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Review

Operational Embedding of Digital Twins in Building Operations and Maintenance: A China-Relevant Systematic Scoping Review with Implications for Existing Residential Buildings

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Abstract

Digital twins can supply building data while remaining weakly connected to maintenance decisions. This systematic scoping review examines the technical, organisational and institutional conditions of operational embedding and develops a framework for evaluation in existing residential buildings in China. Web of Science retrieval identified 198 retained publications, of which 104 underwent detailed coding: six residential-context anchors and 98 sources assigned adjacent evidence roles. Descriptive mapping of titles and reviewer-extracted summaries retained 58 terms describing BIM adoption, digital twin systems, technology integration and operational management. Qualitative synthesis links candidate barriers to six information functions: generation, quality assurance, integration, interpretation, use and learning. Source-reported residential problems are separated from functional evidence and review-derived propositions. Systemic misalignment specifies relationships between information resources, accountable actors and maintenance decisions, subject to ownership, funding, resident participation and physical-access conditions. Seventeen candidate critical success factors organise possible interventions. The contribution is a decision-level framework and an explicit account of the conditions for transferring adjacent evidence.

Keywords: digital twin; existing residential buildings; facilities management; operational embedding; systematic scoping review; data governance; socio-technical systems

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1. Introduction

1.1. Problem Framing

Digital twin (DT) research has developed a substantial conceptual and technical basis for applications in the built environment [1–3]. Its operational use in existing residential building operations and maintenance (BO&M) requires the coordination of legacy information, established work routines, resident-related data and governance responsibilities [3–6]. DTs can connect physical assets, digital representations, sensing, analytics, maintenance records, carbon data and resident feedback. Their operational value de-

pends on incorporating these resources into a governed and updateable information environment that supports identifiable decisions [7,8].

The problem addressed in this review is that the feasibility of DT adoption in existing residential BO&M is not guaranteed by the presence of enabling technologies [9]. A DT platform may exist, yet remain poorly connected to as-is asset information, maintenance routines, resident feedback, procurement incentives or governance responsibilities [5,6,10–12]. In this review, residential BO&M is treated as a setting in which resident conditions and operational responsibilities require joint consideration. Dwelling studies address comfort, indoor air quality and operational carbon [4–6], while adjacent sources address sensor information [13] and building-handover processes [14]. The review therefore distinguishes delayed adoption, partial deployment, weak operational embedding and low adoption readiness, while treating symbolic deployment as a source-specific interpretation requiring evidence of signalling or compliance-oriented use.

The review examines the relevance of existing evidence to residential BO&M in China. Residential studies establish the context, while digital twin, building information modelling–facility management (BIM–FM), sensing, governance and adoption research from adjacent settings informs the proposed mechanisms.

1.2. Literature Gap

Three strands of literature motivate the review. First, reviews of DT applications in construction and the built environment map technological developments, applications, implementation challenges and future research directions [15,16]. Second, the DT and existing-asset/FM literature highlights the importance of baseline modelling, data capture, semantic integration, monitoring and lifecycle information continuity [17]. Third, adoption and implementation research in BIM, FM, smart buildings and DT-adjacent settings identifies organisational capability, stakeholder coordination, value-case clarity, institutional support and procurement conditions as adoption determinants [8,14]. These strands are individually useful, but they remain insufficiently integrated for existing residential BO&M.

The literature identifies adoption constraints involving fragmented information, organisational capability, accountability and incentives [8,14,17–19]. The unresolved question is how these conditions interrupt particular decisions in occupied residential buildings. This review links three barrier domains to six information functions and specifies the actors, routines and authority involved in each proposed interruption. Residential observations, mechanisms drawn from adjacent settings and relationships developed through synthesis carry different evidential roles. The resulting contribution is a set of conditional explanations and candidate interventions that can be examined against maintenance records and decisions.

1.3. Aim, Research Questions

The study aims to develop a systematic scoping review, reported using PRISMA–ScR, of barriers and enabling conditions for DT adoption in BO&M, and to specify their conditional relevance to existing residential buildings in China. It connects technical, organisational and institutional constraints to interruptions in information use, identifies candidate critical success factors (CSFs), and develops a decision-level framework and item-development foundation for subsequent empirical testing.

RQ1. What technical, organisational and institutional barriers to DT adoption are reported in the literature on existing residential buildings and related BO&M contexts?

RQ2. What reported or inferred mechanisms link these barriers to delayed, partial or weakly embedded DT adoption?

RQ3. Which CSFs are reported or proposed to support operationally embedded DT adoption in existing residential buildings, and what evidence supports their relevance?

RQ4. How can these findings be synthesised into a systemic misalignment framework and empirical validation agenda for future testing?

The review links three barrier domains, six functions associated with the data-rich, information-poor (DRIP) dilemma and candidate CSF configurations. Together, these elements provide a framework for examining how interruptions in the use of information may contribute to delayed adoption, partial implementation or weak operational embedding.

2. Conceptual Background

2.1. Digital Twins as Operational BO&M Information Infrastructure

In BO&M, a DT is best understood as lifecycle information infrastructure that links physical assets, digital representations, operational data, analytics, decisions and feedback [20–22]. BIM provides the asset and geometry backbone; IoT sensors, building management system/building automation system (BMS/BAS) data, FM records, work orders, resident feedback, energy/carbon data and analytics provide dynamic operational content [23,24]. The transition from BIM or monitoring platform to DT depends on updating, interoperability, semantic alignment, actionability and governance rather than visualisation alone [25].

This distinction matters in existing residential BO&M because the corpus captures the infrastructural conditions through which BIM-FM, sensing, monitoring and data-governance arrangements evolve toward DT-enabled BO&M [6,8,11,14]. The main adoption question is whether baseline asset truth, data integration, work routines and governance conditions allow a DT platform to become operationally embedded decision infrastructure. Operational embedding denotes sustained incorporation of DT information into identifiable BO&M decisions, supported by assigned responsibilities, executable workflows and feedback that informs subsequent action. Related research on BIM-enabled asset information management in China identifies interdependencies among governance, interoperability and maintenance workflow capability [26].

2.2. Existing Residential BO&M as a Brownfield Adoption Context

Existing residential BO&M takes place in occupied buildings where asset information, spatial conditions and maintenance responsibilities must be considered together. The corpus includes dwelling-level carbon, comfort and indoor air quality studies [4–6], smart student accommodation [27], and adjacent evidence from modular construction and green office-building FM [28,29]. Where legacy records are incomplete, operational application requires as-is asset information sufficient for the intended decision [30–32]. Occupant-centred monitoring and retrofit assessment provide further evidence about energy use, environmental conditions and enclosure performance [33]. Table 1 summarises the physical, informational and organisational dimensions relevant to residential application.

Residential applicability depends on the relationship between the physical asset and the authority to maintain it. Under China's Civil Code, owners hold rights in exclusive units and share rights and management responsibilities in common parts; specified matters involve collective decisions, and management may be delegated to a property-service enterprise [34]. A technically actionable diagnosis may therefore require a separate decision about access, expenditure or service interruption. This allocation of authority is a substantive contextual condition for the proposed institutional mechanisms.

The physical baseline must also establish how an asset can be observed and

reached. As-is capture and spatially organised FM provide relevant foundations [32,35,36]. For residential application, the proposed baseline includes concealed service routes, structural and compartment boundaries, working clearances, circulation and the relationship between private and common spaces. These attributes constrain feasible sensor locations, survey coverage and maintenance access. An unobserved location should retain an explicit uncertainty status until verified. These deployment requirements extend the cited information-management foundations through physical and operational reasoning.

Table 1. Conceptual dimensions of brownfield residential BO&M for DT adoption.

Dimension	Existing Residential BO&M Interpretation	DT Adoption Implication	Representative Evidence
Place	Occupied dwelling, estate/community and local governance context.	Sensor locations, survey coverage and maintenance routes depend on circulation, working clearances and access to private and common spaces.	[4,27,37]
Product	Building fabric, mechanical, electrical, and plumbing systems, sensors, BIM/DT artefacts, asset registers and legacy records.	As-is models must identify assets, service dependencies, verified locations and unresolved information uncertainty at the level needed for the intended task.	[35,38,39]
Process	Audit, reverse modelling, monitoring, maintenance, retrofit/renewal, handover and carbon/IAQ/comfort feedback.	Information generation, verification, authorisation, physical access, maintenance and record updating must form an executable operational process.	[8,40,41]
People	Residents, owners, property managers, FM teams, contractors, vendors and regulators.	Operational embedding requires an explicit allocation of data, access and maintenance responsibilities, together with usable resident feedback and the capability to act.	[17,28,42]

Note: The implications specify synthesis-informed requirements for residential application; the cited sources provide the relevant contextual or information-management foundations.

