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# Digital Twins in Smart Infrastructure: A State-of-the-Art Review of Applications, Challenges, and Future Directions

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## Abstract

Digital twins—virtual representations in sync with physical assets via bi-directional data—are no longer exclusive to aerospace and manufacturing, and are now proposed for the built environment and cities, buildings, transport networks, and utilities. In this up-to-date review, she brings together that migration and concludes that it isn't quite as simple as the literature suggests. Unlike the manufacturing environments in which digital twin theory has developed, infrastructure has a long lifespan (between 50 and 100 years) and software and vendors have a shorter lifecycle (around 5 years); most current infrastructure does not have any kind of digital "birth" record and therefore a digital twin must be created from scratch; ownership is dispersed across institutions; and the impact of differences between the digital twin and the asset is felt in the public sphere. The review categorises applications by five infrastructure classes and extracts a layered reference architecture, then formulates the idea of twin drift—the progressive divergence of a twin from its asset as a characteristic failure mode of the domain, with the asset being the known hardware while the twin is the unknown hardware. From this analysis, the limiting factor for infrastructure twins is not the fidelity of the simulation, but rather the cost of synchronisation — who will be bearing the burden of maintaining the twin true, on a continuous basis over a period of decades? The review thus redefines the digital twin as a governance artefact instead of modelling artefact, introduces evaluation criteria not only on visual fidelity but also on currency, provenance and decision latency, as well as introduces a research agenda ranging from federating beyond institutional boundaries to measuring the drift of a digital twin to introducing whole-life stewardship models. No empirical data are reported; maturity assessments can be seen as qualitative syntheses that can be challenged.

***Keywords: digital twin; smart infrastructure; smart cities; asset management; interoperability; cyber-physical systems***

## 1. Introduction

There is no concept which has reached so far, so fast as the digital twin. The digital twin originated in product lifecycle management in the early 2000s, was formalised as an emergent behaviour mitigation strategy for complex systems in 2017 (Grieves & Vickers), then operationalised as ultra-high fidelity simulation of individual flight vehicles by NASA and the U.S. Air Force in 2012 (Glaessgen &

Stargel), and then industrialised in manufacturing over the next decade (Tao et al., 2019) until now it has become an organizing ambition for the built environment: digital twins of buildings, bridges, railways, water networks, power grids and whole cities (Deng et al., 2021; Huzzat et al., 2025). The ambition of creating a national digital twin of infrastructure has been institutionalised through national programmes – the United Kingdom's Gemini Principles, for example, have proposed an ethics and architecture for a national digital twin of infrastructure (Centre for Digital Built Britain, 2018), while the European Union's Destination Earth initiative, whose climate and extremes twins have entered in a third, operational phase confirmed in February 2026, has shown that continental-scale twinning is an engineering reality, not a metaphor (ECMWF, 2026).

But the spread of the concept has outrun the discipline. Over the years, a number of surveys have repeatedly confirmed that most of what is called a digital twin is not a true digital twin: A categorical review of manufacturing literature revealed that the vast majority of claimed twins were digital models or digital shadows with limited or one-way automated data flow with a genuine twin (Kritzinger et al., 2018). The term is used for everything from static 3D visualisations to closed loop control systems (Negri et al., 2017; Jones et al., 2020). But where it's a problem in manufacturing it's a problem in infrastructure: procurement processes in public funds are taking place against a term that has no established referent.

Rather, as this review contends, the infrastructure domain has a structural difference from the domains in which the digital twin theory developed, in four ways that are not well priced in the literature transferred. First, lifespan asymmetry – infrastructure lasts for 50-100 years, but the software platforms, data formats and vendors that power their twins change in 5-10 years. Second, the missing birth certificate: Most designs are in existence before the advent of digital records, and the infrastructure of the rest of the world was built before digital sensing (Lu et al., 2020). Third, institutional fragmentation: infrastructure value chains span regulatory and jurisdictional and ownership boundaries and the twin of any system of interest is a system of twins – a federation of twins – that no single actor can manage (Centre for Digital Built Britain, 2018). Fourth, consequence asymmetry - A manufacture firm loses efficiency when a manufacturing twin diverges from the line, an infrastructure firm discovers the error publicly when a infrastructure twin diverges from the infrastructure.

