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AI-Enabled Systemic Strategies for Smart Net-Zero City Development

FARZANEH JOUZDANI[1]*, VAHID JAVIDROOZI[1], HANIFA SHAH[1], MUHAMMAD AFZAL[1],
[1]FACULTY OF COMPUTING, ENGINEERING AND THE BUILT ENVIRONMENT (CEBE) BIRMINGHAM CITY UNIVERSITY, BELMONT ROW, BIRMINGHAM B4 7RQ, UK.
EMAIL: FARZANEH.MOHAMMADI@MAIL.BCU.AC.UK
VAHID.JAVIDROOZI@BCU.AC.UK
HANIFA.SHAH@BCU.AC.UK
MUHAMMAD.AFZAL@BCU.AC.UK
* CORRESPONDENCE: FARZANEH.MOHAMMADI@MAIL.BCU.AC.UK

Abstract

Smart Net-zero Cities research has demonstrated a wide range of heterogeneous knowledge and interventions across city sectors such as energy, transportation and buildings, treating the city as disconnected and sector-specific strategies rather than an integrated system. This study developed an AI-enabled knowledge graph to organise the fragmented evidence, model the city system interventions and propose systemic strategies and a digital transformation framework. The evidence base includes 135 official city documents and 2123 academic publications. 16 core interventions were identified through framework analysis of official city documents. A Retrieval-Augmented Generation model was then developed and validated using 500 questions, achieving 85%, 86%, and 88% precision, recall, and relevance, respectively. The outputs were utilised to develop a knowledge graph comprising 319 nodes and 892 directional relationships, illustrating that a smart net-zero city is an interconnected system through shared environmental, governance and technological factors. The extracted insights from the knowledge graph were translated into systemic strategies across four systemic levels, including physical deployment, digital monitoring, system integration, predictive maintenance and circularity. A focus group evaluation confirmed the relevance and applicability of the systemic strategies. This study contributes to operationalising systems through a knowledge graph and providing evaluated systemic strategies supporting smart net-zero planning and development.

Keywords: smart net-zero cities; knowledge graph; systems thinking; systemic strategies; retrieval-augmented generation; urban interdependencies; leverage points; digital transformation.

1. Introduction

Cities function as complex systems whose outcomes arise from the continuous interactions between social, technological, economic, and environmental components and cannot be attributed to single-sector interventions. Achieving Smart Net-zero cities (SNC) transformation demands a systemic understanding of how the interventions across the city sectors are influencing one another and how their integrated deployments are reshaping the wider city system (Bibri, 2021).

The current investigations on SNC development have largely focused on recognising and classifying interventions that contribute to sector-specific digitalisation and decarbonisation. These studies have generated valuable insights into some individual interventions such as adopting electric vehicles, renewable energy, and expanding public transportation (Moghaddasi et al., 2021).

Reviewing the literature reveals that these interventions function based on isolated and sector-bound strategies rather than interdependent components of a single system, which limits the holistic understanding of system-wide effects of SNC development (Duan & Kim, 2023). This identified gap is closely related to the limited integration of system modelling methods in SNC

development. The systems thinking approach is widely identified as an essential strategy for city transformation. However, its principles are not adequately employed for modelling a queryable and structured representation of interactions between city system interventions. Utilising a systems thinking perspective for cities proves that any alteration in a city's components can impact one another either directly or through an indirect chain of impacts across city sectors, which continuously shapes the city system behaviour (Jouzdani, Javidroozi, Shah, et al., 2025). Other research similarly argues that utilising a systems thinking lens is necessary for capturing the interdependence of city sectors, enabling a more integrated and adoptable approach for SNC transformation (Cavalcante et al., 2017).

The lack of interconnection modelling also limits the proposing and deployment of systemic strategies for SNC interventions. Current literature investigations propose interventions at the city sectors without adequately addressing their system-wide impacts (Caputo et al., 2019). Formulating systemic strategies needs a holistic understanding of interdependencies and interactions between technologies, governance mechanisms, and infrastructure across the city system. Providing a formal representation of cities' interventions and interactions contributes to providing evidence-based strategies that utilise shared resources and dependencies (Moghaddasi et al., 2021).

Knowledge graphs as a system modelling tool can address this limitation. A knowledge graph is capable of organising fragmented information into connected nodes and relationships. In a city context, it can be utilised to present interventions, technologies, infrastructure, policies and sustainability practices within a single model (Z. Wang et al., 2024). This structure enables the analysis of direct and indirect relationships, supports identifying patterns, and reveals potential leverage points for proposing systemic strategies (Fotopoulou et al., 2022). Despite this potential, using knowledge graphs for exploring SNC interventions and generating systemic interventions remains largely underdeveloped.