2.3. Mechanism Lens: From the DRIP Dilemma to Systemic Misalignment

The data-rich, information-poor (DRIP) dilemma separates data availability from operational intelligence. In existing residential BO&M, surveys, BIM models, sensor streams, carbon and IAQ records, work orders and resident feedback may be present, but they become decision-grade only when they are validated, integrated, interpreted, used and fed back into future action [43–45].

Systemic misalignment refers to recurring incompatibilities between the information a DT supplies, the operational tasks actors are expected to perform, and the responsibilities, resources or incentives available for action. It is examined across data infrastructures, work routines, resident-sensitive feedback, procurement and governance arrangements. This lens proposes an explanation for delayed, partial or weakly embedded adoption even when individual technologies are available. Misalignment should be identified through a specified mismatch between these elements, rather than inferred from limited adoption alone.

2.4. Integrated Theoretical Lens: TOE, STS and Institutional Theory

The theoretical lenses have complementary analytical roles. The technology–organisation–environment (TOE) framework locates adoption conditions in technological, organisational and environmental contexts [46,47]. Socio-technical systems (STS) theory

examines the interdependence between technical arrangements and the organisation of work [48,49]. Institutional theory addresses how coercive, normative and mimetic pressures shape organisational practices and legitimacy [50–52]. Together, they direct attention to the information infrastructure, the work required to use it, and the authority and incentives governing that work.

The proposed synthesis contributes a decision-level specification of the relationship between these conditions. Its unit of analysis connects an information resource, an accountable actor and an identifiable BO&M decision. A barrier becomes analytically useful when it is linked to an interruption in generation, quality assurance, integration, interpretation, use or learning. Systemic misalignment identifies cross-domain conditions under which that interruption may persist. A valid alert without an authorised responder, or without a feasible route to the asset, illustrates a testable mismatch. The 17 CSFs organise candidate responses; their effects and the conditions under which they work remain empirical questions.

3. Methodology

3.1. Review Design

This study combines a systematic scoping review reported in accordance with the PRISMA extension for Scoping Reviews (PRISMA-ScR) [53] with descriptive term mapping, qualitative coding, evidence appraisal and theory-led thematic synthesis. A review protocol was developed before the review began; it was not registered. The 198-publication corpus supports descriptive profiling and term mapping. A purposively selected analytical subset of 104 publications supports detailed coding and mechanism development. Supplementary Tables A1–A3 document reviewer responsibilities, selection counts and exclusions; Supplementary Table A4 provides the PRISMA-ScR checklist.

3.2. Search Strategy, Screening Logic and Corpus Architecture

The Web of Science Core Collection was searched on 17 May 2026 and updated on 31 July 2026. The initial publication-year range began in 2010, with no additional database filters for language or document type. Figure 1 reproduces the Boolean logic. The search string was ALL = ((“digital twin” OR DT OR “building information model” OR BIM OR “internet of things” OR IoT) AND (“built environment” OR “building operation” OR “facility management” OR “facilities management” OR FM OR retrofi*) AND (China OR Chinese)). Web of Science provided a consistent multidisciplinary record structure for retrieval, bibliographic profiling and the source register. The use of one database defines a bounded corpus: Chinese-language research indexed primarily in CNKI, professional practice reports and material exclusive to other databases may be underrepresented.

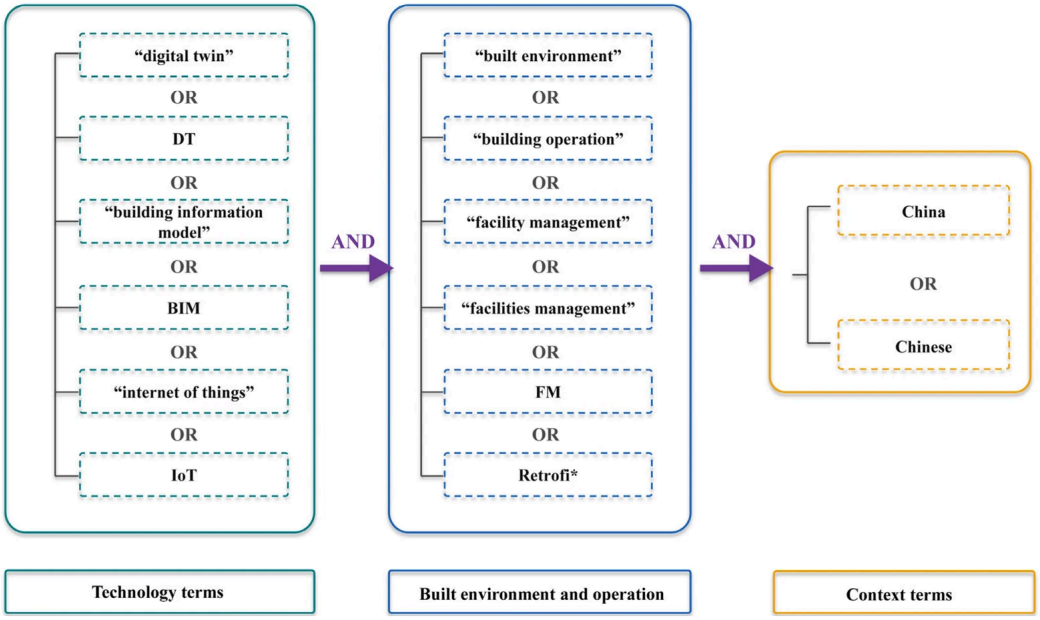


Figure 1. Executed Web of Science Core Collection search logic using the ALL field. Terms within each concept group are joined by OR, and the three groups are joined by AND. The initial search was conducted on 17 May 2026 and updated on 31 July 2026. Retrieval began with publication years starting 2010; subsequent date screening retained records from 2015 onwards. The asterisk (*) is a truncation wildcard representing zero or more characters; thus, retrofi* retrieves terms such as retrofit, retrofits and retrofitting.

Publication-year screening subsequently retained records from 2015 onwards. This was an eligibility refinement after the broader retrieval, and the change is retained in the selection accounting. The final period defines the scope of the synthesis around contemporary digital integration and operational implementation; it does not represent an established technological breakpoint. Its consequence is reduced coverage of earlier BIM/FM foundations. The 789 date exclusions are reported separately from relevance screening.

The ALL field searches across the bibliographic record, including address-related information. China/Chinese therefore defines a retrieval boundary and does not establish that every hit reports a Chinese case. Substantive China relevance concerns whether a mechanism addresses ownership and collective decision-making, delegated property management, maintenance financing and lawful processing of resident information in the target setting. Geographic coding and institutional applicability are interpreted separately.

Figure 2 summarises the study-selection process and allocation of the retained publications to the analytical and contextual subsets. The updated search identified 2434 records. Publication-year screening excluded 789 records published before 2015, leaving 1645 for title, abstract and keyword screening. Exclusion of 1157 records left 488 reports sought for retrieval. Six reports could not be obtained; two retracted publications were excluded before matrix entry. The remaining 480 records entered the evidence matrix for profiling and eligibility assessment. Eligibility exclusions comprised 159 technical-adjacent, 56 background-only, 45 distant-analogy and 20 policy-adjacent records, plus two redundant duplicates, giving 282 exclusions and 198 retained publications. No duplicates were removed before matrix entry. Supplementary Tables A2 and A3 report this accounting, and Supplementary Table B1 preserves the source-gate register. The retained set partitions into 104 analytical publications and 94 contextual publications, with no

overlap. The analytical subset contains six residential-context anchors and 98 publications assigned adjacent evidence roles; the contextual register and its context profiles appear in Supplementary Tables B2a–B2b.

One reviewer (Q.W.) conducted publication-year filtering, title, abstract and keyword screening, full-text eligibility assessment and allocation to the analytical and contextual subsets. N.B.Z. reviewed the final screening and eligibility outcomes.