The review therefore asks:

RQ1. What is the current application landscape of digital twins across smart infrastructure classes, and what shared architecture underlies it?

RQ2. Which challenges are generic to digital twins and which are structural to infrastructure and what failure mode do the structural ones jointly produce?

RQ3. What evaluation criteria and research directions follow if the infrastructure twin is understood as a long-lived governance artefact rather than a modelling artefact?

## 2. Literature Review

### *2.1 Origins and Definitional Discipline*

The digital twin's intellectual ancestry dates back to Grieves' formulation of the physical product, virtual product and the data connection between them (Grieves & Vickers, 2017), and through Glaessgen and Stargel's formalisation of the term's link to high fidelity per-asset simulation in the field of aerospace (Glaessgen & Stargel, 2012). The concept was disciplined by two traditions of reviews. Kritzinger et al. (2018) provided the most popular distinction, distinguishing systems as a digital model (where data flows manually both ways), a digital shadow (where data flows automatically between physical and virtual systems) and a digital twin proper (where data flows automatically both ways between physical and virtual systems). Table 2 summarizes the differences and extends the stage infrastructure that is required for: the federated twin, where several twins are under different owners, who exchange state through controlled interfaces. The results of characterisation reviews included the

definitional core physical entity, virtual counterpart, synchronising connection, and a purpose, as well as the quantity of published systems with all four characteristics (Negri et al., 2017; Jones et al., 2020).

**Table 2.** *The definitional spectrum, extended for infrastructure*

| Stage | Physical→virtual flow | Virtual→physical flow | What it supports | Infrastructure example |
|---|---|---|---|---|
| Digital model | Manual | Manual | Design, documentation, visualisation | As-designed BIM handed over at commissioning |
| Digital shadow | Automated | Manual | Monitoring, condition dashboards | Bridge SHM feed over a static structural model |
| Digital twin | Automated | Automated | Prediction, optimisation, control | Grid twin issuing switching recommendations |
| Federated twin | Automated, cross-owner | Governed, cross-owner | System-of-systems decisions | City platform spanning utility, transport, and building twins |

### *2.2 The Infrastructure and City Strand*

There was a separate strand in the built environment. In the construction industry, the twin was presented as the replacement of building information modelling (BIM) (Boje et al., 2020) and construction-phase twinning was underpinned with an information-systems basis (Sacks et al., 2020). Building- and campus-scale twins built from disparate legacy data showed how reconstruction is a cost of brownfield twins, highlighting this cost (Lu et al., 2020). The city-scale literature started off as sceptical, and by now it has evolved into a range of systematic reviews, including those of city digital twin as a governance tool (Deng et al., 2021; Shahat et al., 2021), and more recent comprehensive surveys that show that city digital twins are growing in the urban energy, mobility, and utilities sectors, while there are still ongoing interoperability and governance issues (Naderi & Shojaei, 2022; Huzzat et al., 2025). The infrastructure strand draws on the IoT literature (Atzori et al., 2010; Gubbi et al., 2013; Al-Fuqaha et al., 2015) for its sensing substrate, while the structural dynamics strand provides engineering-grade insights into the essence of model updating, when using monitoring data (Wagg et al., 2020).

### *2.3 The Gap*

Partial ownership sits with each strand: manufacturing with the definitional discipline, construction with the framing of the lifecycles, urban science with the questions of governance and engineering dynamics with the rigour needed for model updating. What no strand can provide is an explanation of the unique “failure mode” and “timescale” of the twin infrastructure, the experience of a twin over 15 years, three proprietary generations of technology and two ownership transitions following commissioning. The reviews are closest to this question and see interoperability and standardisation as open challenges (Fuller et al., 2020; Huzzat et al., 2025), yet they still consider it a technical residue rather than the structural centre. This review makes them the centre of the review.

