

Evolution Toward Cognitive Urban Intelligence: A Systematic Review of Multi-Domain Digital Twins Integrated with Large Language Models

Aakanksha Mukati, Prof. Sharad Marolia

M.Tech. Scholar, Information and Technology Department, Mahakal Institute of Technology, Ujjain
Assistant Professor, Computer Science Department, Mahakal Institute of Technology, Ujjain

Abstract

As civilized area transform into industry 5.0 ecosystems (It's about humans and smart machines working together to create products that are better for both people and the planet), For that transform Digital Twins (DTs) are shifting from passive monitoring technologies to independent Cognitive Digital Twins (CDT). This research paper undertakes a systematic review of existing developments on Cognitive Digital Twin technologies for urban areas, particularly on the integration of knowledge Graphs (KGs) and Large Language Models (LLMs). Based on the 'Ingest to Actuate' operational pipeline (Yu et al., 2025) and Knowledge Graphs (Dang et al., 2025), this study reviews the state of the art on existing urban simulations between 2024-2026. Although existing studies set CDT logic into individual sectors areas, a significant 'Interdependency Gap' is recognized regarding the ripple effect between sectors. This systematic review reveals the need for unified framework that is able to synchronize heterogeneous domains of urban areas. The combination of Llama 3.1 and Neo4j is proposed as a potential combination of sufficient depth to bridge this gap for 'What-If' analysis for sustainable urban governance.

Keywords: Cognitive Digital Twins, Knowledge Graphs, Large Language Models, Neo4j Database, Llama 3.1, GraphRAG.

1. Introduction

The standard of urban management in 2026 has shift from simple data visualization to active cognitive reasoning which is applying logic to solve complex problems, plans or make decision. As city grows into "System of Systems" it is a task-oriented system that collaborate to achieve unique capabilities none can accomplish alone, the "Siloed Data" problem remains the largest barrier to true urban resilience (It refers to city's ability to absorb, adapt to and recover from shocks). While traditional concept of Digital Twins does not have the "intelligence" required to understand the ripple effects cause when initial small disturbance or action spreads through a system, causing progressively larger often unplanned and interconnected consequences.

This review paper has been based on two main pillars:

1. The Operational Pillar (Yu et al., 2025): Developing a lifecycle of 6 stages (Ingest, Synchronize, Simulate, Predict, Decide, Actuate) for engineering feasibility.
 2. The Cognitive Pillar (Dang et al., 2025): Using Neo4j Knowledge Graphs to make complex city data searchable as semantic network.
- Through these approaches, we have identified the Reasoning Gap in current systems are either strategic but not interactive or interactive but limited to static rules. This project fills this gap by introducing a framework for What-if dynamic natural language reasoning through a 20-domain framework using Llama 3.1.

3. Methodology (The PRISMA Protocol)

In order to ensure a rigorous and plagiarism-free synthesis of the review, this review will follow the PRISMA 2020 (Preferred Reporting Items for

Systematic Reviews and Meta-Analyses) guidelines.

3.1. Selection of Base Papers

The framework selection was based on the ability to bridge the gap between "Structure" and "Intelligence":

- Base Paper 1 [Yu et al., 2025]: Chosen for its use of DT-IRL (Implementation Readiness Level) scale, which provides a metric for city maturity.
- Base Paper 2 [Dang et al., 2025]: Chosen for its pioneering use of Neo4j database technology to solve the query complexity of 3D city models (CityGML).

3.2. Search Strategy

Digital libraries such as IEEE Xplore and Scopus were also utilized with a specific search string for the technical landscape of 2026: ("Cognitive Digital Twin") AND ("Llama 3.1" OR "GenAI") AND ("Smart City"). After screening 64 studies, 21 were selected for final analysis.

4. Thematic Analysis of Research Gaps

The 21 studies reviewed in the dissertation identify three research gaps that this dissertation aims to solves:

1. The Interdependency Gap: Most researchers only study 1 or 2 domains. What is needed is a logic that can connect the dots among 20 domains.
2. The Accessibility Gap: What is needed is a “Participatory Layer” where a city planner can ask the city a question in plain English, without needing an expert to run the digital twin.
3. The Validation Gap: Real-world testing is dangerous. Therefore, the only way to safely validate a reasoning engine for 20 domains is with Synthetic Data, as discussed in Russo et al., (2025).

Section 4: Thematic Taxonomy and Comparative Analysis

The following table categorizes the analysed literature based on four critical dimensions of Cognitive Digital Twins: Architectural Flow, Cognitive Depth, Domain Diversity, and Human-Machine Interaction (HMI).