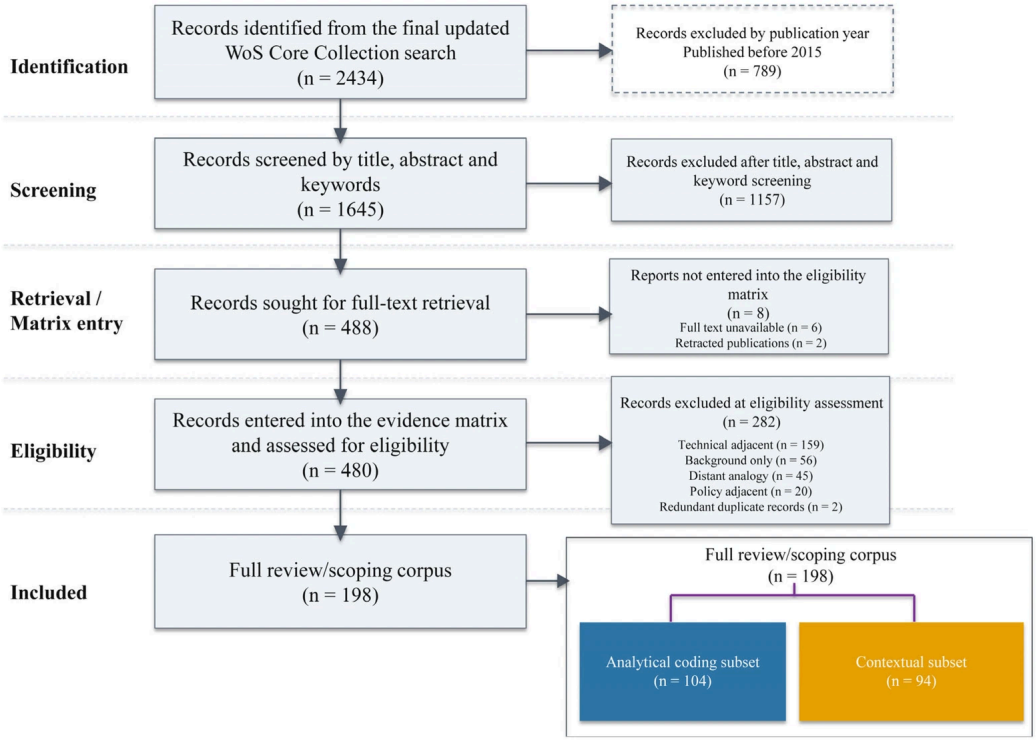


Figure 2. Study selection and allocation to the retained, analytical and contextual corpora. Counts reflect the search updated on 31 July 2026. The 104 analytical and 94 contextual publications are disjoint subsets of the 198-publication retained corpus. The six residential-context anchors are evidence roles within the analytical subset.

3.3. Eligibility and Source-Gate Rules

Retention required a core-direct or strong-adjacent contribution. Core-direct sources established the residential context; strong-adjacent sources contributed to DT-enabled BO&M, enabling information infrastructure, or adoption and implementation mechanisms. Topics included BIM-to-DT integration, sensing, smart FM, existing-building capture, performance feedback, governance, interoperability and lifecycle information continuity. Sources classified only as technical-adjacent, background, distant analogy or policy-adjacent were excluded. Within the retained corpus, allocation to the analytical subset was purposive and considered contribution to detailed coding, mechanism synthesis and thematic coverage. The remaining 94 publications supplied context and audit material. Source roles are recorded in Supplementary Table B1, analytical context in Supplementary Table D2b and study appraisal in Supplementary Tables F2c–F2d. These evidence roles describe use within the synthesis; a residential building label alone does not determine analytical eligibility or anchor status. Legal, theoretical and later contextual sources used to interpret the findings were not added to the frozen 198-publication corpus.

For the interpretation, transfer to residential BO&M is considered through four questions: whether the source addresses a comparable operational task; whether the re-

quired information and technical capability exist; whether an accountable actor can authorise and execute the action; and whether physical access, resident participation and funding are compatible with the response. These questions define the interpretive conditions of the synthesis. A high appraisal score for a hospital or infrastructure study cannot substitute for examining these conditions.

Hospitals and campuses can inform condition monitoring and maintenance scheduling when residential assets, staff capability and work-order authority are comparable; their centralised ownership, staffing and access assumptions require separate assessment [36,54,55]. Infrastructure studies can inform asset identification and condition updates, subject to differences in scale, failure consequences and operational control [56–58]. Construction research can inform handover and information requirements where responsibilities continue into occupation [8,14,28,59]. Temporary project arrangements do not establish sustained residential use. Supplementary Table J3 specifies these transfer conditions and examples.

3.4. Data Extraction and Coding

Q.W. conducted primary extraction, coding and appraisal, and N.B.Z. reviewed the final outputs. The extraction structure covered bibliographic and contextual information, technology, lifecycle, barriers, mechanisms, CSFs, outcomes and survey implications. The frozen codebook comprised 105 operational codes in 12 parent families. Supplementary Tables C1–C5 document the code structure and operational mappings; Supplementary Tables D1a and D2b–D2d contain the analytical study register, context descriptions and assignments. Supplementary Table D3 records selected thematic contributions and their interpretation.

The coding unit encompassed a meaningful finding, barrier statement, mechanism explanation, recommendation, outcome, case lesson or theoretical statement; an introductory passage was eligible when it contained a specific conceptual claim (Supplementary Table C2). Code-specific inclusion and exclusion rules determined assignment (Supplementary Table C4b). For example, TB4 included incompatible schemas, vendor formats, missing interfaces, IFC limitations, middleware needs or platform lock-in, and excluded general organisational silos without a technical or semantic exchange failure. This approach supported conceptual synthesis and could include both reported constraints and interpretive material.

For the evidence interpretation, an explicit barrier requires a source passage that identifies a difficulty, constraint, failure or unmet requirement and relates it to a specified information or operational task. A source-author explanation is distinguished from the underlying observation, and a review-derived inference is labelled as a proposition. Demonstrating an enabling technology, recommending a capability or mentioning a topic does not, by itself, establish an observed barrier. One study may support several categories, but repeated mentions do not create additional study-level occurrences. Supplementary Table J2 applies this distinction to the selected residential evidence.

The saved 104-study assignment matrix permits reproduction of the original coding totals. The totals describe thematic coding coverage within the analytical corpus. Section 4.2 presents the evidential status of selected residential interpretations.

The analytical categories were derived from the frozen codebook and the cumulative literature matrix. Resident and user evidence was mapped to T2 Organisational Work-as-Done, T3 Institutional Constraints or relationships across domains. Labels for mechanisms, outcomes and potential survey constructs were retained separately because they serve different analytical purposes. The eight DRIP operational codes were synthesised into six functions, with data inaccessibility and distrust treated as conditions affect-

ing multiple functions. The eight systemic misalignment codes were grouped into six analytical categories. Supplementary Table C4c records these mappings and preserves the original code identifiers and associated reliability calculations.

3.5. Inter-Coder Reliability and Coding Calibration

Inter-coder reliability was assessed using a stratified 25-study sample covering technical/data, organisational, institutional and source-boundary cases. Y.W. independently applied the frozen codebook to evidence class, main domain, barrier codes, DRIP codes, systemic misalignment codes and CSF codes without access to Q.W.'s coding assignments. The independently completed coding was compared with Q.W.'s primary coding, and N.B.Z. reviewed the comparison and final coding results.

Agreement was $\kappa = 1.000$ for evidence-class distinction and $\kappa = 0.861$ for main-domain assignment. For multi-label dimensions, binary code-wise Cohen's kappa and observed agreement were calculated. Median kappas were 0.905 for barrier codes, 0.662 for DRIP codes, 0.681 for systemic misalignment codes and 0.757 for CSF codes; corresponding mean agreements were 0.941, 0.845, 0.830 and 0.885. Code-wise kappas ranged from 0.451 to 1.000, 0.348 to 0.803, 0.328 to 0.905 and 0.171 to 1.000, respectively (Supplementary Tables E1–E3). This dispersion identifies categories requiring further refinement. In particular, CSF14 had $\kappa = 0.171$ and agreement = 0.520. Agreement describes reproducibility of the applied categories.

The 104 analytical studies were appraised for methodological quality, contextual relevance and empirical depth. Normalised 0–1 scores were combined into an evidence-weight indicator, with mean values of 0.846, 0.840, 0.774 and 0.820 for the three dimensions and combined indicator, respectively (Supplementary Tables F2b–F2d and F4). These are descriptive appraisal indicators. Residential interpretation additionally depends on the source's setting, evidential role and transfer conditions.