## 3. Research Methodology

### *3.1 Design*

This state-of-the-art review is in the style of critical-narrative reviews, in that it seeks to be integrative and diagnostic in nature, helping to characterize the field's current state and making a diagnosis about where the field's constraint is. The diversity of the corpus (engineering, computer science, construction informatics, urban studies; simulations, case studies, surveys, programme documents) calls into question the assumptions of the meta-analysis, and narrative synthesis is the tool for the task. Quality practices abide by the rules of a good review: a clear scope, an open search process and a detached presentation of reported results from arguments made by the author.

### *3.2 Search Strategy and Corpus*

The corpus was constructed through structured searches in Scopus, Web of Science, IEEE Xplore using the search terms for digital twin and the infrastructure terms (smart infrastructure, smart city, built environment, asset management, bridge, railway, water network, power grid, BIM), as well as backward and forward citation chasing. Inclusion enthusiasts sources that (a) influenced the area's definitions and architecture, (b) reported deployments of infrastructure with detail of implementation, or (c) synthesized a domain. Table 1 summarises the strategy. The corpus is not exhaustive, no PRISMA flow or study census is claimed.

**Table 1.** *Corpus strategy*

| Element | Specification |
|---|---|
| Databases | Scopus; Web of Science; IEEE Xplore |
| Core terms | "digital twin" combined with: smart infrastructure; smart city; built environment; asset management; bridge; railway; water network; power grid; BIM |
| Supplementary sources | Backward/forward citation chasing from landmark works; programme documentation of national and continental initiatives |
| Period | Foundational works from 2010; emphasis on 2018–2026 |
| Inclusion | Definitional/architectural contributions; infrastructure deployments with implementation detail; domain syntheses |
| Exclusion | Manufacturing, healthcare, and product twins except as theory sources; marketing material without technical content |

### *3.3 Analytical Approach*

These three research questions were presented to sources.Sources were presented with the three research questions. The application synthesis (Table 3) is based on infrastructure class, which is the standard in the asset-management world. The taxonomy of challenges presented here (Table 4) distinguishes challenges that the infrastructure domain has in common with all digital twinning from those that are created by the structure of the domain, which were used as constraints for any plausible description of infrastructure that is worth considering.

### *3.4 Scope and Limitations of Method*

Civil and urban infrastructure buildings, transport, energy, water, and integrated city platforms, are covered in the review, with the exception of product twins as a source of theory, and manufacturing and healthcare buildings are not covered. This mirrors the literature's own emphasis on high income deployments. No empirical data were collected; the quantities discussed are either quoted findings or in a clearly schematic form.

## 4. Analysis and Synthesis

### *4.1 The Application Landscape*

Applications are grouped by infrastructure class in Table 3. Buildings or campuses focus on operations and maintenance energy optimisation, space management and predictive maintenance which is the simplest starting point for BIM inheritance and twinning (Boje et al., 2020; Lu et al., 2020). Transport infrastructure focuses on condition: Structural health monitoring (SHM) twins for bridges and railways that are based on physics-based model updating (Wagg et al., 2020). Energy systems are an example of some of the most operationally mature twins, as grid operators have years of experience using SCADA telemetry and simulation for which twinning builds. The applications of water and wastewater focuses on network hydraulics, leakage and flood response. City-scale platforms span across classes for planning and scenario analysis, and flagship deployments sit atop a long-tail of pilots, both in small cities with high resource capacity and in smaller cities with pilots (Deng et al., 2021; Shahat et al., 2021; Huzzat et al., 2025). Above the city, the current practice and institutional precondition of the climate-adaptation and weather-extremes twins of continental environmental twinning Destination Earth (2026) is illustrated by its ceiling.

**Table 3.** *The application landscape by infrastructure class*

| Infrastructure class | Representative applications | Characteristic data substrate | Evidence maturity |
|---|---|---|---|
| Buildings and campuses | Energy optimisation; space and facilities management; predictive maintenance | BIM inheritance plus retrofitted BMS/IoT sensing | Deployments common; outcome evidence thin; drift-prone after handover |
| Transport (bridges, rail, roads) | Structural health monitoring; condition-based maintenance; capacity management | Dense per-asset sensing over physics-based models | Engineering-grade validation at single-asset scale |
| Energy networks | State estimation; contingency simulation; outage and DER management | Decades of SCADA telemetry and simulation practice | Operationally the most mature class |
| Water and wastewater | Network hydraulics; leakage detection; flood response | Sparse, ageing sensing over hydraulic models | Pilots dominant; sensing gaps binding |
| City-scale platforms | Planning scenarios; mobility and energy integration; resilience analysis | Federated municipal, utility, and third-party data | Flagships in well-resourced cities; long tail |