Research Reference	Core Framework	AI/Cognitive Layer	Domain Scope	Primary Research Gap
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Yu et al. [2] (Base 1)	6-Step Pipeline	Minimal (Predictive)	Energy	Lack of interactive reasoning.
Dang et al. [3] (Base 2)	Neo4j + CityGML	Rule-based Chatbot	3D Geometry	Limited to static queries.
Liu et al. [12]	Hybrid AI-IoT	CNN-LSTM	Infrastructure	No natural language support.
Herath et al. [13]	Edge-Core Architecture	LSTM (Edge)	Traffic/Air	Centralized core vulnerability.
Pawar et al. [16]	GRU-CNN Hybrid	Anomaly Detection	Traffic	Isolated from other city sectors.
Chiaro et al. [17]	GenAI-Empowered	LLM (Generative)	General/Survey	High cloud latency ; privacy risks.
Ge & Qin [18]	Lifecycle Resilience	Multi-Agent	Flooding	Water-only; no traffic link.
Russo et al. [22]	Synthetic Framework	LSTM-GAN	Mobility	No cross-domain synthetic data.
Snap4City [24]	Multi-Layer Tiling	Web-based IoT	Public Health	Complex menu-driven UI.

Shen et al. [27]	BIM-IoT-DT	STGCN	Underground	"Hidden city" signal blockage.
Li & Shao [19]	4D Modeling	Intelligent Feedback	Governance	Ignored human element.
Proposed Work	Graph RAG Architecture	Llama 3.1 + Neo4j	20 Urban Domains	None (Fills the Integration Gap)

Section 5: Identifying the "Multi-Domain Reasoning Gap"

By analysing the taxonomy above, we can visualize where the current state-of-the-art limitations. Most research in period of 2024–2026 is currently "Siloed."

As seen in the interdependency map above, a city is not a collection of parts, but a web of connections.

- The "Ripple Effect" Problem: Paper [18] knows how to manage a flood, but it doesn't know that the flood will cut power to the Hospital [12], which then requires the Traffic system [16] to prioritize ambulances.
- The "Cognitive" Solution: By using Llama 3.1, our system acts as a "Translator" that reads the entire 20-domain Knowledge Graph to explain these ripples to a human in plain English.

Section 6: Proposed Conceptual Framework

To bridge these gaps, we propose a framework that merges the engineering discipline of Yu et al. with the semantic intelligence of Dang et al.

1. Data Ingestion Layer: Uses the 6-step pipeline to ingest data from 20 domains.
2. Semantic Layer: Maps all 20 domains into a single Neo4j instance to show how they are connected.
3. Cognitive Layer: Llama 3.1 runs on top of this graph (using Retrieval-Augmented Generation) to answer "What-If" questions.

7. Conclusion

This systematic review has identified the evolution of urban management ranging from monitoring to the dawn of Cognitive Urban Intelligence. By uniting the operational rigor of the "Ingest-to-Actuate" pipeline (Yu et al., 2025) with the semantic depth of Knowledge Graph-driven query systems (Dang et al., 2025), we have identified that the main challenge facing current urban intelligence research is the Interdependency Gap. While the 21 papers reviewed showing considerable advancement in individual domain such as mobility, flooding and energy it has also identified that current urban intelligence solutions are technology-siloed.

This prevent urban resilience from being achieved as there is currently a lack of a unified reasoning engine to handle multi-domain scenarios. This study has identified that the integration of Llama 3.1 and Neo4j can solve this problem as it can unify 20 heterogeneous domains into a single cognitive framework allowing a “What-if reasoning capability that is explainable, proactive, and accessible to non-expert stakeholders.

8. Future Scope and Challenges

The move towards a 20 domain Cognitive Digital Twin (CDT) is a technically challenging but high reward effort. Future research and the subsequent implementation phase of this project will focus on the following:

- **Real-time Edge-Cloud Synchronization:** Developing a strategy to ensure that Llama 3. when running on local "Edge" hardware can synchronize with real-time IoT streams from all 20 domains without latency.
- **GraphRAG Optimization:** Refining the Retrieval-Augmented Generation (RAG) process to ensure that the LLM extracts the most relevant information from the Neo4j database for the domains during a crisis situation.
- **Privacy-Preserving Governance:** Developing a system of decentralized data protocols to ensure that while the 20 domains are connected and sharing information citizen data is maintained securely and adheres to the data sovereignty requirements of the year 2026.

- **Multi-Modal Interaction:** Extending the chat-based interface beyond text-based data exchange and exploring the integration of 3D spatial visualized such that the "Cognitive Brain" is able to point to specific urban assets while explaining its reasoning.

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