3.6. Synthesis Procedure

Descriptive statistics used the 198 retained publications. VOSviewer (version 1.6.21) mapped the recorded title together with the Core Argument and Key Findings fields, which are reviewer-extracted summaries. This input describes the operational topics represented in the evidence matrix and facilitates comparison across heterogeneous studies. It also incorporates reviewer selection and paraphrase, which may amplify terminology introduced during extraction. The procedure is therefore reported as descriptive term mapping of a curated representation of the corpus. Binary counting, a five-document minimum and association-strength normalisation were used; terms meeting the threshold were retained after the documented thesaurus rules. Supplementary Tables G7–G8 report the primary network and its complete term list.

Two comparisons used the same thesaurus and general mapping approach. The first mapped the nested 104-publication analytical subset from titles and summaries with a three-document minimum. The second mapped publication titles alone for all 198 records with a five-document minimum (Supplementary Table G9). The nested comparison changes both corpus membership and the occurrence threshold. The titles-only comparison more directly assesses dependence on the summary fields, although titles contain less descriptive detail than abstracts. Calculations compare the saved term tables using shared labels, top-20 overlap, occurrence ranks and cluster assignments (Supplementary Table G9). They are descriptive comparisons of existing network exports.

Coded barriers were organised into technical, organisational and institutional domains. Six DRIP functions located possible interruptions between available information and operational decisions; relationships across domains informed the systemic misalign-

ment propositions. CSFs were grouped by their proposed intervention function and linked to candidate constructs. The synthesis gives source-reported residential problems, residential functional evidence and adjacent mechanisms distinct roles, with transfer conditions stated in the interpretation. Figure 3 summarises the workflow.

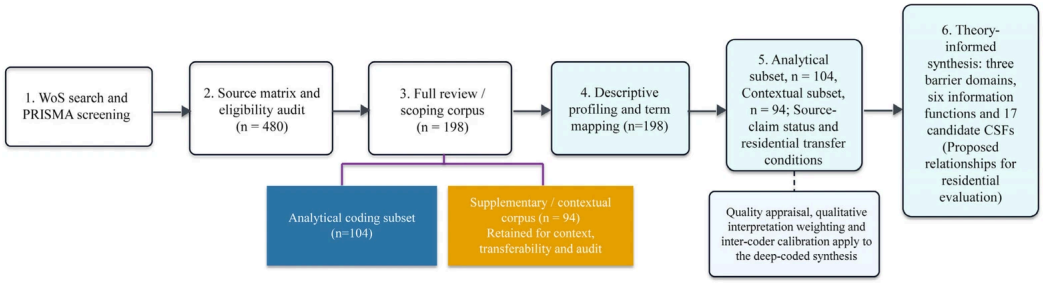


Figure 3. Review workflow and the roles of the retained evidence subsets. Descriptive profiling and term mapping use the 198-publication corpus; detailed coding uses the 104-publication analytical subset. Contextual records inform interpretation. Source appraisal, coding agreement and residential transfer conditions qualify the theory-informed synthesis.

4. Results

4.1. Descriptive Profile and Term Mapping of the Review Corpus

The 198-publication retained corpus was used for descriptive profiling and the primary term map of publication titles and reviewer-extracted summaries. The 104-publication analytical subset was deep-coded for barrier, DRIP, systemic misalignment, CSF, outcome and construct synthesis; the remaining 94 publications supported contextual interpretation and audit. Companion term maps examined the nested 104-publication subset and the titles of all 198 publications alone.

Figure 4 presents the publication years recorded in the frozen corpus matrix: 24 publications fall in 2015–2018, 70 in 2019–2022 and 104 in 2023–2026; the recorded peak is 2025. The 2026 count is partial and ends at the search update on 31 July 2026. Geographic coding identifies 154 of 198 publications as China-related, 25 as international or not country-specific, and the remainder as other or unclear regions.

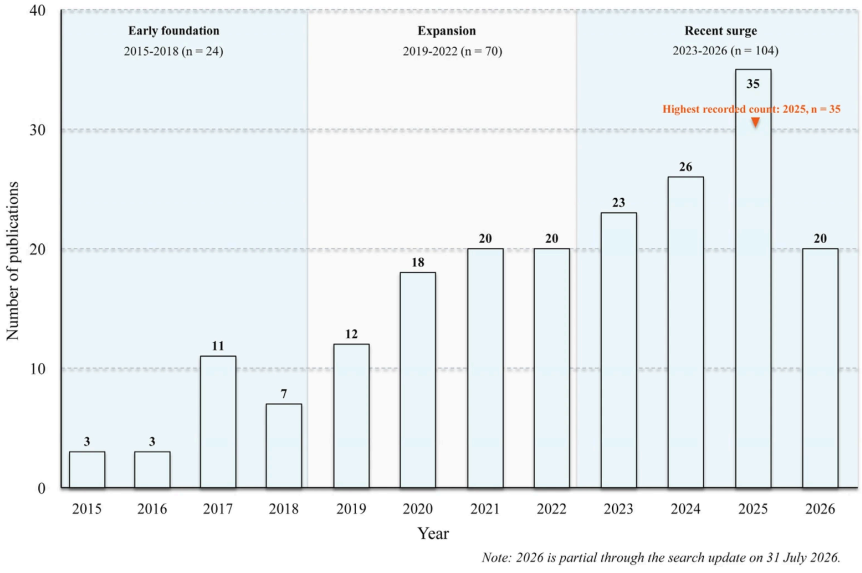


Figure 4. Publication years recorded in the 198-publication evidence matrix. The three displayed periods contain 24, 70 and 104 publications, respectively. The 2026 count is partial through the search update on 31 July 2026.

Table 2 summarises selected building-context, lifecycle, DT-maturity and methodological characteristics of the 198-publication corpus. The recorded profile includes 67 publications on buildings or FM broadly, 50 on AEC or construction projects, and 25 on public, commercial or institutional buildings. The reported residential-related count of 24 is reconstructed from the free-text context descriptions and includes mixed, conceptual and residential-like settings. Of these records, six are analytical anchors, nine are adjacent analytical publications and nine belong to the contextual subset (Supplementary Table J1). Thus, 98 adjacent analytical sources include some publications with residential descriptions; adjacency concerns their evidential relationship to the review question. The original normalised category flags are not reproduced in the supplement, so this crosswalk is presented as an explicit reconstruction, with borderline entries retained for inspection. Across the full corpus, 130 publications concern operation and maintenance or FM. BIM or openBIM appears in 136 records, sensing or monitoring in 75, FM information in 72, data integration or semantic/cloud platforms in 66, and analytics or control in 55; these overlapping technology categories describe enabling foundations as well as operational DT applications.

Table 2. Selected building, lifecycle, DT-maturity and method profiles of the 198-publication corpus.

Profile Dimension	Selected Category	Count	Percent of 198
Building context	Buildings/FM broadly	67	33.8%
Building context	AEC/construction projects	50	25.3%
Building context	Broad residential-related context descriptors	24	12.1%
Lifecycle	Operation and maintenance/FM	130	65.7%
Lifecycle	Retrofit/renovation/renewal as primary lifecycle classification	2	1.0%
DT maturity	BIM/FM foundation; no formal DT	85	42.9%
DT maturity	Conceptual/review-level DT or Cyber-Physical Systems	67	33.8%
DT maturity	Operational/decision-support DT	23	11.6%
Method profile	Case/field/platform validation	56	28.3%
Method profile	Review/synthesis	45	22.7%
Method profile	Survey/Delphi/SEM modelling	30	15.2%

Figure 5 presents the saved co-occurrence network of titles and reviewer-extracted summaries for the 198-publication corpus. The network contains 58 terms in one connected component, with 1082 unique links and total raw edge weight 3216. BIM has 86 publication occurrences and total link strength (TLS) 454; management has 54 and 318, data 49 and 270, system 43 and 187, operation 41 and 227, and integration 40 and 262 (Table 3). The four clusters contain 18, 17, 13 and 10 terms, respectively, and their interpretive labels are reported in Table 4. These clusters describe the lexical organisation of the curated title-and-summary input; the comparison with titles alone qualifies the stability of their membership.

