From Physical Assets to Cognitive Infrastructure: The Role of Digital Twins in Enabling Circular Economy and Resilient Design

Rekha Mishra[1] and Anindita Chatterjee[2]

[1] School of Leadership and Management,
Manav Rachna International Institute of Research and Studies,
Faridabad, Haryana, India
[2] Faculty of Management Science, Adani University
Ahmedabad, Gujarat, India
[2]Anindita.chatterjee@adaniuni.ac.in

Abstract: Infrastructure systems are under increasing pressure from climate uncertainty, resource constraints, and the growing burden of ageing assets. Conventional infrastructure management approaches remain predominantly linear, reactive, and asset-centric, limiting their capacity to support long-term sustainability and adaptive performance. In parallel, digital twin technologies and circular economy principles are widely promoted as transformative solutions. However, existing scholarship largely treats these domains in isolation and offers limited theoretical explanation of how they may be coherently integrated within long-life infrastructure systems. This paper addresses this gap by developing a conceptual framework for cognitive infrastructure, defined as infrastructure systems capable of learning, adaptation, and informed lifecycle decision-making through the strategic use of digital twins. Drawing on systems theory, complexity theory, circular economy theory, and resilience engineering, the study explains how digital twin capability can function as an integrating mechanism that aligns circular resource strategies with anticipatory and adaptive resilience objectives. Each theoretical perspective is assigned a distinct explanatory role, reducing conceptual ambiguity and strengthening internal coherence. The study adopts a theory-building approach based on structured synthesis of the literature and analytical reasoning. It does not undertake empirical testing or system-level modelling. Instead, it develops analytically grounded propositions that explain how feedback, learning, and governance conditions shape the transition from digitally enabled infrastructure to cognitive infrastructure. The paper contributes to infrastructure and sustainability scholarship in three ways. First, it introduces cognitive infrastructure as a theoretically integrated construct. Second, it clarifies the conditions under which digital twins extend beyond efficiency optimisation to support systemic sustainability. Third, it outlines conceptual limitations and directions for future empirical research and policy development.

Keywords: Digital Twin; Cognitive Infrastructure; Circular Economy; Infrastructure Resilience; Systems Thinking.

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1 Introduction and Background of the Study

Infrastructure systems underpin economic activity, social wellbeing, and environmental stability. Railways, roads, bridges, energy networks, and water systems enable daily life, yet many of these assets are ageing, resource-intensive, and increasingly exposed to climate-related disruption. Conventional infrastructure management remains largely linear and reactive, focused on maintenance, replacement, and short-term efficiency. Such approaches struggle to address long-term sustainability, uncertainty, and systemic risk [1]. In parallel, two influential trajectories have emerged. The first is the growing adoption of digital twin technologies, enabled by advances in sensors, cyber–physical systems, data analytics, and artificial intelligence. Digital twins allow physical assets to be represented, monitored, and understood through dynamic digital counterparts that evolve over time [2]. The second trajectory is the rise of the circular economy, which challenges linear "take–make–dispose" models by emphasising lifecycle extension, reuse, repair, remanufacture, and resource regeneration [3]. Although both trajectories are widely discussed, existing research treats them largely as separate domains. Digital twin studies in infrastructure often prioritise operational efficiency, predictive maintenance, or risk monitoring, with limited engagement with circular resource strategies or long-term sustainability outcomes [4]. Conversely, circular economy research in the built environment frequently focuses on buildings, materials, or manufacturing supply chains, offering limited insight into large-scale, networked infrastructure systems characterised by long lifespans, institutional complexity, and public governance [5].

Recent scholarship has begun to acknowledge this disconnect. Systematic reviews suggest that digital twins have the potential to support lifecycle transparency and decision-making across design, operation, and end-of-life stages, yet their role in enabling circular infrastructure remains conceptually underdeveloped [6]. Similarly, studies on resilient infrastructure increasingly recognise the need for anticipatory, data-driven capabilities, but often lack an integrative framework linking resilience, circularity, and digital intelligence [7]. This fragmentation reveals a clear research gap. There is a lack of infrastructure-specific conceptual frameworks explaining how digital twin capabilities can integrate circular economy principles with resilience objectives in long-life, socio-technical systems. Existing studies rarely address how learning, feedback, governance, and organisational capacity shape this integration. As a result, infrastructure continues to be conceptualised as static assets rather than adaptive systems.

This study addresses that gap by proposing a conceptual framework for cognitive infrastructure. Cognitive infrastructure is defined as infrastructure that can learn, adapt, and inform lifecycle decisions through digital twins, while embedding circular economy and resilience logics. The study adopts a theory-building approach grounded in systems theory, complexity theory, circular economy theory, and resilience engineering. It does not undertake empirical testing or system-level modelling. Instead, it develops analytically grounded propositions through structured synthesis of the literature. The research is guided by the following question:

How can digital twin capabilities conceptually enable the transition of infrastructure systems from linear, asset-oriented management towards cognitive, circular, and resilient systems?

