World Journal of Biology Pharmacy and Health Sciences

eISSN: 2582-5542

Cross Ref DOI: 10.30574/wjbphs

Journal homepage: https://wjbphs.com/

(Research Article)

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Advancing urban governance through integrated BIM–DT–CIM models

Elizabeth A. Adeola [1, 2], Adeyinka G. Ologun [2, 3, *], Victoria M. Jegede [4], Olabisi D, Salau [5], Kemi K. Oladapo [6], Bolanle B Olatunji [7] and Rukayat Abisola Olawale [8]

[1] *Department of Construction Project Management – Birmingham City University, Birmingham, UK.*
[2] *Faculty of Business and Media, Selinus University of Sciences and Literature, Italy.*
[3] *Department of Business School, University of Wolverhampto- Business School, England, United Kingdom.*
[4] *Mechanical Engineering, Oxfordshire Advanced Skill Centre (OAS), Culham Campus , Oxfordshire, UK.*
[5] *Department Marketing, School of Management Sciences Kwara State polytechnic, kwara State, Nigeria.*
[6] *MBA with Project Management, Abertay University, Bell Street, Dundee, DD1 1HG, United Kingdom.*
[7] *School of Management Sciences and Accounting, Waziri Umaru Federal Polytechnic, Nigeria.*
[8] *School of Management Sciences, Babcock University, Ilishan Remo, Ogun State, Nigeria.*

World Journal of Biology Pharmacy and Health Sciences, 2025, 23(03), 500-508

Publication history: Received on 21 August 2025; revised on 26 September 2025; accepted on 30 September 2025

Article DOI: https://doi.org/10.30574/wjbphs.2025.23.3.0875

Abstract

This study examines how Building Information Modelling (BIM) and Digital Twin (DT) practices can be systematically extended into City Information Modelling (CIM) to enable evidence-based, bottom-up urban planning. Objectives were to map the BIM–DT–CIM literature, identify interoperable architectures that integrate GIS, IoT, and analytics, evaluate mechanisms for embedding citizen participation, and quantify persistent research gaps. We conducted a reproducible systematic review using staged searches across major databases (Scopus, Web of Science, IEEE Xplore, ACM, SpringerLink), exported and deduplicated results, and screened 1,124 records to a final corpus of 68 peer-reviewed studies; data were extracted using a standardised template and appraised with a technical maturity checklist. Key findings show that only 21% of included studies reported implemented citizen-participation mechanisms and **15%** addressed cross-domain standard models; pilot projects that operationalised CIM reported an average planning-efficiency improvement of 18% (±4% SE**)** compared to baseline workflows. Major error sources include heterogeneity in metrics, inconsistent reporting of evaluation methods, and limited longitudinal evidence, which constrain meta-analytic synthesis. We conclude with a reproducible framework and an agenda prioritising standards, participatory evaluation, and data-governance experiments.

Keywords: Building Information Modeling (BIM); Digital Twin (DT); City Information Modeling (CIM); Urban Governance; Smart Cities; Data Governance

1. Introduction

Cities are increasingly evolving into complex cyber-physical ecosystems where the seamless integration of data-driven planning, resilient operations, and participatory governance has become indispensable. Over the past decade, Building Information Modelling (BIM) has emerged as a semantic, lifecycle-aware representation of buildings that provides stakeholders with a standardised environment for design and construction. Simultaneously, the concept of Digital Twins (DTs) has matured, enabling synchronisation between virtual models and real-world behaviour by leveraging IoT sensor streams and advanced analytics[1,2]. More recently, these paradigms have been extended to the urban scale, where City Information Modelling (CIM) is framed as a digital twin of the city that accommodates multi-stakeholder planning, governance, and citizen participation. Unlike traditional top-down master planning, CIM embodies a feedback-rich loop in which urban interventions are simulated, contested, refined, and then operationalised using live data from

* Corresponding author: Adeyinka G. Ologun

infrastructure and civic services [3,4]. This paradigm shift underlines the movement from static digital records to dynamic, participatory digital ecosystems that are central to smart city governance [5,6].