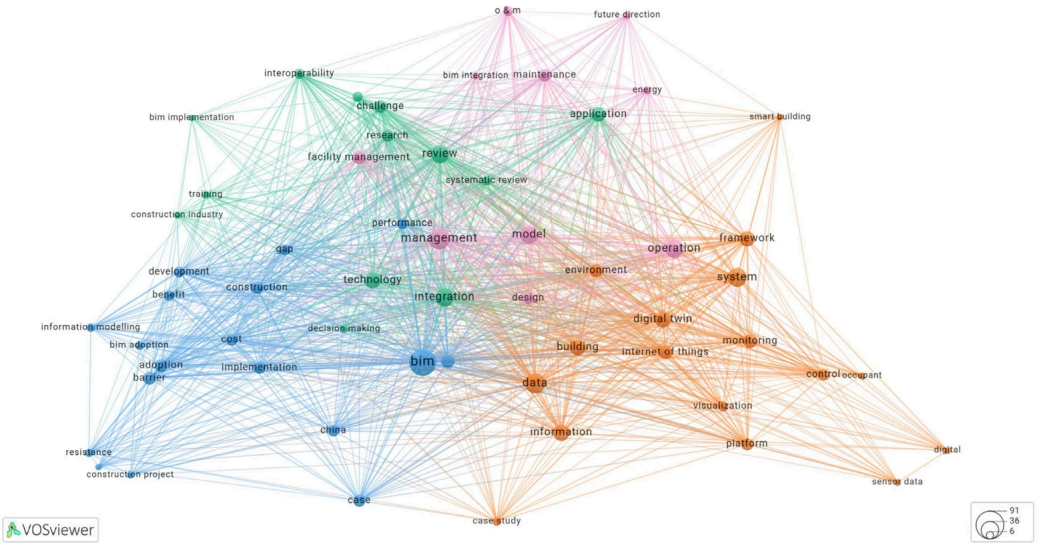


Figure 5. Co-occurrence network of publication titles and reviewer-extracted Core Argument and Key findings summaries for 198 retained publications. The saved network uses binary counting, a minimum occurrence of five publications and association-strength normalisation, and contains 58 terms in four clusters with 1082 unique links. Colours identify the saved clusters. Complete term values and input comparisons are reported in Supplementary Tables G7–G9.

The nested analytical-subset map retained 68 terms in six clusters at the three-publication threshold. It shared 48 terms with the primary map, including 16 in the two top-20 lists; the reported shared-term occurrence-rank correlation was Spearman ρ = 0.915 (Supplementary Table G9). The titles-only map retained 23 terms in four clusters. All 23 also occur in the primary map, but only nine terms are common to the two top-20 lists. Partition correspondence among the 23 shared terms was low (adjusted Rand index = 0.076; normalised mutual information = 0.273; Supplementary Table G9). For example, BIM, digital twin, operation and maintenance occur together in a titles-only cluster but span three primary-map clusters. Broad vocabulary therefore persists while thematic partitioning depends on the text input.

Table 3. High-frequency terms and total link strengths in the co-occurrence map.

Keyword/Term	Cluster	Occurrences	Total Link Strength
bim	1	86	454
management	4	54	318
data	2	49	270
system	2	43	187
operation	4	41	227
integration	3	40	262
review	3	38	230
model	4	38	186
information	2	32	163
technology	3	31	197
digital twin	2	31	187
building	2	29	142
framework	2	28	148
application	3	25	166

Keyword/Term	Cluster	Occurrences	Total Link Strength
monitoring	2	23	131
internet of things	2	22	134

Note: Occurrences count publication records under the stated text-extraction and cleaning rules. Total link strength is the sum of a term's incident raw co-occurrence weights. Terms are ordered by occurrence, then total link strength, then label. These counts describe the selected title and summary text; they are distinct from the technology classifications in Table 2.

Table 4. VOSviewer clusters and interpretive labels.

Cluster	Interpretive Label	Representative Terms
1	BIM adoption, barriers and value	bim; adoption; barrier; implementation; cost; benefit; resistance
2	Digital twin systems, monitoring and control	data; system; information; digital twin; monitoring; internet of things; platform; control
3	Technology integration and implementation research	integration; review; technology; application; challenge; interoperability; collaboration; training
4	Models for operation and facility management	management; operation; model; facility management; maintenance; design; o & m; energy

4.2. Barrier Mechanisms Across Technical, Organisational and Institutional Domains

The synthesis organises candidate barriers into T1 Technical Foundations, T2 Organisational Work-as-Done and T3 Institutional Constraints. The categories address potential interruptions of representation, sensing, integration, work allocation and authorised action. Resident participation, access, privacy, usability and feedback cut across T2 and T3. The evidential status of a residential interpretation depends on the particular source and claim.

Table 5 links the barrier categories to the BO&M functions they may interrupt and identifies the selected evidence basis for their residential interpretation. The table distinguishes a source-reported residential problem from a demonstrated information function and an inferred residential extension of adjacent evidence.

Table 5. Candidate barrier mechanisms, operational functions and evidential basis for residential interpretation.

Domain	Code	Barrier	Selected Evidence Basis for Residential Interpretation	Interrupted BO&M/DT Function	Representative Evidence
T1 Technical	TB4	BIM, IoT, FM and IFC-based interoperability and system interoperability gap	AT; residential extension inferred	Cross-platform data exchange, model-system connection and operational integration.	[13,60]
	TB5	Semantic asset, Mechanical, Electrical,	AT; residential extension inferred	Asset-object matching, MEP logic, FM	[61–63]

Domain	Code	Barrier	Selected Evidence Basis for Residential Interpretation	Interrupted BO&M/DT Function	Representative Evidence
		and Plumbing (MEP) and facility matching gap		classification and actionability.	
	TB6	Limited analytics, feedback and control readiness	RF for monitoring, assessment and control; broader analytics and control-readiness constraint inferred	Prediction, diagnosis, control, alerting and feedback-to-action.	[6,11,30,55,64]
	TB2	Weak baseline and as-is building information	SR for missing baseline information	As-is model creation, asset registers and retrofit-readiness assessment.	[5,31,32,65]
	TB1	Data silos and fragmented multi-source data	SR for information silos	BIM, IoT, BMS, maintenance, carbon, IAQ and residents-feedback integration.	[6,60,66,67]
	TB7	Cybersecurity, data ownership and technical trust limitations	AT; residential extension inferred	Data access, sharing legitimacy, security and confidence in DT outputs.	[68,69]
	TB3	Sensor deployment, data-quality and processing constraints	RF for dwelling measurement; deployment constraints inferred	Low-intervention sensing, monitoring reliability, calibration and processing.	[4,6,18,70]
T2 Organisational	EB1	High upfront cost, resource and manpower constraints	AT; residential extension inferred	Investment continuity, staffing, platform operation and model maintenance.	[71,72]
	EB2	Unclear value case, payback and benefit allocation	RI from residential renewal and value context [10]	Business-case justification, value distribution and adoption commitment.	[10,20,73,74]
	EB3	Split incentives between owners, landlords, residents and FM actors	RI; split-incentive mechanism requires testing	Benefit sharing, data provision, residents cooperation and funding alignment.	[20,74]
	EB4	Procurement does not reward lifecycle data or feedback	AT; no historical assignment to six anchors	Information requirements, model updating, handover and post-occupancy learning.	[14,75]
	UB5	Digital exclusion, usability and trust barriers	AT; no historical assignment to six anchors	Resident participation, interface usability, trust and feedback quality.	[76,77]
	LB3	Intervention, commissioning and handover data loss	AT; no historical assignment to six anchors	Lifecycle information continuity from intervention to BO&M.	[8,14,75]

Domain	Code	Barrier	Selected Evidence Basis for Residential Interpretation	Interrupted BO&M/DT Function	Representative Evidence
	OB1	Siloed project and FM workflows	SR for identification–resolution gap	Work orders, maintenance prioritisation, decision rights and operational embedding.	[6,54,78]
	OB2	Unclear data/model responsibility	AT; accountability mechanism inferred	Model updating, validation, stewardship, access rights and action authority.	[79,80]
	LB2	Design-operation disconnect	SR for evaluation–design–operation fragmentation	Feedback from operation to retrofit/design decisions and model requirements.	[11,81,82]
T3 Institutional	IB5	Policy uncertainty and regulatory misfit	RI; institutional effect requires testing	Legitimacy, compliance, approval and alignment with policy incentives.	[83,84]
	IB2	Authority, control and compliance constraints	RI from authority and approval conditions	Who may collect, validate, access and act on DT-enabled data.	[34,85,86]
	IB1	Standards, protocol, metadata and governance gap	AT; residential extension inferred	Information standards, metadata rules, data governance and interoperability.	[87,88]
	IB4	Conservation and low-intervention requirements	SR for historic-dwelling intervention constraints; broader access inferred	Occupied-home access, conservation-compatible monitoring and non-invasive deployment.	[5,89,90]
	IB3	Unresolved resident-data processing and governance responsibilities	RI from statutory processing duties; operational constraint requires testing	Resident-sensitive data collection, consent, privacy and cybersecurity safeguards.	[91–93]
	IB6	Property-renewal and ownership fragmentation	RI from property-plot renewal and ownership context	Decision authority, value distribution and renewal/management responsibilities.	[10,34,94]

Note: T1 denotes technical/data foundations; T2, organisational work-as-done; and T3, institutional constraints. SR denotes a problem or constraint explicitly described by a residential source. RF denotes a demonstrated residential information function, with the barrier interpretation inferred in this review. AT denotes an adjacent-source function. RI denotes a residential contextual or institutional interpretation developed in the review.