The objectives are to:

1. Conceptualise a framework linking digital twin capability with circular economy and infrastructure resilience.
2. Identify key technological, organisational, and governance enablers and constraints shaping this transition.
3. Develop conceptual propositions explaining how predictive analytics within digital twins can support adaptive lifecycle decision-making.
4. Clarify the implications for infrastructure governance, skills, and policy.

The study contributes to theory by integrating fragmented literatures into a coherent conceptual model. It contributes to practice and policy by offering a structured way to rethink infrastructure strategy beyond efficiency, towards learning and regeneration. By reframing infrastructure as cognitive rather than static, the paper responds to growing societal demands for sustainability, resilience, and responsible digital transformation.

The remainder of the paper reviews the relevant theoretical foundations, develops the conceptual framework, and discusses implications for future research and infrastructure policy.

2 Literature Review

2.1 Theoretical Foundations

Digital twins (DTs) originated within product lifecycle management as dynamic digital representations capable of mirroring physical systems across design, operation, and end-of-life stages [8]. Subsequent research extended this concept by embedding real-time data, simulation, and feedback loops, enabling continuous optimisation rather than static representation [9]. In infrastructure contexts, DTs are increasingly understood not merely as monitoring tools, but as socio-technical systems that support learning, anticipation, and adaptation [10]. This evolution draws implicitly on systems theory and complexity theory. Systems theory conceptualises infrastructure as an interconnected whole, where performance emerges from interactions among technical components, organisations, and governance arrangements [11]. Complexity theory complements this view by framing infrastructure as adaptive and non-linear, shaped by feedback, emergence, and uncertainty [12]. Digital twins embody both perspectives.

They formalise system structure while enabling adaptive learning through data-driven feedback.

Circular economy (CE) theory provides a normative sustainability anchor. Rooted in ecological economics, CE seeks to decouple economic value creation from resource depletion by closing material and energy loops [13] [14]. In infrastructure, CE translates into asset longevity, modularity, reuse, and material recovery across long lifecycles [15]. Recent studies argue that digital technologies can operationalise CE by improving lifecycle visibility and decision-making, though empirical integration remains limited [16].

Resilience theory, initially developed in ecology, has evolved to describe the capacity of systems to absorb disturbance, adapt, and transform under uncertainty [17]. In infrastructure studies, resilience encompasses technical robustness, organisational flexibility, and socio-institutional capacity [18]. Predictive analytics embedded in DTs offers a pathway to operationalise resilience by enabling stress testing, anticipatory maintenance, and adaptive response [19].

Despite conceptual overlap, the literature remains fragmented. DTs are often framed as technological artefacts, CE as an economic or policy agenda, and resilience as a governance outcome [20]. Few studies explicitly integrate these perspectives into a unified conceptual lens. This fragmentation motivates the present study's focus on cognitive infrastructure, which treats infrastructure as a learning system shaped by digital intelligence, circular logic, and adaptive capacity.

2.2 Contextual Perspectives

Empirical adoption of DTs in infrastructure has expanded rapidly but unevenly. Most applications focus on urban systems, energy networks, and transport corridors, often within smart city initiatives in high-income countries [21]. Civil infrastructure such as roads, bridges, and water networks is increasingly addressed, yet integration with CE principles remains limited and largely experimental [22].

European countries, including the United Kingdom, the Netherlands, and Finland, have embedded DTs within national digital infrastructure strategies [23]. In contrast, emerging economies such as India and Indonesia face challenges related to data interoperability, institutional readiness, and skills capacity, despite growing policy interest [24]. Contextual variation is also evident across scales. Large programmes deploy system-level DTs, while smaller projects rely on isolated, asset-level models [20].

A similar pattern appears in CE research. Much of the infrastructure-related CE literature focuses on construction waste, recycling, or material efficiency, rather than data-driven lifecycle cognition [25]. Studies remain sectoral and fragmented, offering limited insight into how circularity can be governed across interconnected infrastructure networks [26].

Resilience-oriented DT studies tend to focus on post-disaster assessment or climate adaptation scenarios [27]. More recent work highlights predictive resilience, where real-time data enables anticipation rather than reaction [28]. However, this emerging perspective is rarely linked to circular resource strategies.

These contextual disparities reveal two gaps: an overemphasis on technological feasibility at the expense of systemic transformation, and limited attention to socio-technical conditions in diverse institutional settings.

2.3 Defining Characteristics of Digital Twin–Enabled Infrastructure

The literature identifies several defining characteristics of contemporary DTs: connectivity, intelligence, adaptability, and sustainability alignment. Early DTs focused on representation. Recent generations emphasise cognition, where systems learn from data and support prescriptive decision-making [29]. This shift distinguishes DTs from traditional Building Information Modelling.

Predictive analytics and semantic interoperability are critical to this transition [30]. They enable anticipatory management, moving infrastructure away from reactive maintenance towards adaptive optimisation [31]. Blockchain and distributed ledgers further support traceability of materials and data, reinforcing circular economy applications [32].

However, definitional inconsistency persists. Some studies frame DTs as data ecosystems, others as simulation tools, and few as cognitive systems capable of continuous learning [10] [16]. This ambiguity limits theoretical consolidation.