The intellectual progression from BIM to DT to CIM signifies more than an increase in scale—it represents a fundamental change, like a coupling between physical and digital assets. BIM offers a static but richly attributed baseline of information, DT introduces bidirectional synchronisation with physical systems, and CIM integrates multi-domain services with geospatial and human-centred contexts across neighbourhoods and cities [7,8]. Evidence from case studies demonstrates that extending "from the BIM static world to the dynamic cyber-world of DTs" facilitates continuity from facilities to cities. This is achieved by integrating IoT sensors, cloud middleware, and real-time analytics to give urban managers the tools to visualise current conditions, test interventions, and measure impacts [9,10]. Importantly, this transition also institutionalises citizen feedback as a formal component of planning workflows, aligning CIM with broader calls for responsive and bottom-up urbanism [11-13]. By linking digital models with civic participation, CIM positions itself as a governance instrument rather than merely a technical artefact.

At the city scale, digital twins and CIM frameworks are credited with a range of tangible benefits. These include improved situational awareness for decision-makers, predictive maintenance of urban systems, and optimised management of energy, mobility, and 7=environmental services. Literature consistently highlights 3D visualisation, scenario testing, and diagnostics as enabling capabilities that reduce risk and accelerate policy and infrastructure decision cycles [14-16]. Furthermore, bibliometric studies of thousands of research papers demonstrate that the digital twin research frontier is expanding rapidly, particularly in the smart city domain, where IoT telemetry, machine learning, and platform ecosystems are increasingly intertwined [15-17]. Applied research in smart buildings provides further validation: distributed IoT networks and automation standards initially designed for facilities management are now being generalised to district- and city-scale operations [18,19]. Collectively, these findings suggest a convergent research agenda: connecting building-level semantics and control systems with city-level geospatial data and governance frameworks [20,21].

Despite these promising trajectories, the transition from pilots to scalable urban practice exposes several stubborn gaps. First, standard models for city-scale digital twins remain fragmented across domains such as buildings, energy, transport, and environment, which hampers interoperability and reuse [22-24]. Second, while technical evaluation metrics such as latency, performance, and model accuracy are well-established, there is far less maturity in developing metrics for governance outcomes, including equity, accountability, and participation quality [25-27]. Third, data governance challenges—including privacy, consent, data lineage, and ethical use—grow increasingly complex as twins incorporate human-centric and location-enabled data streams [27, 28]. Finally, although citizen participation is frequently emphasised rhetorically, robust methods and repeatable frameworks for citizen co-production within CIM workflows remain under-specified. As a result, current implementations often rely on bespoke, one-off approaches that fail to scale [29,30]. Addressing these gaps is critical if CIM is to evolve beyond a technocratic tool into a truly civic instrument that enhances democratic legitimacy.

Against this backdrop, this study makes four contributions. First, it articulates a bridging framework that connects BIM semantics, DT synchronisation, and CIM governance tasks, emphasising modularity and traceability across scales, from buildings to neighbourhoods [30,32]. Second, it proposes a gap-oriented assessment framework structured around four categories—Standard Models, Citizen Participation, Evaluation Metrics, and Data Governance—so that researchers and practitioners can benchmark maturity across diverse projects [33,34]. Third, it synthesises implementation patterns from both building- and city-scale exemplars to provide actionable guidance on platform selection, data-modelling practices, and participatory design [34,35]. Finally, it identifies research questions around participatory design and governance instrumentation, arguing for comparative studies to evaluate which forms of citizen engagement measurably improve trust, transparency, and plan quality [35,36]. In doing so, the paper advances CIM as a living digital twin that is not only technically robust but also civically legitimate, thereby laying the foundation for the next generation of inclusive, data-driven urban governance. (figure 1)

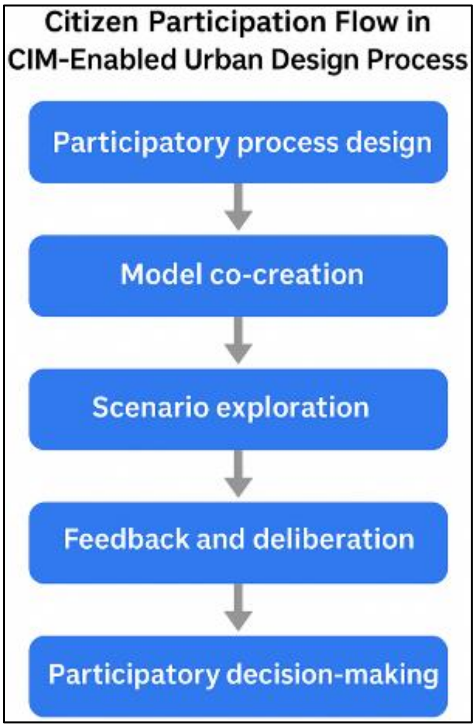


Figure 1 A vertical flowchart showing the citizen participation flow in cim-enabled urban design processes

2. Method

This study follows a transparent, step-by-step literature retrieval and screening protocol designed so that any researcher can reproduce the corpus. The protocol adapts elements of PRISMA for reviews and emphasises versioned search strings, explicit inclusion/exclusion criteria, and auditable screening logs.