Selected residential sources explicitly describe information and workflow problems. Qian et al. describe information silos and a gap between identifying an IAQ problem and resolving it for end users [6], supporting the relevance of TB1 and OB1. Their vernacular-dwelling decarbonisation study identifies fragmentation across evaluation, design and operation [11], which informs LB2 and the feedback problem. The historic-dwelling carbon study discusses missing architectural drawings and constraints on in-

tervention [5]; this supports a source-reported baseline-information limitation and the conservation-specific aspect of IB4.

T1 concerns the technical basis for using DT information in BO&M. Adjacent studies establish functions for semantic matching, interoperable exchange, as-is modelling, diagnosis and control [13,31,32,35,60]. Residential thermal-comfort, IAQ and carbon studies establish the relevance of spatially and temporally specific observations and their integration into assessment [4,6,11]. The review infers that unreliable asset identity, incomplete baseline information or unsuitable sensing coverage can interrupt these functions. Each interpretation requires verification of the asset, space, measurement and intended decision in the target building.

The physical interpretation of T1 extends baseline and sensing requirements to spatial feasibility [30,38,64]. A model may identify a component while omitting the route needed to inspect or replace it. Concealed services restrict verification; structural and compartment boundaries constrain installation; and access through private dwellings or occupied circulation routes affects scheduling. These considerations specify variables for future residential evaluation. CSF1 and CSF3 should establish feasible sensing and verified spatial records, while CSF5 should connect components to service dependencies, access routes and intervention locations.

T2 concerns the routines through which information enters maintenance work. Adjacent studies on handover, organisational change and maintenance scheduling support the relevance of information requirements, work orders and update responsibilities [8,14,20,54,73,78]. The proposed residential mechanisms include resource continuity, value allocation, procurement, model stewardship and resident communication. In the historical coding record, EB4 lifecycle procurement, UB5 digital exclusion and usability, and LB3 handover loss have no assignments to the six residential anchors. Their relevance to residential BO&M is therefore advanced through adjacent evidence and explicit reasoning, rather than as a direct finding from those anchors.

Residents contribute information about comfort, IAQ, behaviour and service problems, as illustrated by dwelling, smart-living and occupant-behaviour research [4,6,27,37,42]. Translating such evidence into work-as-done requires a usable feedback channel, a named responder and a procedure for reporting the outcome. Privacy, permission to enter a dwelling and participation in a maintenance decision are separate requirements; satisfaction of one does not establish the others. Their operational relationship is a proposition to examine in the target management arrangement.

T3 concerns authority and obligations governing the use of DT information. In Chinese multi-owner residential settings, exclusive and common property have different implications for access and expenditure. Civil Code provisions on collective decisions and shared maintenance funds make approval routes relevant to common-asset repair and renewal [34]. These provisions inform the interpretation of IB2 and IB6. Personal-information processing is additionally governed by requirements concerning purpose, proportionate collection, a lawful basis, notification and processor responsibilities [93]. Consent is relevant where it is the applicable legal basis. The residential renewal and monitoring sources [5,6,10,11] provide contextual and functional evidence, while adjacent security and governance studies [68,85–87] inform possible arrangements for stewardship and access.

The domains may interact at the point of action. An uncertain asset model can undermine interpretation; a valid diagnosis may still lack an authorised responder, an agreed funding route or feasible physical access. TOE locates these conditions, STS examines their interdependence in work, and institutional theory addresses authority and incentives. The framework treats these connections as conditional explanations to test

through decision records, completed work and unresolved or deferred maintenance episodes.

4.3. How DRIP Converts Data Availability into Information Poverty

DRIP describes a failure to turn available data into information that supports operational decisions. The six functions locate distinct interruptions: missing data, unreliable records, disconnected systems, weak interpretation, limited use and absent feedback. Generation and quality affect the representation of the building; integration and interpretation affect decision support; use and learning concern what happens after information reaches operational staff. Systemic misalignment proposes how responsibilities, routines and governance may allow these interruptions to persist. Figure 6 summarises the six functions.

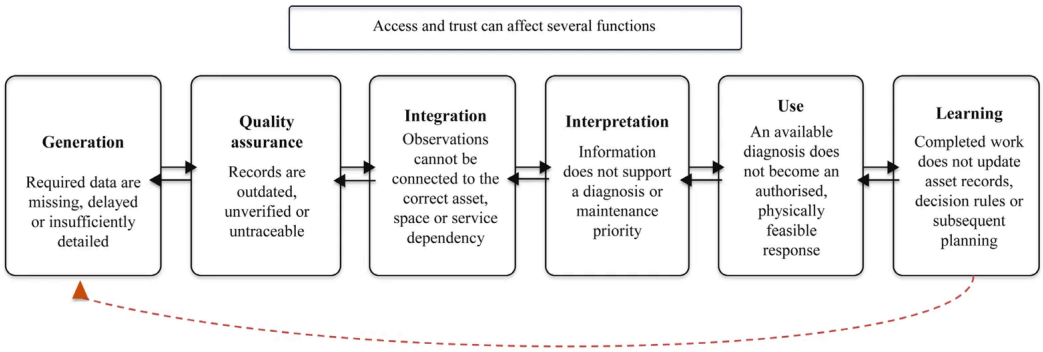


Figure 6. Six interacting information functions and synthesis-derived examples of interruption in existing residential BO&M.

Table 6 identifies six analytical points at which residential BO&M data may fail to become decision-grade intelligence. The functions are interdependent rather than a fixed cumulative sequence: limitations in generation and quality may undermine baseline trust, integration and interpretation may constrain decision support, and use and feedback may reveal a need to revise earlier information. This pathway links DRIP to systemic misalignment by locating potential interruptions through which technical, organisational and institutional constraints affect data-to-action processes.

Table 6. Six DRIP functions, illustrative interruptions and proposed implications for operational embedding.

DRIP Function	Failure Condition	Illustrative BO&M/Residential Example	Proposed Implication for Operational Embedding	Representative Evidence Basis
Data generation failure	Necessary data are not collected, collected too late or unavailable at needed granularity.	Missing as-built drawings, incomplete condition survey, limited IAQ/comfort sensing, restricted occupied-home access.	The DT begins with a partial or uncertain representation.	[95–97]
Data quality failure	Data are inaccurate, inconsistent, outdated, unvalidated or insufficiently trusted.	Uncalibrated sensors, outdated asset registers, inaccurate MEP information, poorly maintained BIM/FM records.	Actors hesitate to rely on DT outputs for decisions.	[6,8,11,98]
Data integration failure	Data exist in multiple systems but cannot be	BIM, IoT, BMS, maintenance logs, complaints, carbon data	Adoption remains partial, platform-	[99–101]

DRIP Function	Failure Condition	Illustrative BO&M/Residential Example	Proposed Implication for Operational Embedding	Representative Evidence Basis
	connected into a lifecycle information environment.	and retrofit records remain separate.	specific or pilot-like.	
Data interpretation failure	Visible or integrated data are not translated into diagnoses, priorities or decision rules.	Dashboards show IAQ, energy or carbon metrics but no thresholds, escalation rules or responsibility allocation.	The DT becomes a display system rather than decision infrastructure.	[62,102,103]
Data-use failure	Information is available but does not change routines, procurement, maintenance or resident engagement.	An IAQ or energy-management platform provides measurements or predictions, but no corresponding control or maintenance response is initiated.	Information may remain weakly connected to recurring operational decisions.	[6,11,30]
Data-learning/feedback failure	Operational experience is not fed back into models, future retrofit, maintenance planning or organisational learning.	Monitoring or asset-condition information is not used to update maintenance planning or subsequent operational decisions.	The DT does not mature into a learning infrastructure.	[56,104]

Note: The failure conditions and examples are synthesis-derived analytical illustrations. The cited studies inform the relevant data or management functions.