In CE contexts, DTs are expected to support closed-loop data architectures that inform reuse, repair, and recovery decisions [33]. Yet empirical validation of such feedback loops remains scarce. Similarly, resilience-focused DTs struggle with defining measurable indicators for adaptation and transformation [21].

Ethical and governance considerations are also underdeveloped. Scholars increasingly argue that DTs must incorporate ecological and social boundaries to avoid reinforcing resource-intensive growth [19]. Responsible digital cognition remains a conceptual frontier.

2.4 Methodological Trends and Gaps

Methodologically, DT research in infrastructure is dominated by simulation, case studies, and design science approaches. Early work relied on computational models to replicate asset behaviour [9]. More recent studies adopt mixed methods, combining simulation with expert judgement [20].

In CE-linked DT research, methods such as Life Cycle Assessment, Material Flow Analysis, and System Dynamics are often applied in isolation [25]. Only a small number of studies attempt integrative approaches that link circularity and resilience [16][28].

Qualitative exploration of governance, skills, and institutional adaptation remains limited, particularly in emerging economies [24]. Longitudinal studies are rare, constraining understanding of DT maturity over time [30]. Bibliometric reviews also reveal geographic concentration in Europe and China, with limited representation from Africa, South Asia, and Latin America [26].

2.5 Synthesis and Research Gaps

A critical synthesis reveals five interrelated gaps:

1. **Theoretical integration gap**: DT, CE, and resilience remain conceptually siloed, limiting understanding of infrastructure as a learning system.
2. **Contextual diversity gap**: Evidence is concentrated in high-income settings, overlooking socio-technical complexity elsewhere.
3. **Definitional ambiguity**: Inconsistent meanings of "digital twin" impede cumulative knowledge.
4. **Methodological imbalance**: Simulation dominates over systemic, socio-technical analysis.
5. **Ethical and governance blind spots**: Responsible digital cognition is under-theorised.

Addressing these gaps requires a holistic conceptual framework. This study responds by proposing cognitive infrastructure as an integrative lens, positioning digital twins as enablers of circularity, resilience, and responsible adaptation (See table 1).

Table 1. Literature Synthesis

Literature Stream	Key Authors (Year)	Core Argument / Contribution	Limitations / Tensions Identified	Insight Used for Conceptual Model
Digital Twins – Foundations	[8]; [9]	Digital twins enable real-time representation, simulation, and optimisation across asset lifecycles.	Early work treats DTs as technical artefacts, with limited socio-technical or sustainability framing.	DTs provide the *cognitive substrate*—continuous sensing, simulation, and feedback—required for learning infrastructure systems.
Digital Twins in Infrastructure	[10];[21]	DTs improve monitoring, predictive maintenance, and operational efficiency in infrastructure assets.	Focus remains asset-centric and efficiency-driven; weak linkage to circularity or resilience.	DT capability must evolve beyond efficiency towards *system-level cognition*.

Systems Theory	[11]	Infrastructure functions as an interconnected socio-technical system where performance emerges from interactions.	Systems theory alone does not explain adaptation under uncertainty.	Provides the *structural logic* for integrating assets, data, organisations, and governance.
Complexity Theory	[12]	Infrastructure systems are adaptive, non-linear, and shaped by feedback and emergence.	Often abstract; lacks operational mechanisms.	Justifies feedback loops and learning processes enabled by DTs.
Circular Economy Theory	[13]; [14]; [15]	CE promotes closed-loop resource use, lifecycle extension, and regeneration.	CE remains normative and policy-driven; operationalisation in infrastructure is weak.	CE provides the *sustainability logic* embedded into DT-enabled decision-making.
DT–CE Integration	DT–CE Integration	DTs can support lifecycle transparency and circular decision-making.	Predominantly product- or building-focused; infrastructure underexplored.	DTs act as *operational enablers* of circular strategies in long-life assets.
Resilience Theory	[17]; [18]	Resilience emphasises adaptive capacity, recovery, and transformation under disturbance.	Often treated as post-disaster response rather than anticipatory capability.	Resilience frames the adaptive outcome of cognitive infrastructure.
DTs and Resilience	[19]; [28]	Predictive analytics and simulation support anticipatory resilience.	Weak linkage to resource circularity and governance.	Weak linkage to resource circularity and governance.
Governance and Ethics	[19]; [24]	Digital infrastructures require ethical, institutional, and skill alignment.	Governance and ethics often treated as secondary concerns.	Cognitive infrastructure must embed responsible learning and decision-making.
Methodological Reviews	[20]; [26]	DT research is dominated by simulation and case studies.	Limited theoretical consolidation and geographic diversity.	Justifies a *conceptual, theory-building approach* rather than empirical testing.