| Infrastructure class | Representative applications | Characteristic data substrate | Evidence maturity |
|---|---|---|---|
| | | | of pilots; descriptive evidence |
| Continental environmental | Climate adaptation and extreme-event simulation for infrastructure planning | Satellite EO, NWP models, EuroHPC-scale computation | Operational with standing institutional operators (ECMWF, 2026) |

There were a couple of cross-cutting observations to make. First, evidence density declines with the level of scope: single asset twins have engineering-level evidence, city scale twins have mostly descriptive case studies. This isn't a coincidence. A bridge twin is owned by one owner, has one physics, and one decision maker, so that its claims can be tested; a city twin has dozens of data custodians and hundreds of decision contexts, so the evaluations default to narrative. Second, very little of the reported value focuses on operations and maintenance – which is consistent with the asset-management framing of the cost, risk and data of infrastructure, which all exists in the decades following handover (Lu et al., 2020). The design phase twin is basically BIM repackaged, the operational twin is where it can start to do something that a static model can't and where the domain's very special problems start.
There is a third observation to make about the landscape: What it does not show. Applications start to concentrate where sensing is cheap, then moving on, then building and thinning out exactly where infrastructure gaps are greatest: unsensored water networks, informal settlements and asset bases of lower income cities. In turn, the literature implicitly assumes that the infrastructure can be managed via the twinning tool, but such data is not always available in the world's infrastructure.

### *4.2 The Reference Architecture*

Figure 1 locates infrastructure systems on the definitional spectrum, extending the Kritzinger axis with the federation stage that infrastructure requires.

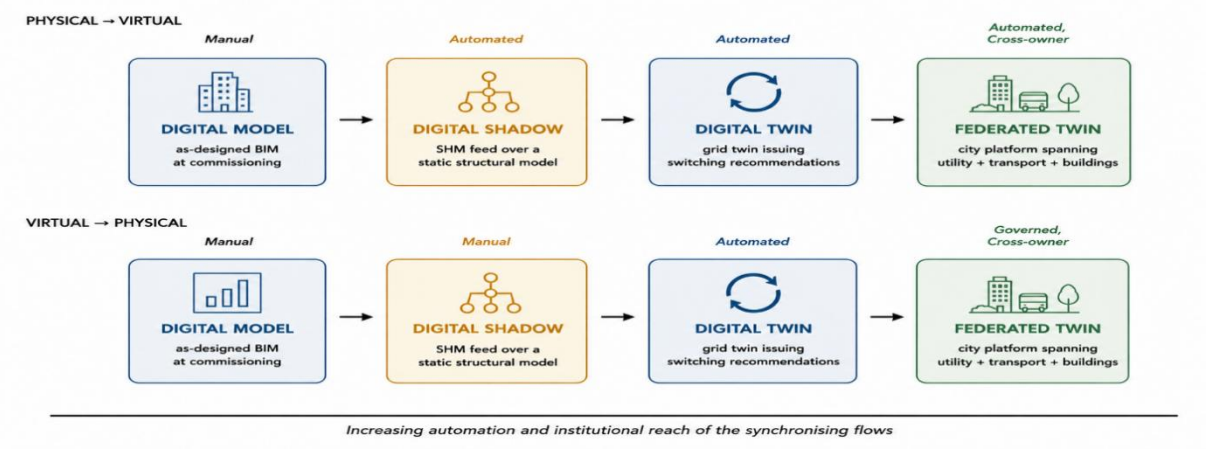


**Figure 1.** *The integration spectrum from digital model to federated twin, defined by automation of the physical–virtual data flows.*

The shared architecture is distilled in Figure 2, which includes an asset layer, a sensing and actuation layer, an integration layer where the domain's toughest issues reside (semantic alignment of BIM, GIS and telemetry standards), a model and analytics layer ranging from physics-based to data-driven to hybrid, and a service layer where decisions are made. The architecture is conventional (Tao et al., 2019) and what the figure adds is the property that each of those layers must possess; namely, infrastructure must have longevity at the asset layer, maintainability at sensing, standards-independence at integration and updateability at the modelling layer, while consumer and manufacturing deployments can partially waive these properties.

