsewhere may therefore have been missed. The common 2015–2026 eligibility period limits conclusions about earlier research. The rapid growth in publications observed in 2025–2026 also indicates that this is a fast-developing field and that the evidence base is likely to change as new studies become available. The identified gaps concern the retrieved academic corpus and do not demonstrate an absence of relevant methods or practices elsewhere.

The included studies also vary substantially in their methodological development and level of validation. The corpus ranges from conceptual frameworks and experimental prototypes to applications evaluated through case studies. This heterogeneity limits direct comparison and may affect the apparent maturity of some technologies. Moreover, the evidence is unevenly distributed across infrastructure domains, with a strong concentration on bridges and roads and much more limited coverage of water infrastructure, ports, and

airports. The findings should therefore not be generalized to all infrastructure sectors without caution.

Finally, the analytical categories were normalized to support a consistent synthesis of the literature. Screening and extraction were performed by one author and checked by the other, rather than through two independent assessments. No formal study-level risk-of-bias scores or inter-rater agreement statistics are available. Assigning a primary role to studies combining several technologies or functional roles inevitably required a degree of interpretive judgment. This process reduced some of the complexity of hybrid studies and made the boundaries between categories less clear-cut. Furthermore, most of the outcomes reported in the included papers are qualitative, demonstrative, or case-specific, preventing a quantitative meta-analysis of technology effects. These limitations constrain inferences about maturity, comparative performance, and sustained maintenance value.

5. Conclusions

This systematic review of 97 primary studies identifies BIM applications that connect asset models, information exchange, operational data and management functions. Interoperability/data modeling is the dominant information role in 65 studies (67.0%), while 77 studies (79.4%) focus on O&M/asset management or the whole lifecycle. These distributions show that the main emphasis of the retrieved literature is on managing and using asset information across the lifecycle. The main conclusion is that operational maturity cannot be inferred from technology combinations alone. Assessment should therefore examine whether a system preserves identity and meaning, receives up-to-date data, meets explicit information requirements, and supports verifiable decisions. Heterogeneous prototypes, conceptual frameworks, and case studies limit conclusions about sustained maintenance value and the relative effectiveness of technologies in infrastructure networks.

The corpus suggests that operational BIM environments rely on information exchange, links to field data, and explicit decision-support functions. The proposed pathway organizes these capabilities into an interpretive framework; it does not establish a universal sequence or demonstrate that every application must pass through the same stages. Future applications should therefore be assessed on real assets and networks and over sufficiently long periods, examining how identity, semantics, updating, governance, and decision support operate together, using reported metrics for data quality, maintenance performance, cost, and risk.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app162110749/s1, Table S1 provides a complete list of the 97 included studies; Table S2 presents the full search strings, filters, and access dates; Tables S3.1–S3.3 present study-level coding, technology co-occurrences and totals for the dominant information roles.

Author Contributions: Conceptualization, A.P. and L.I.; methodology, A.P. and L.I.; investigation, A.P.; data curation, A.P.; formal analysis, A.P. and L.I.; writing—original draft preparation, A.P.; writing—review and editing, A.P. and L.I.; supervision, L.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data analyzed in this systematic review were obtained from published sources. The Supplementary Materials provide a complete list of the included studies, the full search strings, and study-level analytical coding.

Acknowledgments: During the preparation of this study and manuscript, the authors used ChatGPT Work (OpenAI; GPT-5-based Codex) for limited organizational and editorial support, specifically

to assist with the presentation of the synthesis matrix, the structure of the manuscript, and English-language editing. Study selection, data extraction, classification, analysis, and scientific interpretation were performed by the authors and verified against the original sources. The authors reviewed and edited the assisted output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AIR	Asset Information Requirements
AMS	Asset Management System
BIM	Building Information Modeling
BMS	Bridge Management System
BrIM	Bridge Information Modeling
CDE	Common Data Environment
COBie	Construction-Operations Building information exchange
DSS	Decision Support System
DT	Digital Twin
GIS	Geographic Information System
ICDD	Information Container for Linked Document Delivery
IDS	Information Delivery Specification
IFC	Industry Foundation Classes
IoT	Internet of Things
O&M	Operation and Maintenance
OIR	Organizational Information Requirements
PMS	Pavement Management System
SHM	Structural Health Monitoring
UAV	Unmanned Aerial Vehicle
EIR	Exchange Information Requirements
GPR	Ground-Penetrating Radar
HBIM	Historic Building Information Modeling
TLS	Terrestrial Laser Scanning
RDF	Resource Description Framework
OWL	Web Ontology Language
AI	Artificial Intelligence
JSON	JavaScript Object Notation

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