3 Conceptual Framework: Cognitive Infrastructure

3.1 Conceptual Foundation

This study proposes Cognitive Infrastructure (CI) as a higher-order conceptual construct that emerges from the interaction of three interrelated dimensions: Digital Twin Capability (DTC), Circular Economy Enablement (CEE), and Infrastructure Resilience (IR). The framework is theory-driven and explanatory in nature. It does not aim to test causal relationships empirically but to clarify how these dimensions logically cohere within infrastructure systems. The framework draws on four complementary theoretical traditions. Systems theory provides the structural foundation by conceptualising infrastructure as an interconnected socio-technical system in which performance arises from interactions among physical assets, digital technologies, organisations, and governance arrangements. This perspective highlights interdependence rather than isolated optimisation.

Complexity theory extends this view by explaining how infrastructure systems evolve over time through non-linear interactions, feedback loops, and learning under conditions of uncertainty. Such dynamics are particularly relevant in the context of climate variability, ageing assets, and cascading system risks.

Circular economy theory introduces the sustainability logic. It reframes infrastructure assets as long-life resource stocks whose value can be retained through lifecycle extension, reuse, modularity, and regeneration. However, circular principles alone do not specify how such decisions are informed or coordinated across complex systems.

Resilience theory complements circular thinking by focusing on adaptive capacity, recovery, and transformation in the face of disturbance. It ensures that circular strategies remain viable when infrastructure systems experience shocks or stress.

Within this theoretical configuration, digital twins act as the integrating mechanism. Digital twins operationalise system interdependencies, enable feedback and learning, inform circular lifecycle decisions, and support anticipatory adaptation. Cognitive infrastructure emerges when digital twins are deployed not only for operational efficiency, but as learning systems embedded within organisational and governance processes across the infrastructure lifecycle.

3.2 Core Components and Theoretical Alignment

The conceptual framework comprises four components, each grounded in a distinct but complementary theoretical foundation (See table 2).

Table 2. Components and Theoretical Alignment

Construct	Conceptual Role	Indicative Dimensions	Theoretical Anchors
Digital Twin Capability (DTC)	Enables sensing, integration, and interpretive understanding of infrastructure systems	Real-time data, simulation capacity, predictive insight	Cyber–physical systems; data-driven decision theory
Circular Economy Enablement (CEE)	Guides lifecycle decisions towards resource retention and regeneration	Asset longevity, reuse potential, modularity	Industrial ecology; cradle-to-cradle design
Infrastructure Resilience (IR)	Supports adaptive response and continuity under uncertainty	Flexibility, recovery capacity, transformability	Resilience engineering; systems dynamics
Cognitive Infrastructure (CI)	Represents system-level learning and adaptive governance	Feedback-driven optimisation, decision autonomy	Organisational learning; cognitive systems theory

3.3 Conceptual Relationships and Logic

The framework proposes that digital twin capability acts as a foundational enabler that supports both circular economy enablement and infrastructure resilience. Through continuous sensing, simulation, and interpretation, digital twins provide the informational basis for understanding asset condition, resource flows, and system vulnerabilities.

Circular economy enablement is conceptualised as a mediating dimension. By extending asset lifecycles and reducing material vulnerability, circular strategies strengthen resilience outcomes. Infrastructure resilience, in turn, reflects the system's capacity to absorb disruption and adapt without compromising long-term sustainability.

Cognitive infrastructure emerges when digital capability, circular logic, and resilience co-evolve within an institutional context that supports learning and informed decision-making. These relationships are presented as conceptual propositions rather than testable hypotheses. Their strength and form are expected to vary across contexts depending on governance quality, organisational culture, and data maturity.

3.4 Conceptual Process Flow

The framework can be understood as a layered process of learning and adaptation:

1. **Input Layer:** Infrastructure condition data, lifecycle records, maintenance histories, and material flow information are combined with expert knowledge on governance, skills, and organisational readiness.
2. **Digital Twin Cognition Layer:** Digital twins integrate and interpret data through simulation and predictive reasoning, supporting scenario exploration related to degradation, reuse, and system stress.
3. **Circular Economy Decision Layer:** Insights from digital twins inform lifecycle optimisation, including repair, reuse, modular redesign, and resource recovery strategies.
4. **Resilience Outcome Layer:** Infrastructure systems enhance adaptive capacity through anticipatory maintenance, flexible reconfiguration, and improved recovery pathways.
5. **Feedback and Learning Layer:** Outcomes inform organisational learning, policy refinement, and strategic adjustment, reinforcing the cognitive capability of the infrastructure system over time.

This conceptual framework provides a coherent explanation of how digital twins can enable infrastructure systems to move beyond static, asset-centric management towards learning-oriented, circular, and resilient configurations. It establishes a theoretical foundation for future empirical investigation while remaining firmly grounded in conceptual reasoning.

3.5 Conceptual Propositions: Towards Cognitive Infrastructure

Building on the theoretical synthesis and conceptual framework, this study advances a set of propositions that clarify the logical relationships among digital twin capability, circular economy enablement, and infrastructure resilience. These propositions are interpretive and explanatory. They are not empirically tested in this study but are intended to guide future analytical and empirical research.