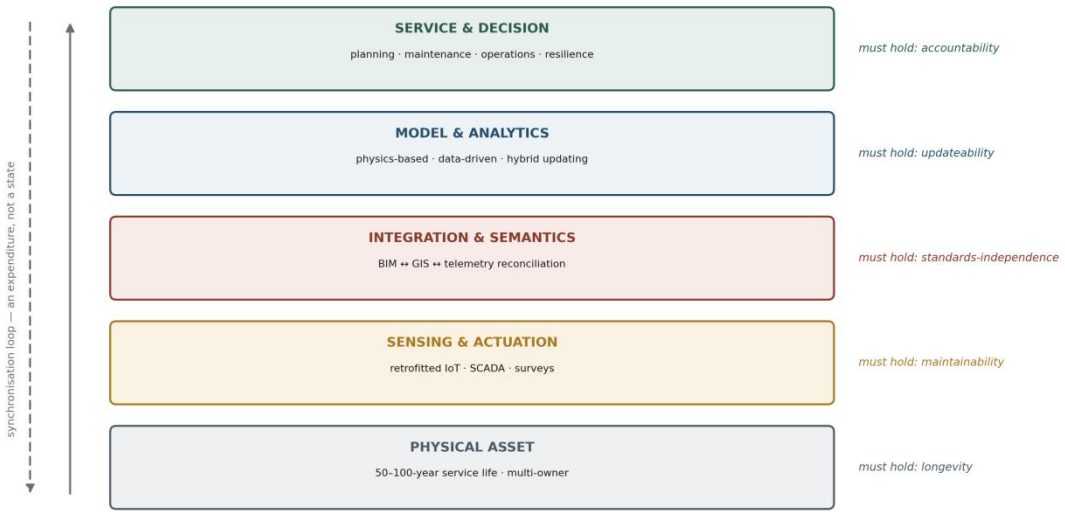



**Figure 2.** *Layered reference architecture of infrastructure digital twins, with the property each layer must hold over the asset's life.*

The integration layer is a crucial element to highlight. Three families of standards are to be reconciled - geometry, semantics, and update cadence - and the infrastructure twins is not a one-off mapping, but an artefact to be maintained, with its own drift. The unsolved problems do not lie in the field of modeling (Fuller et al., 2020; Naderi & Shojaei, 2022; Huzzat et al., 2025), but in the architectural signature of the argument developed next - the weakest layer of the twins.

### *4.3 Twin Drift and Synchronisation Economics*

The review's central synthesis is Figure 3.