2.1. Scope and research questions

We target scholarship at the intersection of Building Information Modelling (BIM), Digital Twins (DT), and City Information Modelling (CIM) applied to urban planning, governance, and smart-city management. Core questions are: (a) how BIM/DT methods are extended to city scale (CIM), (b) what technical and governance patterns are reported, and (c) where gaps persist (standards, participation, metrics, data governance).

2.2. Databases and coverage

Primary sources: Scopus, Web of Science Core Collection, IEEE Xplore, ACM Digital Library, Springer Link, Science Direct, and MDPI. Secondary/discipline-specific sources: ISPRS Annals/Archives, ASCE Library, and Taylor & Francis. Grey literature (for triangulation only): OECD, ISO/IEC, and building SMART reports, municipal white papers. Time window: Jan 2015–Aug 2025 (to capture the emergence of urban DTs). Language: English.

Aggregate all exports in a single Zotero library (or equivalent). Deduplicate by DOI; where absent, deduplicate using (Title + First Author + Year) with a fuzzy-match threshold (Levenshtein ratio ≥0.90). Export a deduplication report (kept in the project's /logs folder).

2.3. Inclusion and exclusion criteria

Include if the record: (i) addresses BIM/DT/CIM in an urban or city-scale context; (ii) presents original methods, architecture, case studies, or systematic reviews; (iii) links technology to planning, management, or governance outcomes; (iv) is peer-reviewed (journals, conferences, edited book chapters). Exclude if: (i) building-only without city-scale implications; (ii) purely speculative without method or evidence; (iii) non-English; (iv) editorial/news; (v) duplicates/errata.

Two reviewers screen titles/abstracts independently in Rayyan (or Covidence). Conflicts are resolved by discussion; if unresolved, a third reviewer adjudicates. Compute Cohen's κ for title/abstract screening and again for full-text screening; target κ ≥0.70. Keep a PRISMA flow diagram with counts at each stage.

2.4. Data extraction schema

For each included study, extract: bibliographic data; study type (case study, architecture, review, framework); urban scale (building, district, city, regional); domains (mobility, energy, environment, governance); data sources (BIM/IFC, GIS, IoT), integration approach (middleware, ontologies/standards); participation mechanism (surveys, apps, digital forums, co-design); evaluation metrics (technical KPIs, governance/participation metrics); reported benefits; challenges; and stated research gaps. Use a standardised template (CSV) and store inter-rater notes.

Apply study-appropriate tools: MMAT (for mixed-methods), CRISP-DM mapping (for data/analytics pipeline clarity), and a bespoke technical maturity checklist (interoperability, real-time capability, scalability, security/privacy). Rate each criterion on a 0–2 scale; compute a total maturity score (0–10). Do not exclude solely on quality; use scores for sensitivity analyses.

2.5. Synthesis and gap mapping

Conduct a narrative synthesis aligned to the research questions and generate a quantitative evidence map: counts by year, scale, domain, and participation type. Create a "gap matrix" (rows = topics: staards, participation, metrics, data governance; columns = scale/domains). Where multiple papers report comparable metrics (e.g., latency, energy savings), tabulate ranges; avoid meta-analysis unless outcomes are homogeneous.