Proposition 1 (Digital Twin Capability as a Cognitive Enabler)
Digital twin capability enables cognitive infrastructure by transforming infrastructure systems from static, asset-centric entities into learning-oriented socio-technical systems through continuous sensing, integration, and interpretive feedback. This proposition draws on systems and complexity theory, which emphasizes learning, feedback, and emergence as defining characteristics of adaptive systems. Digital twins provide the informational and analytical basis for such learning.

Proposition 2 (Digital Twins and Circular Economy Enablement)
Higher levels of digital twin capability conceptually strengthen circular economy enablement by improving lifecycle visibility and supporting informed decisions related

to asset reuse, repair, modularity, and resource recovery. Here, digital twins act as operational mechanisms that translate circular economy principles from normative aspirations into actionable lifecycle intelligence, particularly in long-life infrastructure systems.

Proposition 3 (Circular Economy as a Pathway to Resilience)
Circular economy enablement contributes to infrastructure resilience by reducing resource vulnerability, extending asset functionality, and enhancing system flexibility under conditions of stress and disruption. This proposition aligns circularity with resilience outcomes, reframing resource efficiency as a contributor to adaptive capacity rather than solely an environmental objective.

Proposition 4 (Digital Twins and Anticipatory Resilience)
Digital twin capability supports anticipatory forms of infrastructure resilience by enabling scenario exploration, stress anticipation, and proactive adaptation rather than reactive recovery. This proposition reflects a shift in resilience thinking from post-disruption response to forward-looking preparedness enabled by predictive digital cognition.

Proposition 5 (Co-evolution of Circularity and Resilience)
Circular economy enablement and infrastructure resilience co-evolve within digital twin-enabled systems, reinforcing one another through shared feedback mechanisms and lifecycle learning processes. Rather than operating as parallel objectives, circularity and resilience are conceptualised as mutually reinforcing dimensions of cognitive infrastructure.

Proposition 6 (Role of Organisational and Governance Conditions)
The emergence of cognitive infrastructure is contingent upon organisational learning capacity, governance alignment, and responsible data stewardship that enable digital twins to inform decision-making beyond technical optimisation. This proposition highlights that cognitive infrastructure is not purely technological but depends on institutional and ethical conditions that shape how digital intelligence is used.

Positioning of Propositions within the Study

Together, these propositions articulate the internal logic of the cognitive infrastructure framework. They clarify how digital twins integrate circular economy and resilience logics through learning and feedback, while recognising the socio-technical conditions required for such integration. The propositions establish a structured agenda for future empirical research, simulation studies, and policy experimentation, without extending beyond the conceptual scope of the present study.

4 Conceptual Hypotheses for Future Empirical Research

Although the present study is conceptual, the proposed framework lends itself to future empirical examination. To support subsequent testing, the conceptual propositions are reframed below as formal hypotheses. These hypotheses are not tested in this study and are presented to guide future quantitative, qualitative, or mixed-method research.

Hypothesis 1 (H1): Digital Twin Capability and Cognitive Infrastructure
H1: Higher levels of digital twin capability are positively associated with the emergence of cognitive infrastructure in long-life infrastructure systems. This hypothesis reflects the premise that continuous sensing, data integration, and interpretive analytics enable infrastructure systems to shift from static asset management towards learning-oriented configurations.

Hypothesis 2 (H2): Digital Twin Capability and Circular Economy Enablement
H2: Digital twin capability is positively associated with circular economy enablement in infrastructure systems. This hypothesis operationalises the role of digital twins in improving lifecycle visibility and supporting decisions related to reuse, repair, modularity, and resource recovery.

Hypothesis 3 (H3): Circular Economy Enablement and Infrastructure Resilience
H3: Circular economy enablement is positively associated with infrastructure resilience. Here, circular strategies are expected to reduce resource vulnerability and enhance adaptive capacity, thereby strengthening resilience outcomes.

Hypothesis 4 (H4): Digital Twin Capability and Infrastructure Resilience
H4: Digital twin capability is positively associated with infrastructure resilience. This hypothesis reflects the role of predictive analytics, simulation, and anticipatory insight in enabling proactive adaptation rather than reactive recovery.

Hypothesis 5 (H5): Mediating Role of Circular Economy Enablement
H5: Circular economy enablement mediates the relationship between digital twin capability and infrastructure resilience. This hypothesis captures the co-evolutionary logic of the framework, suggesting that part of the resilience benefit of digital twins operates through circular lifecycle strategies.

Hypothesis 6 (H6): Moderating Role of Organisational and Governance Conditions
H6: Organisational learning capacity and governance alignment positively moderate the relationship between digital twin capability and cognitive infrastructure outcomes. This hypothesis recognises that technological capability alone is insufficient and that institutional conditions shape how digital intelligence is translated into system-level learning. Mapping of Hypotheses to Conceptual Framework is shown in Table 3

Table 3. Hypothesis-to-Framework Mapping

Hypothesis	Relationship Tested	Framework Element
H1	Digital Twin Capability → Cognitive Infrastructure	Core vertical pathway
H2	Digital Twin Capability → Circular Economy Enablement	Enabling pathway
H3	Circular Economy Enablement → Infrastructure Resilience	Sustainability–resilience linkage
H4	Digital Twin Capability → Infrastructure Resilience	Direct anticipatory pathway
H5	DTC → CEE → IR (Mediation)	Co-evolutionary mechanism
H6	Moderation by organisational and governance conditions	Contextual boundary conditions