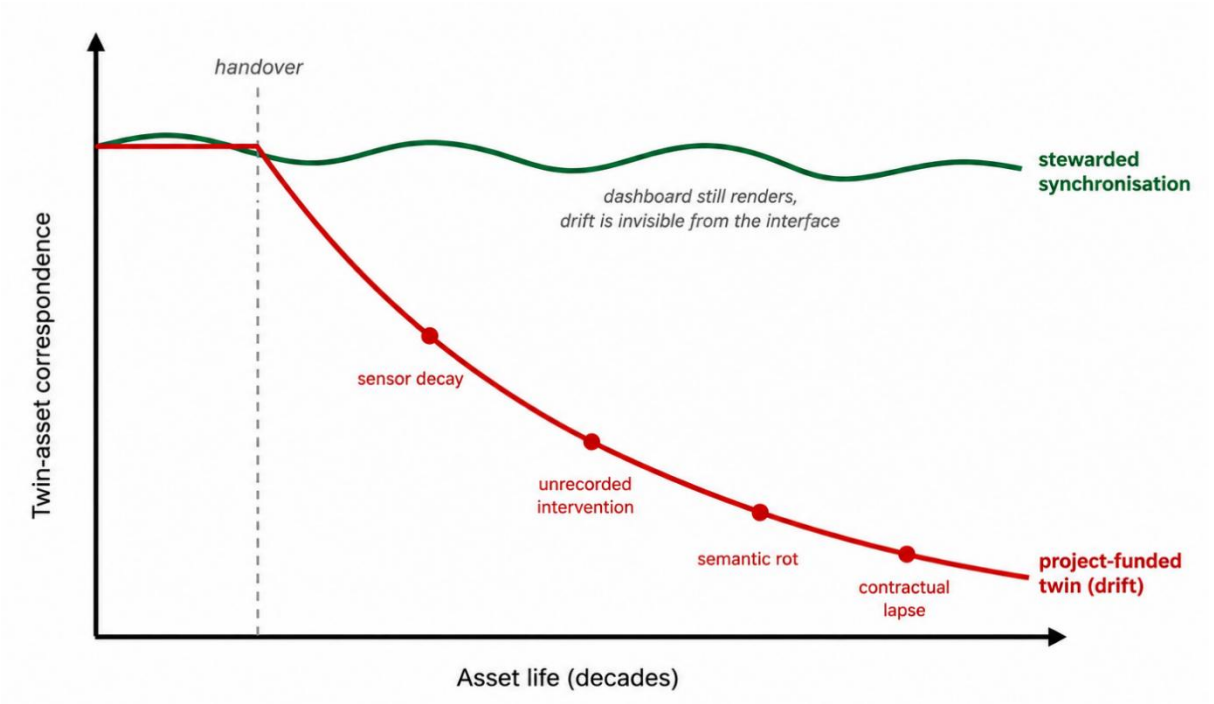



Figure 3. Twin drift: difference between twin and asset over the life of the asset in project-funded and stewarded synchronisation. The curves are not estimates of values. A Digital Twin is characterised by synchronisation – synchronisation is a spending, not a state. Sensors go bad and never get recharged or recalibrated; modifications to assets are made without corresponding model changes; employees who knew the semantic mappings leave; and the two entities still look great but have strayed from the asset they say they represent. This is the progressive and often unnoticeable deterioration of correspondence between twin and asset: twin drift. The oldest finding in the infrastructure informatics, namely the drift of as-built records, is no longer in the realm of the imagination but is now working at the speed of the machine, and concealed behind the facade of a live-looking interface. A drifted twin is worse than an absent twin because it generates missing information into a confident misinformation.

Drift is generated by the combination of the four structural asymmetries of section 1. As long or longer than the lifespan of their original platform, format and vendor, lifespan asymmetry ensures that each infrastructure twin lives multiple lives. The beginning of correspondence was not ideal and costly due to the missing birth certificate. Institutional fragmentation refers to the fact that no single institution is responsible for all components of the synchronisation bill. Consequences asymmetry is the fact that the consequences of drift are externalized until they are catastrophic. The binding constraint of infrastructure twinning is not the fidelity of the simulation, but synchronisation economics: the funding, staffing and contracting arrangements that ensure decades of data flows and that keep models up to date for decades. I can recognize the vectors of drift, and giving them names makes it manageable instead of just lamentable. Physical to virtual flow is lost first, through sensor decay: batteries, calibration and vandalism; and dashboards don't identify a quiet sensor from a quiet asset. Unrecorded intervention: Maintenance personnel work on assets more rapidly than model update workflows are able to record the changes made, so the twin retains the asset as it was, not as it is. Semantic rot: the reference relationships between the families of standards fade with schema versions and staff who created them. Contractual lapse: data-sharing contracts, licences and vendor support are completed in a timeframe that is ten times less than the asset's lifespan. Every vector is individually petty; together and in compound they ensure disunity in every pair of twins that is not actively opposed to them.

This is why the review classifies the infrastructure twin as a governance artefact: what makes some infrastructure twins successful is not the model itself, but how they are being managed, who is

operating them at a standing level, what funds are allocated to operations and maintenance, and who is updating them, and who is not, under terms agreed in asset-management contracts – these are the institutional features visible in the continental twins that work (ECMWF, 2026) and in the principles literature (Centre for Digital Built Britain, 2018). The comparison is useful: Destination Earth's twins are technically the most demanding of all time, but they are the ones missing the institutional form known as entrusted entities, the phased funding of public money, an operator who has a mission that is the twin, and a persistence in operation that is institutional rather than technological.