Table 6 identifies potential interruptions across the six data functions. Residential studies illustrate the use of monitoring data for indoor-air-quality control and carbon assessment [6,11], while a net-zero-energy building study links integrated O&M data, simulation and automated feedback [30]. The resulting data-use proposition concerns the conditions under which an available diagnosis becomes an authorised operational response. Adjacent studies address technology-supported university FM [104], integrated asset-condition assessment [56] and the combination of lifecycle asset information with post-hazard condition data [57]. These studies inform the information-management functions represented in the framework. The proposed learning mechanism concerns whether the outcome of an action updates asset records, decision rules and subsequent maintenance planning.

4.4. Systemic Misalignment Framework and Intervention Configurations

Figure 7 connects barrier domains, proposed misalignment mechanisms and interruptions of the six information functions. The links represent proposed relationships for empirical evaluation. Table 7 specifies these relationships and candidate interventions. The unit of analysis is an information resource, an accountable actor and an identifiable maintenance decision, considered within the ownership and spatial conditions that make action possible.

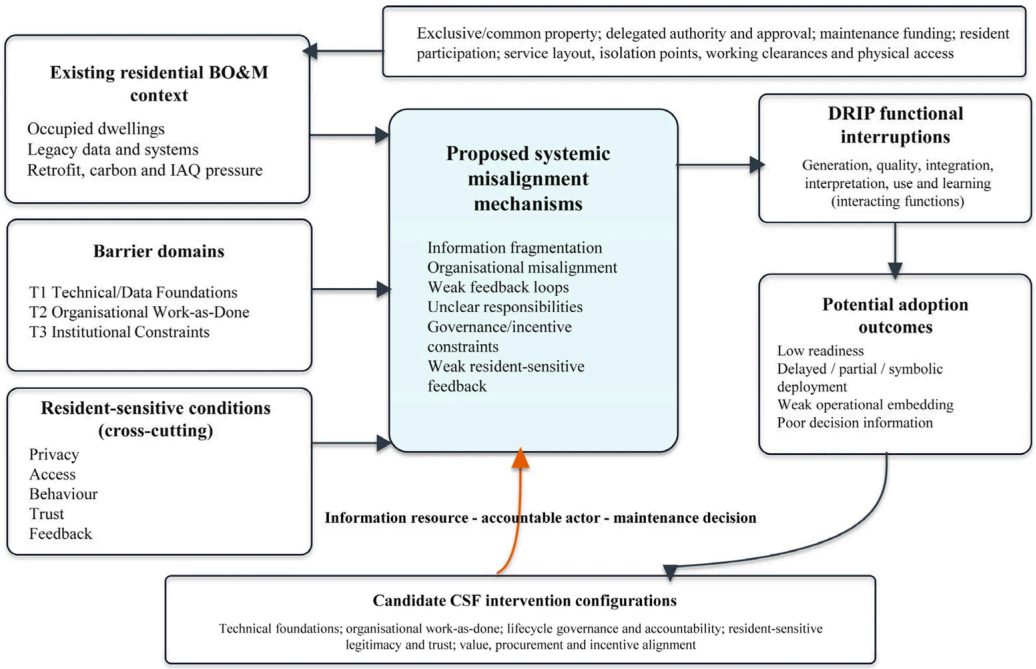


Figure 7. Proposed systemic misalignment framework for DT use in existing residential BO&M. The framework links an information resource, an accountable actor and an identifiable maintenance decision under specified ownership, governance and physical-access conditions.

Table 7. Proposed systemic misalignment mechanisms and candidate intervention logic.

Proposed Mechanism	Definition	Proposed Interruption of DT Adoption or Embedding	Candidate CSF Interventions	Representative References
Information fragmentation	Building, residents, energy, carbon, maintenance, retrofit and model information are split across systems, actors and phases.	Prevents a coherent DT information environment and increases uncertainty about model validity.	Lifecycle information requirements; as-is modelling; multimodal integration; IFC/ontology/middleware.	[36,58,66]
Organisational misalignment	Technical systems, routines, decision rights, procurement and residents-facing practices are not aligned with DT-enabled work.	DT outputs remain outside work orders, maintenance prioritisation, residents communication and model updating.	Training; actionable visualisation; manager-residents/FM feedback; predictive maintenance; phased deployment.	[59,73,105]
Weak feedback loops	Monitoring, post-occupancy evaluation and building performance evaluation (POE/BPE), resident feedback and maintenance evidence are not returned to models or future decisions.	The DT remains static or display-oriented rather than becoming a learning infrastructure.	POE/BPE protocols; model-update plans; lifecycle handover; organisational learning routines.	[41,54,82]
Unclear responsibilities	No actor clearly owns data collection, validation, model updating, residents-data governance, access rights or action authority.	Actors hesitate to use DT outputs because accountability and legitimacy are uncertain.	Data stewardship; responsibility matrices; access rules; action escalation procedures.	[69,75,87]

Proposed Mechanism	Definition	Proposed Interruption of DT Adoption or Embedding	Candidate CSF Interventions	Representative References
Governance and incentive constraints	Rules, standards, procurement, funding and incentives do not consistently reward lifecycle data and operational learning.	Rules and incentives may favour initial delivery or compliance over continuing operational use.	Procurement alignment; value-case clarity; policy support; standards and metadata governance.	[20,28,74]
Weak resident-sensitive feedback	Residents are treated as data subjects or sources of uncertainty rather than feedback participants.	Consent, trust, behaviour, comfort and complaints are excluded from decision loops.	Consent protocols; residents communication; feedback interfaces; privacy-by-design safeguards.	[27,37,42]

The mechanisms in Table 7 can be examined through their distinct operational consequences. Fragmentation concerns whether records can be connected [36,58,66]; unclear responsibility concerns who validates information and acts on it [69,75,87]. Work organisation concerns whether the decision enters a feasible task and schedule [59,73,105], while governance and incentives concern the authority and resources required for that task [20,28,74]. Feedback concerns whether the intervention and residents' experience revise subsequent information and decisions [6,8,11,14,27,37,42].

Table 8 groups 17 literature-derived CSFs into five candidate intervention configurations: technical foundations, organisational work-as-done, lifecycle governance and accountability, resident-sensitive legitimacy and trust, and value, procurement and incentive alignment. Each configuration addresses one or more mechanisms in Table 7.

Table 8. Candidate CSF intervention configurations for BO&M-oriented DT adoption.

Intervention Configuration	Code	Candidate Critical Success Factor	Proposed Intervention Logic	Representative Evidence Basis
Technical foundations	CSF1	Low-intervention sensing and baseline monitoring	Creates reliable, minimally disruptive dwelling condition, comfort, energy, IAQ and carbon data.	[4,37]
Technical foundations	CSF2	Multimodal BIM/IoT/cloud/ML data integration	Connects as-is models, sensors, analytics and operational records into a lifecycle information environment.	[30,67]
Technical foundations	CSF3	As-is/reverse modelling and asset baseline creation	Creates trustworthy brownfield baseline models and asset registers.	[31,38]
Technical foundations	CSF4	Common schemas, IFC, ontology and middleware	Enables data exchange across platforms, systems and phases.	[13,60]
Technical foundations	CSF5	Semantic assets and MEP relationship modelling	Links spaces, assets, MEP dependencies and facility relationships to action.	[13,60,67,98]
Organisational work-as-done	CSF6	Manager-residents/FM feedback loop and actionable visualisation	Connects detection, interpretation, manager action and resident response.	[17,41]
Organisational work-as-done	CSF7	Shift from reactive to predictive/condition-based maintenance	Moves BO&M from complaint-driven or delayed response to DT-supported maintenance planning.	[55,102]

Intervention Configuration	Code	Candidate Critical Success Factor	Proposed Intervention Logic	Representative Evidence Basis
Organisational work-as-done	CSF8	Training, professional capability and adoption compatibility	Builds interpretive capacity, change readiness and usable interfaces.	[73,106]
Lifecycle governance and accountability	CSF9	Standardised acquisition, metadata and handover requirements	Defines information, validation, handover and update procedures before delivery.	[8,14]
Resident-sensitive legitimacy and trust	CSF10	Conservation-compatible and low-disruption governance	Specifies conservation-compatible intervention and low-disruption access appropriate to the target building.	[89,90]
Value, procurement and incentive alignment	CSF11	Economic, social, environmental and value evaluation	Clarifies carbon, comfort, maintenance, social and property-value benefits.	[10,107]
Organisational work-as-done	CSF12	Phased retrofit/deployment readiness	Stages adoption from baseline and pilot to integration, monitoring and scaling.	[6,11]
Resident-sensitive legitimacy and trust	CSF13	Privacy, control and compliance safeguards	Specifies lawful resident-data processing, defined purposes, access control and accountable security safeguards.	[18,79,86,93]
Lifecycle governance and accountability	CSF14	Data management, quality control and traceability	Creates auditable routines for validation, provenance, quality scoring, versioning and maintenance.	[80,87]
Lifecycle governance and accountability	CSF15	Clear data/model ownership and accountability	Assigns stewardship, validation, update duties, access rights and action authority.	[75,86]
Resident-sensitive legitimacy and trust	CSF16	Resident engagement, access and applicable consent procedures	Creates resident feedback and communication procedures; distinguishes dwelling access from lawful personal-data processing.	[6,11,27]
Value, procurement and incentive alignment	CSF17	Procurement and incentive alignment	Aligns contracts, funding, subsidies, procurement criteria and benefit sharing with lifecycle learning.	[28,74]

Note: The 17 CSFs are proposed enabling conditions grouped by their intended function. Each has one primary configuration, although several may contribute to the same maintenance decision.