5 Research Methodology

5.1 Research Design

This study adopts a theory-building conceptual research design. Its purpose is to develop a coherent and analytically grounded framework explaining how digital twin capability enables circular economy practices and infrastructure resilience, and how their interaction gives rise to cognitive infrastructure. The study does not undertake empirical testing. Instead, it aims to consolidate fragmented literatures and clarify causal logic before large-scale data-driven validation. Conceptual research is appropriate where phenomena are emergent, complex, and insufficiently theorised [34]. Digital twins in infrastructure, circular economy application in long-life assets, and resilience engineering have largely evolved in parallel. Empirical convergence remains limited due to uneven technological maturity and restricted access to operational system data. A conceptual design allows analytical rigour without premature quantification.

The study follows an explanatory–integrative design, combining systematic literature synthesis with structured causal reasoning. This approach aligns with established guidance for theory development in sustainability and systems research [35][36].

5.2 Methodological Framework

(Theory–Context–Characteristics–Methodology) with systems-based analytical reasoning. TCCM enables disciplined organisation of diverse literature while avoiding descriptive accumulation [37]. It supports the identification of theoretical fragmentation, contextual bias, definitional ambiguity, and methodological limitations.

To enhance explanatory coherence, the study complements TCCM with principles from systems theory and complexity theory, enabling articulation of interdependencies, feedback loops, and emergent behaviour. This combined framework ensures both breadth and analytical depth across infrastructure engineering, sustainability science, and digital systems research.

5.3 Literature Sampling and Data Sources

A purposive, theory-driven sampling strategy was employed. The objective was conceptual relevance rather than exhaustive coverage. Literature was drawn from high-impact, peer-reviewed journals in infrastructure systems, digital engineering, sustainability, and governance.
Selection criteria included:

- Explicit engagement with digital twins, circular economy, or resilience at system or lifecycle levels.
- Strong theoretical or analytical contribution.
- Publication primarily between 2020 and 2025.
- Methodological transparency and disciplinary credibility.

Sources included journals such as Automation in Construction, Journal of Cleaner Production, Technological Forecasting and Social Change, Advanced Engineering Informatics, and Environment and Planning B. Grey literature was used selectively for contextual grounding but not for theory development

5.4 Analytical Procedure

The analysis followed a structured abstraction and synthesis process. Each source was examined for underlying theoretical assumptions, construct definitions, implied causal mechanisms, and governance implications. Analytical memos were developed iteratively to capture complementarities, tensions, and gaps across disciplines.

Rather than thematic coding, the study employed analytical comparison, consistent with conceptual research practice [38]. This enabled disciplined synthesis while preserving theoretical nuance.

5.5 Construct Operationalisation

Although empirical measurement is deferred, constructs were analytically operationalised to ensure conceptual clarity and future testability.

- Digital Twin Capability (DTC) was defined as the maturity of real-time sensing, data integration, simulation, and predictive analytics supporting decision-making [29].
- Circular Economy Enablement (CEE) was operationalised as the capacity to support lifecycle extension, reuse, remanufacture, and recovery in infrastructure systems [14].
- Infrastructure Resilience (IR) was conceptualised as adaptive capacity, recovery potential, and transformability under disruption [18].
- Cognitive Infrastructure (CI) was defined as an emergent system property reflecting learning, feedback-driven optimisation, and decision autonomy across asset lifecycles.

This operational discipline avoids conceptual ambiguity and positions the framework for subsequent empirical validation.

5.6 Objective-wise Analytical Logic

Each research objective was addressed through a distinct analytical approach. For framework conceptualisation, the study applied cross-theoretical synthesis, assessing compatibility among systems theory, complexity theory, circular economy theory, and resilience engineering. Compatibility was justified through shared principles such as feedback, adaptation, and lifecycle orientation. For identifying enablers and constraints, the study employed comparative analytical reasoning across organisational, technological, and governance dimensions. This approach highlights non-technological determinants often underplayed in digital twin research. Relationships among constructs were articulated using structured causal logic rather than statistical estimation. This preserves explanatory clarity while avoiding speculative inference [36].

5.7 Methodological Contribution

The methodological contribution is threefold. First, the study reframes digital twins as **socio-technical cognition systems**, extending beyond simulation or efficiency tools. Second, it positions circular economy enablement as a **mediating logic** between digital capability and resilience, rather than treating these domains in isolation. Third, it introduces **analytical readiness** by defining constructs and causal paths without empirical overreach, strengthening conceptual validity.

5.8 Ethical Considerations and Rigor

Although no primary data are used, ethical considerations remain relevant. Interpretive bias was mitigated through transparent construct definitions, explicit boundary conditions, and acknowledgement of contextual limitations. The study avoids technological determinism by explicitly incorporating governance, skills, and organisational learning.

Rigor was ensured through theoretical triangulation, analytical transparency, and internal coherence, consistent with quality criteria for conceptual research [34].