### *4.4 Reframing Evaluation*

If drift is the failure mode, fidelity is the wrong headline metric a twin can be photorealistic and false. Table 4's challenge taxonomy and Figure 4's maturity map therefore evaluate on different axes: currency (how stale is the twin's state relative to the asset), provenance (can every twin assertion be traced to a dated, owned source), and decision latency (how quickly does the twin turn asset change into decision-grade information).

**Table 4.** *Challenge taxonomy: generic versus structural*

| Challenge | Type | Infrastructure manifestation | Drift vector engaged |
|---|---|---|---|
| Model fidelity and validation | Generic | Physics/data hybrid updating against sparse sensing | — |
| Data volume and velocity | Generic | Streaming telemetry across thousands of assets | Sensor decay |
| Interoperability and semantics | Structural | BIM–GIS–telemetry reconciliation as a maintained artefact | Semantic rot |
| Lifecycle continuity | Structural | 50–100-year assets vs 5–10-year platform and vendor cycles | Contractual lapse |
| Brownfield reconstruction | Structural | No digital birth record; survey-based twin assembly (Lu et al., 2020) | Unrecorded intervention |
| Institutional federation | Structural | Multi-owner data governance across regulatory boundaries | Contractual lapse; semantic rot |
| Security and safety coupling | Generic, amplified | Twin compromise as a public-safety vector | — |
| Funding and stewardship | Structural | Twin budgeted as project capital, not whole-life operation | All vectors |

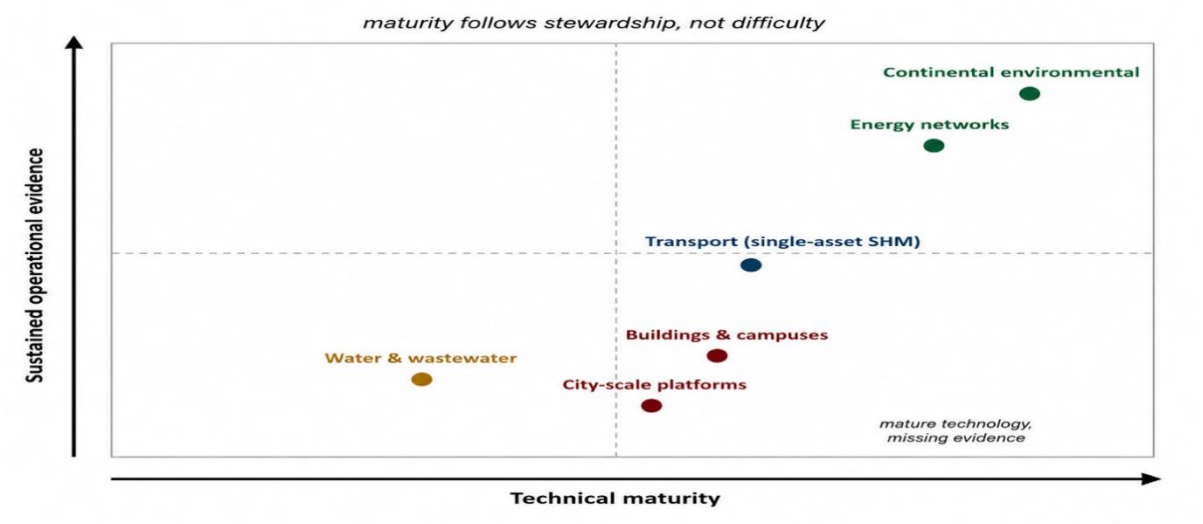



**Figure 4.** *Technical maturity versus sustained operational evidence by infrastructure class. Placements are the authors' qualitative synthesis (schematic, not bibliometric).*

## 5. Discussion

### *5.1 Theoretical Implications*

The analysis moves digital twin's identity conditions. The definitional literature considers whether or not data flows are automated (Kritzinger et al., 2018); the infrastructure setting then reveals that the easy part of the question is the automation of data flow – the hard part is the institutional, synchronised property of the data flow. This removes an apparent paradox from the maturity data (Figure 4): the technically most challenging twins (continental environmental systems) are technically most successful in operation, while the technically routine twins (building twins) are operationally most successful without making a noise about it, since the first group benefit from having standing operators, while the last one benefits from project funding. Stewardship leads to maturity, not hardship.