The configurations guide the selection of a response to a specified operational interruption. For example, improving interoperability may require both a technical exchange standard and an assigned responsibility for maintaining the data. The relevant combination should be evaluated against the decision it is intended to support.

Consider a hypothetical occupied apartment building with recurrent pressure loss in a shared water-supply riser. The intended decision is whether to inspect the riser, commission a repair or prepare a replacement proposal. The property manager needs to connect the anomaly to a verified asset and supply zone, check it against inspection evidence and identify the affected households. The spatial baseline must show the service-cupboard access route, isolation points and working clearances. If a location is inaccessible or unverified, the work order records that constraint and the investigation required.

Verification and subsequent intervention follow the applicable access and approval

procedures. Routine work may fall within delegated responsibilities; common-asset renewal involving shared funds requires the relevant owner-decision and funding procedures. Resident communication addresses access and service interruption, while resident-related information is processed under applicable safeguards. The manager assigns the task, the maintenance team records the intervention, and the asset information is updated after completion.

The example distinguishes interruptions requiring different responses. An uncertain sensor-to-asset link calls for CSF3, CSF5 and CSF14. An alert without an authorised or physically feasible task calls for CSF6 and CSF15. An unfunded renewal proposal calls for CSF11 and CSF17. Evaluation would record time from verified alert to authorisation, time from authorisation to physical access, work-order completion and closure of the model update. Unresolved or deferred decisions would remain in the record with their documented reasons. These measures provide a basis for testing the proposed explanation.

4.5. Integrative Results Synthesis

The integrative result connects an identified information or governance condition to an affected information function, a responsible actor, a decision and an intervention for evaluation. Residential sources establish specific problems or information functions; adjacent studies supply mechanisms subject to stated transfer conditions; theory supplies relationships to test. The configurations organise candidate responses whose effects can be examined through operational records and maintenance outcomes.

5. Discussion

The synthesis connects barriers to identifiable maintenance decisions and the conditions required to execute them. The descriptive term map characterises the vocabulary of the curated corpus, while qualitative interpretation specifies information needs, actor responsibilities, spatial feasibility and authority. The explanatory propositions arise from the interpretation of source evidence and the stated transfer conditions. Linking them to an observable maintenance decision provides a basis for evaluating the proposed interventions.

The review distinguishes technical functionality from operational embedding. Monitoring, diagnosis, prediction and optimisation describe different capabilities; they do not by themselves show whether information is used repeatedly in maintenance decisions. Predictive and optimisation uses require attention to data trust, decision authority, resident communication, workflow integration and model updating [20,83,108]. Operational embedding should therefore be assessed separately through evidence of recurrent use, accountable action and information updating, rather than assumed from technical sophistication.

The framework's explanatory contribution is the specification of a constraint–decision relationship. TOE identifies relevant conditions; STS examines the interdependence of information and work; institutional theory explains the rules and incentives governing action. The synthesis connects these lenses to six information functions and candidate interventions at a defined task. If integration improves while maintenance action remains unchanged, authority, workflow and access become competing explanations to examine. If action occurs but records remain outdated, the interruption concerns feedback and stewardship. If reliable information supports a documented decision to defer an intervention, that outcome indicates use of information even though implementation has been postponed. These distinctions make the propositions discriminating and open to contrary evidence.

For facility managers, DT planning should begin with a defined operational decision, a minimum information set, a responsible person, an approval route and feasible access. Owners and owners' committees should specify delegated decisions, matters requiring collective approval, common-cost financing and how outcomes are reported. Procurement can translate these requirements into asset-identifier rules, data handover obligations, update responsibilities and access to exportable maintenance histories [8,14,71,75,78]. A pilot should track both completed and unresolved maintenance episodes, including authorisation and access delays, documented decisions to defer work, and subsequent information updates. A monitoring-only deployment can be evaluated against its intended purpose; predictive sophistication is a separate capability. These practices allow each CSF configuration to be judged against the decision it is intended to improve.

6. Limitations and Future Research

The evidence is bounded by Web of Science coverage, the ALL-fields China/Chinese query and the post-retrieval restriction to 2015 onwards. Material indexed in CNKI or other databases, Chinese-language practice knowledge and earlier BIM/FM work may alter the mechanisms identified. The findings therefore apply to the specified retrieval frame. The effect of excluding pre-2015 publications was not assessed through a separate synthesis.

The six residential anchors constitute 5.8% of the analytical publications. Four concern traditional or historic dwellings, one rural-housing renovation and one property-plot renewal. These publications do not establish six independent sites: the dwelling research includes related settings, and independence of sites, platforms and datasets has not been established. The broad 24-record context reconstruction includes mixed and residential-like descriptions and cannot be used as the number of direct empirical residential studies. Transfer is especially uncertain when an adjacent source assumes centralised ownership, unrestricted access, dedicated technical staff or stable capital funding. The framework's generalisation is consequently conditional and analytical; prevalence, causal effects and intervention efficacy require residential empirical evidence.

Future work should combine original bibliographic text mapping with a claim-level extraction ledger and follow residential maintenance episodes from observation through decision, authorisation, physical access, completed or deferred work and record updating. Comparative cases should include different ownership, management and spatial arrangements, as well as cases in which the proposed interruption does not occur.

7. Conclusions

This systematic scoping review connects candidate barriers to the information functions and maintenance decisions they may interrupt. The 198-publication corpus provides a descriptive profile; the 104-publication analytical subset provides heterogeneous evidence for synthesis. Six residential anchors establish specific contexts and functions, while adjacent sources support conditional mechanisms. Generation, quality assurance, integration, interpretation, use and learning locate potential interruptions in the conversion of data into accountable action.

Systemic misalignment specifies proposed relationships among information resources, responsibilities, work routines, resident participation, access and incentives. Seventeen candidate CSFs are organised into five intervention configurations. The framework directs attention to the decision a DT should support, the actor able to act and the records needed to assess continuing use. Comparative residential cases and longitudinal operational records can test these propositions and evaluate the conditions un-

der which candidate interventions improve maintenance decisions.

CSF14 provides an item-development starting point through two candidate statements: "For the assets under my responsibility, maintenance records identify when the information was last verified" and "Changes to asset information can be traced to the person who made them." Responses could use an agreement scale with a separate not-applicable option and a clearly specified asset group and reporting period. The items address verification recency and provenance, respectively. Expert review, cognitive interviews and measurement testing would establish whether they capture the intended practices. Sampled asset records and change logs could provide operational corroboration.

Supplementary Materials: The following supporting information can be downloaded at: https://zenodo.org/records/24494136. The supplementary document contains the review protocol and PRISMA-ScR checklist, source registers, the operational codebook and coded evidence register, inter-coder reliability and quality appraisal results, descriptive and bibliometric analyses, synthesis tables, and preliminary constructs, survey items and a future empirical validation agenda.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
AEC	Architecture, engineering and construction
BAS	Building automation system
BIM	Building information modelling
BIM-FM	Building information modelling–facility management
BMS	Building management system
BO&M	Building operations and maintenance
BPE	Building performance evaluation
CSF	Critical success factor
DRIP	Data-rich, information-poor
DT	Digital twin
FM	Facility management

IAQ	Indoor air quality
IFC	Industry Foundation Classes
IoT	Internet of Things
MEP	Mechanical, electrical and plumbing
ML	Machine learning
O&M	Operation and maintenance
POE	Post-occupancy evaluation
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SEM	Structural equation modelling
STS	Socio-technical systems
TOE	Technology–Organisation–Environment

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