5.9 Limitations

The absence of empirical testing limits claims regarding magnitude and causality. The framework also abstracts across infrastructure sectors, potentially masking sector-specific dynamics. These limitations are intentional design choices, positioning the study as a foundation for future empirical research.

6 Findings and Discussion

This study set out to conceptually examine how digital twin capability can enable circular economy practices and infrastructure resilience, and how their interaction gives rise to cognitive infrastructure. As the study is conceptual in nature, the findings are analytical and theory-driven rather than empirical. They emerge from systematic synthesis of contemporary literature, cross-theoretical integration, and structured reasoning aligned with the proposed framework.

6.1 Findings Aligned with Research Objectives

Finding 1: Digital Twin Capability Functions as a Foundational Enabler of Cognitive Infrastructure.

The first objective sought to conceptualise a framework linking digital twin capability (DTC) with circular economy enablement (CEE) and infrastructure resilience (IR). The analysis finds that DTC acts as a foundational capability rather than an isolated technological tool. Across the reviewed literature, digital twins consistently appear as integrative mechanisms that connect physical assets, digital data streams, organisational processes, and governance structures [10][2]. The framework demonstrates that cognitive infrastructure does not emerge from digitalisation alone. It emerges when real-time sensing, predictive analytics, and simulation are embedded within feedback-driven decision loops that span the full infrastructure lifecycle. This aligns with systems theory, which views infrastructure performance as an emergent outcome of interactions among interdependent components [11].

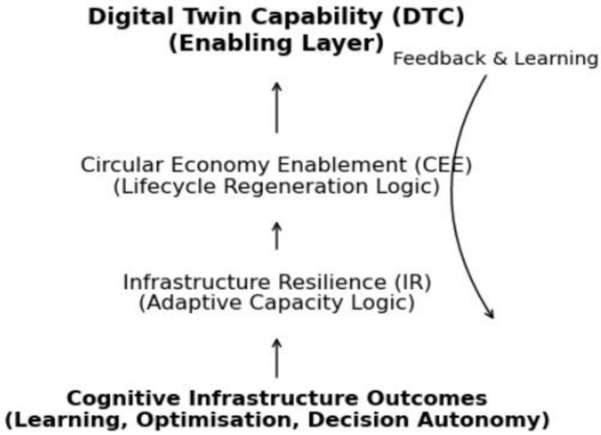

Fig. 1. (Conceptual Cognitive Infrastructure Framework) illustrates this foundational role, positioning DTC as the enabling layer that activates circular and resilience logics rather than replacing them.
Source: From review synthesis

Finding 2: Circular Economy Enablement Mediates the Relationship Between Digital Twins and Resilience.

The second finding relates to the mediating role of circular economy enablement. The conceptual analysis indicates that digital twin investments translate into resilience outcomes primarily when they inform lifecycle decisions such as repair, reuse, modular replacement, and material recovery. This finding extends circular economy theory beyond its traditional focus on resource efficiency towards adaptive lifecycle governance [14][5]. Predictive analytics embedded within digital twins allow infrastructure managers to anticipate degradation and optimise interventions before failure occurs. This reduces resource volatility and exposure to supply shocks, thereby strengthening resilience [28]. In this sense, circularity operates as a resilience mechanism rather than a parallel sustainability objective (See table 4).

Table 4. summarises these analytical relationships by mapping digital twin functions to circular actions and corresponding resilience outcomes.

Digital Twin Function	Core Analytical Role	Circular Economy Actions Enabled	Corresponding Resilience Outcomes
Real-time sensing and monitoring	Continuous visibility of asset condition and material states	Early identification of components suitable for repair, reuse, or life extension	Reduced failure probability; early disturbance detection

Data integration across lifecycle stages	Linking design, operation, maintenance, and end-of-life data	Informed decisions on remanufacture, modular replacement, and material recovery	Improved system coherence; reduced cascading failures
Predictive analytics	Anticipation of degradation, demand shifts, and stress scenarios	Optimisation of maintenance timing; prioritisation of reuse over replacement	Anticipatory resilience; shorter recovery times
Simulation and scenario modelling	Exploration of alternative future states and interventions	Evaluation of circular strategies under different lifecycle and policy scenarios	Enhanced adaptive capacity; robust decision-making under uncertainty
Feedback and learning loops	Continuous refinement of models and decisions	Iterative improvement of circular strategies based on performance outcomes	Transformative resilience through learning and adaptation
Decision-support and autonomy	Translation of insights into actionable recommendations	Alignment of operational decisions with circular and sustainability goals	Faster response and reconfiguration during disruptions

Source: From review synthesis

Finding 3: Cognitive Infrastructure Emerges Only Through Co-evolution of Technology, Organisation, and Governance.