### *5.2 Practical and Policy Implications*

The conclusion to draw as an asset owner is that you need to pick currency, provenance, and decision latency as contracted service levels and that you need to budget the twin as an operating expenditure and not a capital line in a project. A helpful observation from the analysis is that, in year 10, a twin proposal can't name the person who is responsible for updating the model when the asset is updated, and from which Budget it is a proposal for a digital model with a twin's price. The infrastructure analogue of decommissioning bonds are exit obligations, open formats, documented semantics, data escrow, for vendors. The demonstrated pre-condition for twins to continue is the presence of an institution with the required mandate to ensure that they remain true, in the interests of policy, national twin programmes should be seen as federation and standards problems first and platform problems second (Centre for Digital Built Britain, 2018). Also, for public accountability, a drifted twin with a live interface is a risk of misinformation in precisely the circumstances that safety and resilience planning, and where twins are being sold the most.

### *5.3 Limitations*

The review is interpretive, meaning that the maturity placements in Figure 4 are judgements made and made available for discussion rather than measurements. The corpus is weighted towards the use of English and high-income deployments, to the disadvantage of contexts in which infrastructure information is most lacking. It is suggested that twin drift be a synthesis which is compatible with the domain structural properties, and with other nearby findings in the record of decay, while there is no yet extant longitudinal measurement of twin drift, which is the agenda's first item.

### *5.4 Future Research Directions*

Table 5 maps the agenda.

**Table 5.** *Research agenda*

| # | Priority | Central research question | Why it binds |
|---|---|---|---|
| 1 | Drift metrology | How is twin–asset divergence measured, and at what rate does it accumulate in deployed systems? | A failure mode that cannot be measured cannot be contracted against |
| 2 | Federation mechanics | What semantic, contractual, and trust architectures let twins interoperate across owners? | The binding problem for city and national programmes |
| 3 | Synchronisation economics | What whole-life cost models and funding instruments keep twins current for decades? | Drift is an economic phenomenon before it is a technical one |
| 4 | Updating at portfolio scale | How do engineering-grade updating methods extend from single assets to thousands? | Single-asset rigour does not currently scale |
| 5 | Equity of representation | How are data-poor assets and settings twinned credibly? | Twin-informed investment otherwise flows to what is already measured |

The priorities: (1) drift metrology instruments and longitudinal studies that measure twin–asset divergence for deployed systems, as a failure mode that cannot be measured cannot be procured against; (2) federation mechanics, semantic, contractual and trust architectures for twins that cross institutional boundaries, the binding problem for national programmes; (3) synchronisation economics,

whole-life cost models and funding instruments for keeping twins current, including who pays when asset owner and twin beneficiary differ; and (5) equity of representation methods for twinning data-poor infrastructure, without which twin-informed investment will go to what is already well measured.

## 6. Conclusion

The digital twins are a new tool in the toolboxes of smart infrastructure: the city, building, transport, water, energy, and continental environmental twins are all reality and demonstrate the potential ceiling of the digital twins concept. However, the centre of gravity fidelity of the field and platforms and demo lies one step below the real constraint in the field. Infrastructure is the place where software's assumptions get embarrassed: Assets last longer than vendors, records come before formats, ownership gets broken into pieces, and consequences get made public. In those situations, it's no longer about how accurately the digital twin replicates the asset on the day it ships, but what will keep it accurate in year fifteen. That's a question around institutions, budgets and contracts, it's a question around stewardship and it is the twins who have answered that question that thrive. The research agenda outlined below is by no means glamorous, it is precisely because it is not glamorous that it is chosen.The research agenda proposed here is not of the glamorous variety, by design. The other choice is a constructed landscape where there are pretty, but proud, mirrors that are all the wrong way round.

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## Declarations

### Conflict of Interest
The authors declare no conflicts of interest related to this study.

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### Ethical Approval
This study did not involve any human or animal subjects and, therefore, did not require ethical approval.