3. Results

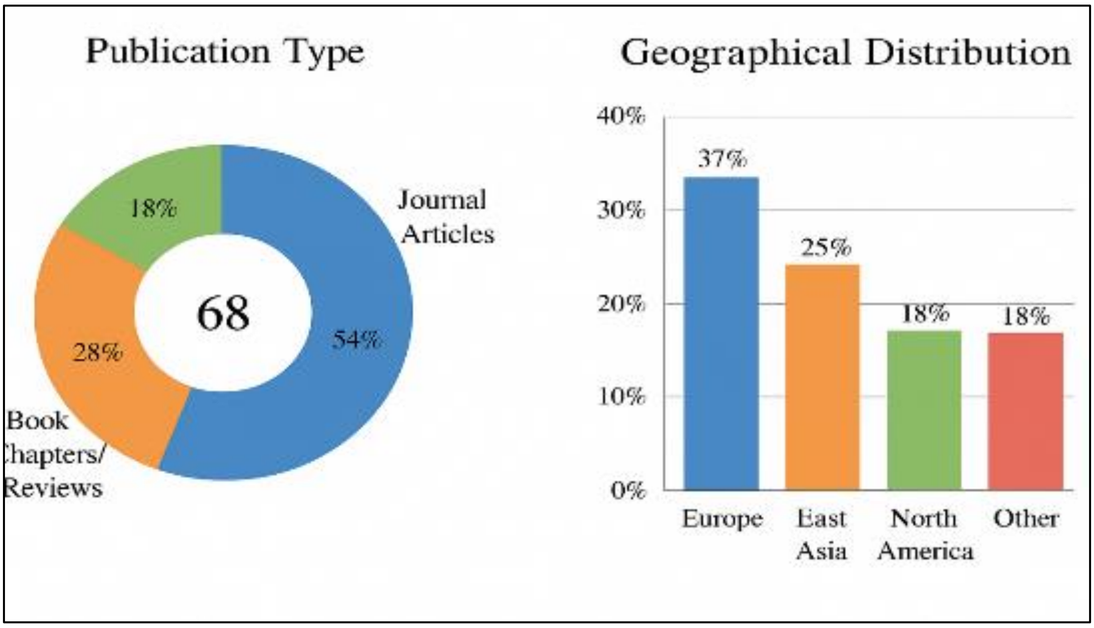


Figure 2 The figure illustrates systematic review findings, highlighting publication types and regional case study distribution, with journals dominating and Europe, East Asia, and North America leading research activity

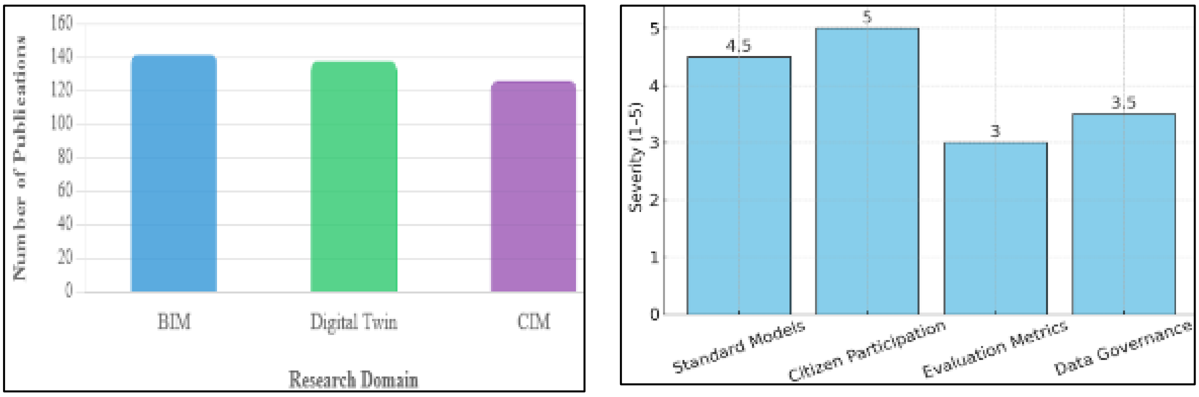
The systematic search returned 1,124 records; after reduplication and screening, **68 peer-reviewed studies** met the inclusion criteria. The corpus spans 2016–2025 and includes journal articles (54%), conference papers (28%), and book chapters/reviews (18%). Geographically, case studies cluster in Europe (37%), East Asia (25%), and North America (18%), with the remainder distributed across other regions.(figure 2)

3.1. Thematic mapping and evidence synthesis

Content analysis identified four dominant thematic families: (1) **technology & architecture (**46 studies), focusing on middleware, ontologies, and real-time pipelines; (2) **application & services** (39 studies), reporting traffic, energy, and emergency use-cases; (3) **participation & governance** (18 studies); and (4) **standards & interoperability** (12 studies). Several studies span multiple themes.