The second research objective focused on identifying technological, organisational, and governance enablers and constraints. The findings reveal that technological maturity alone is insufficient for cognitive infrastructure emergence. Organisational learning capacity, cross-agency coordination, and data governance alignment play decisive roles. Studies from Europe and emerging economies highlight that fragmented ownership, siloed data architectures, and skill shortages often limit the translation of digital twin insights into action [23] [24]. Conversely, contexts with integrated governance and shared data standards demonstrate higher adaptive capacity. This finding supports organisational learning theory and resilience engineering perspectives, which emphasise institutional adaptability and sense-making under uncertainty [18]. Cognitive infrastructure, therefore, reflects not only intelligent assets but intelligent institutions.

Finding 4: Predictive Analytics Transforms Infrastructure from Reactive to Anticipatory Systems.

A cross-cutting analytical insight concerns the role of predictive analytics. The synthesis shows that predictive capabilities embedded in digital twins shift infrastructure management from reactive maintenance towards anticipatory and adaptive regimes. This transition is central to the notion of cognition. Rather than responding to failures post hoc, infrastructure systems begin to simulate future states, evaluate trade-offs, and recommend interventions aligned with circular and resilience objectives [19]. This anticipatory logic differentiates cognitive infrastructure from earlier smart infrastructure models.

6.2 Discussion in Relation to Theory and Prior Research

Theoretical Contributions

This study contributes to theory in three substantive ways. First, it advances digital twin scholarship by repositioning DTs as socio-technical cognition systems rather than technical artefacts. Prior research often treats DTs as simulation or monitoring tools [9]. This study reframes them as learning infrastructures embedded within governance and organisational contexts. Second, the study extends circular economy theory into the infrastructure domain. Existing CE research remains largely product- or building-centric [15] [25]. By conceptualising circularity within long-life, networked infrastructure systems, the framework addresses a recognised theoretical gap. Third, the integration of resilience theory with circular economy via digital twins offers a novel synthesis. While resilience and circularity are often discussed separately, this study demonstrates how circular lifecycle strategies enhance adaptive capacity under uncertainty. This integration supports calls for multi-theoretical sustainability models [20].

Practical and Policy Implications

From a practice perspective, the findings suggest that infrastructure organisations should prioritise capability development over isolated technology adoption. Investments in sensors and analytics must be accompanied by workforce upskilling, data interoperability standards, and cross-agency coordination mechanisms. For policymakers, the framework highlights the need for governance models that support data sharing, lifecycle accountability, and long-term value creation. National digital infrastructure strategies may benefit from explicitly linking digital twin initiatives with circular economy and resilience objectives rather than treating them as parallel agendas.

Unexpected and Counterintuitive Insights

An unexpected insight concerns the limited role of advanced AI in the early stages of cognitive infrastructure development. The literature suggests that basic predictive analytics combined with strong governance often yields greater impact than sophisticated models deployed in fragmented institutional settings. These finding challenges technology-centric narratives and reinforces the importance of socio-technical alignment.

6.3 Limitations

Several limitations must be acknowledged. First, the study is conceptual and does not empirically test the proposed relationships. While this is intentional, it limits claims regarding effect magnitude or causal strength. Second, the framework abstracts across infrastructure sectors. Sector-specific dynamics, such as regulatory constraints in water or safety-critical requirements in transport, may shape outcomes differently. Third, much of the reviewed literature originates from high-income contexts. Although emerging economy perspectives are incorporated, further empirical grounding is required.

6.4 Future Research Opportunities and Next Steps

Building on these limitations, three logical next steps emerge. First, future studies should empirically test the proposed hypotheses using structural equation modelling or system dynamics simulations based on operational infrastructure data. Second, longitudinal case studies should examine how digital twin maturity evolves over time and how circular and resilience benefits co-emerge across asset lifecycles. Third, governance-focused research should explore ethical, legal, and skill-related dimensions of cognitive infrastructure, particularly in resource-constrained contexts. Together, these directions would advance the transition from conceptual clarity to empirical validation and practical implementation.

7 Conclusion

This study advances understanding of sustainable infrastructure transformation by developing a conceptually grounded framework for cognitive infrastructure. It responds to growing pressures from climate uncertainty, resource constraints, and ageing assets by reframing infrastructure not as static capital, but as a learning socio-technical system. By integrating digital twin capability, circular economy enablement, and infrastructure resilience within a unified theoretical structure, the study clarifies how digital technologies can move beyond efficiency gains to support regenerative and adaptive infrastructure lifecycles. The primary contribution lies in positioning digital twins as an integrating mechanism that operationalises systems interdependencies, feedback, and learning. This integration enables circular lifecycle decisions while strengthening anticipatory resilience. The framework also foregrounds organisational learning, governance arrangements, and skills as critical enablers, addressing limitations of technology-centric accounts in existing literature. As a conceptual study, the findings are analytical rather than empirical. The framework does not claim generalisable effects, but offers structured propositions and clearly defined constructs that support future empirical testing. Its value lies in consolidating fragmented scholarship and providing a coherent foundation for interdisciplinary research. For practice and policy, the study highlights the need to align digital infrastructure investments with circular and resilience objectives from the outset. Future research should empirically examine the proposed relationships across infrastructure sectors and governance contexts. Collectively, the study positions cognitive infrastructure as a credible pathway towards sustainable, resilient, and intelligent infrastructure systems.

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