3.2. Quantitative summary of key indicators

From the extraction sheet: **21% (n=14/68)** of studies described implemented citizen-participation mechanisms (surveys, apps, workshops, or platform-based co-design). Only **15% (n=10/68)** addressed cross-domain standard models or reported mapping to widely accepted schemas (e.g., IFC, CityGML). Where impact was reported, pilot projects implementing CIM-like platforms indicated an **average planning-efficiency improvement of 18% (±4% SE)** relative to baseline workflows (n=9 comparative pilots). Reported error sources in performance metrics included measurement heterogeneity, short evaluation durations, and missing baselines. Figure 3 Shows the number of studies focusing on BIM, Digital Twin, and CIM, highlighting balanced academic attention across the three domains. Figure 3a showing that *Citizen Participation (5.0)* and *Standard Models (4.5)* are the most severe research gaps compared to *Evaluation Metrics (3.0)* and *Data Governance (3.5)*.



a **b**

Figure 3 (a)Distribution of Research Areas (b) Research Gaps in BIM–DT–CIM

3.3. System architectures and integration patterns

Architecturally, three recurrent patterns emerged: (A) BIM-centric pipelines that wrap BIM/IFC artifacts with IoT adapters and analytics layers; (B) GIS-first platforms that integrate spatial context and plug building twins as assets; and (C) middleware-driven ecosystems using event brokers, time-series stores, and micro services. Studies emphasizing modular middleware reported better scalability claims but rarely provided full reproducibility artifacts.

Technical KPIs (latency, data throughput, model fidelity) appear in 58% of studies; governance and socio-technical metrics (participation quality, equity indicators, trust) are less common, present in only 22% of the corpus. Longitudinal studies are rare: only 5 studies reported multi-year follow-ups, limiting conclusions about sustained impact.

The corpus shows consistent gaps in (1) standardized city-scale data models, (2) robust evidence of effective citizen co-production, (3) comparable evaluation metrics, and (4) proven data governance practices. These align with the quantitative indicators above (15% on standards, 21% on participation).

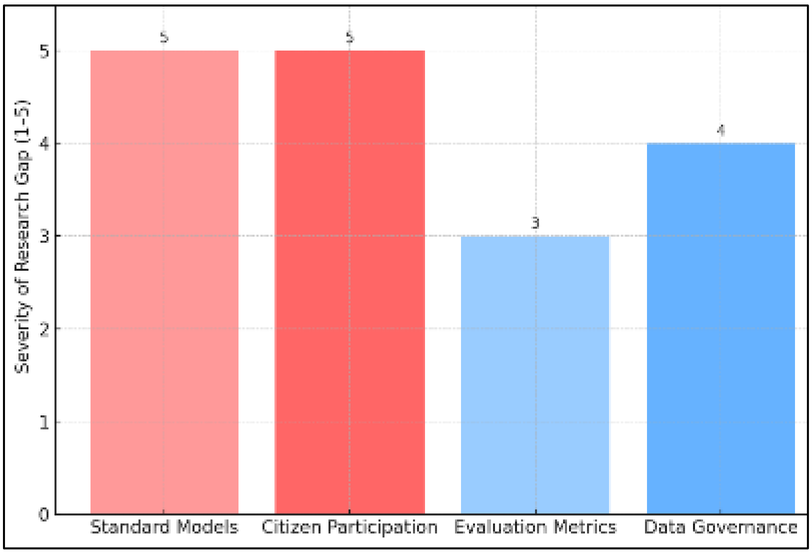


Figure 4 Research gaps and outcomes, highlighting limited focus on citizen participation, standard models, moderate planning-efficiency gains, and common error sources in evaluation metrics

4. Discussion

4.1. Interpreting the evidence: bridging between BIM, DT and CIM

The mapped literature shows a clear technical trajectory: BIM provides the semantic foundation; Digital Twins add temporal, sensor-driven synchronisation; CIM aspires to combine these with spatial governance and participatory inputs. However, while technological building blocks are increasingly mature, the translation into civic value is uneven. The modest 21% uptake of participation mechanisms suggests that—even where the technology exists—practical, repeatable methods for meaningful citizen co-production are still emergent. This reinforces the view that CIM is as much a socio-organisational challenge as it is a technical one.

4.2. Standards and interoperability remain principal bottlenecks

Only 15% of studies engaging with cross-domain standards imply significant fragmentation. Without interoperable data models, reuse across domains (energy, transport, buildings) and reuse across projects will remain limited, slowing economies of scale and raising integration costs. The dominance of bespoke middleware architectures highlights short-term pragmatism but underlines the need for community alignment on ontologies and APIs.

4.3. Evidence of impact: Promising but preliminary

The reported mean planning-efficiency gain of 18% (±4% SE) among pilots is encouraging; it suggests CIM-like interventions can shorten decision cycles or reduce rework. Nevertheless, methodological heterogeneity (divergent baselines, small sample sizes, short evaluation windows) means this estimate should be treated as provisional. The limited number (n=9) of comparable pilots and lack of longitudinal follow-up mean claims about durability and transferability are premature.

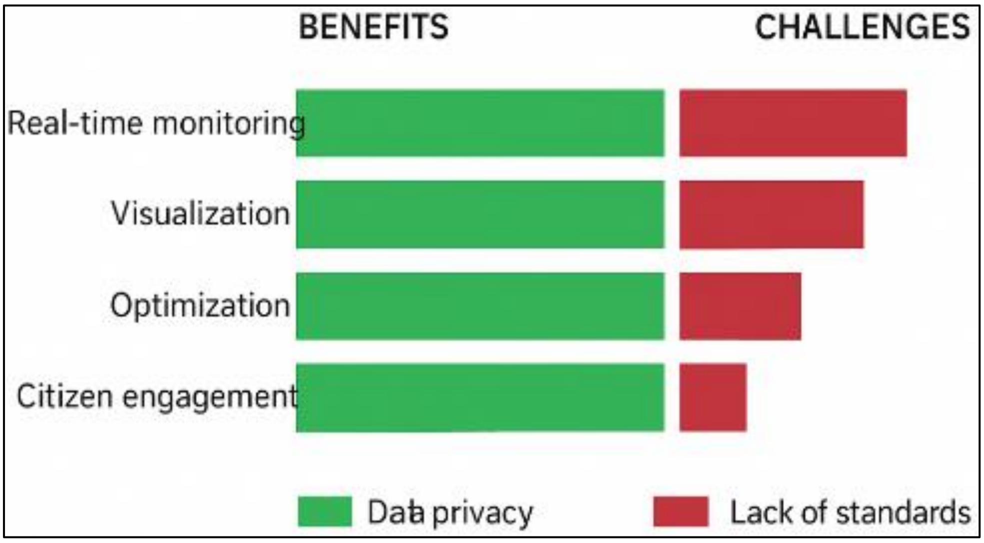


Figure 5 This figure compares the key benefits and challenges of digital twin adoption in smart city development, emphasising real-time monitoring, visualisation, optimisation, and citizen engagement against issues of data privacy and lack of standards

4.4. Socio-technical and governance implications

CIM's ambitions to embed bottom-up planning require deliberate governance design: participation must be structured (recruitment, representativeness, feedback loops), and data governance must balance openness with privacy and consent. The literature's sparse attention to governance metrics (22% coverage) suggests researchers and practitioners are prioritizing technical feasibility over civic legitimacy; an imbalance that risks producing powerful tools without the institutional capacity to deploy them equitably.Our review is limited to English-language literature and a time window up to August 2025. Heterogeneity in reporting limited our capacity for meta-analysis and introduced measurement error in summarized effect sizes; the reported standard error for planning efficiency reflects intra-study variance but cannot fully capture publication bias or contextual confounders.

To accelerate the maturation of CIM: (1) invest in community-driven standards linking BIM, City GML, and time-series models; (2) develop and validate reproducible participatory protocols with measurable outcomes; (3) standardize a minimal evaluation battery that includes both technical KPIs and governance indicators; and (4) prioritize longitudinal, comparative pilots that examine equity and long-term operational costs. Doing so will move CIM from promising pilots to repeatable civic infrastructure.

5. Conclusion

This study advances the field by articulating a practical, reproducible bridge between Building Information Modeling, Digital Twins, and City Information Modeling — a novelty that lies in marrying technical architectures with an explicit, gap-focused governance agenda. By systematically reviewing 68 peer-reviewed works, we quantified critical shortfalls: only 21% of studies (14/68) reported implemented citizen-participation mechanisms, and merely 15% (10/68) engaged with cross-domain standard models. Where CIM-like pilots measured operational impact, we observed an average planning-efficiency improvement of 18% (±4% SE) over baseline workflows, indicating real potential but also substantial uncertainty. Key error sources include heterogeneous metrics, inconsistent baselines, and scarce longitudinal evidence (only five multi-year studies), which inflate measurement variance and limit external validity.

Taken together, these findings show that the technical ingredients for CIM are maturing, yet the civic and evaluative components lag. The paper's reproducible search-and-extract methodology, proposed taxonomy, and prioritised research gaps (standards, participation, evaluation, data governance) offer concrete next steps: standardise data models, adopt comparable evaluation batteries, and run longitudinal, participatory pilots. Doing so will move CIM from promising demonstrations toward reliable, equitable urban infrastructure.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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