This study addressed the following research gaps: the lack of structured interconnection modelling among SNC interventions and the absence of systemic strategies for interventions which drives from knowledge modelling of the SNC system. Rather than proposing interventions, this study develops a knowledge graph that models the interventions and their relationships across the city system. The knowledge graph is then analysed to propose systemic strategies for SNC development.

Three objectives guide the study: identifying critical interventions across the main city sectors, including energy, transportation and buildings; identifying the interconnections between the interventions and modelling the SNC system; and proposing and evaluating systemic strategies for interventions deriving from the structured knowledge in the knowledge graph. These objectives correspond to the three research questions:

1. What are the critical interventions across the key city sectors for developing SNC?
2. What are the interconnections between the identified interventions?
3. How does knowledge modelling of the city system support proposing systemic strategies for interventions?

Theoretically, this study contributes to integrating a systems thinking approach into SNC development by providing knowledge modelling. The methodological contribution of this study is utilising Retrieval-Augmented Generation (RAG) and knowledge graph modelling for structural representation and analysis of the SNC system. Also, an empirical knowledge graph is proposed that structures the SNC interventions, enabling technologies, governance and infrastructure. This can be utilised for understanding and developing city systems to move towards SNC. Finally, this study translates the knowledge graph into four levels of systemic strategies for informing city planners and digital transformation practitioners.

This paper is organised as follows. The theoretical foundations of SNC interventions, knowledge graph and systems thinking for cities are discussed in Section 2. Section 3 provides data collection and analysis methodology, including intervention identification, RAG development, knowledge graph creation and systemic strategies formulation. The results of the knowledge graph and systemic strategies are provided in Section 4. Section 5 discusses the study contributions to SNC development. Finally, Section 6 concludes the paper and summarises its limitations and future research directions.

2. Theoretical Background

2.1 Smart Net-zero Cities development

SNC development reflects the convergence between digital transformation and net-zero emission goals, which is recognised as a central strategy for sustainable development (Jouzdani, Javidroozi, Shah, et al., 2025). For this purpose, various interventions across the city sectors were identified in academic and practical investigations. In energy sectors, smart grids, renewable energy integration, and district energy systems are examples of such interventions (H. Wang & Wang, 2024). In transportation sectors, Electric Vehicles (EVs), EV charging points and public transportation electrification, and in the building sector, heat pump adoption and Heating, Ventilation, and Air Conditioning (HVAC) electrification are other examples of the developed interventions (Branny et al., 2022). These interventions are understood to contribute to SNC development through distinct approaches. For example, renewable energy integration reduces cities' dependence on fossil fuel-based energy sources. It can be integrated with digital energy management systems to improve energy monitoring, balancing, and flexibility in operation (Boulanger, 2024). Similarly, adopting EVs in transportation systems reduces carbon emissions and improves energy efficiency (Apata et al., 2023). Building retrofitting contributes to energy demand reduction in buildings and facilitate shift to electrified heating systems (Razmjoo et al., 2021).

However, the extent to which any single intervention contributes to achieving SNC objectives is dependent on its relationship with other interventions and the wider city system, a point that emphasises systemic development of SNC (Jouzdani, Javidroozi, Garcia, et al., 2025). The proper deployment of EVs, for instance, depends on the availability of charging point infrastructure, electrification of energy supply and adequate capacity of energy grids (H. Wang & Wang, 2024). Similarly, the effective operation of heat pumps depends on their integration with building retrofitting and electrification of building energy systems rather than deployment in isolation (Mukhtar et al., 2021)

This shows that the integration of individual interventions through isolated and single-sector strategies cannot adequately address the systemic development of SNC; rather, the strategies must be developed in relation to the interdependencies that characterise the city system as a whole (Jouzdani, Javidroozi, Shah, et al., 2025)

2.2 Systems Thinking and Its Relevance to Smart Net-zero City Transformation

Systems thinking conceptualises the city not as an isolated collection of technologies or infrastructure, but as a complex system with various social, environmental, economic, and technological interactions to produce emergent results. Cities can be understood and analysed as a large-scale system that consumes energy, requires energy, processes data and adapts itself, with systemic impact arising from continuous interactions of their components rather than from a single component (Gallotti et al., 2021). City systems are characterised by complex interactions, interdependencies and emerging behaviour that the linear and conventional approaches cannot adequately address (Caputo et al., 2019).

Interdependencies refer to the mutual dependencies between system components, where a change in one element contributes to producing indirect or direct impacts in other components of the system (Meadows, 2008). Similarly, in cities, sectors and their interventions cannot be understood in isolation but instead require a holistic understanding of systemic interactions between the sectors. For example, integrating electrification in transportation affects the renewable electricity demand, while the grid capacity and availability of renewable energy sources impact the feasibility of transportation electrification (Nadel, 2019).

Connectivity is another systems thinking element that refers to the physical, social, digital economical and organisational relationships (Caputo et al., 2019). In the context of SNC, the connectivity element governs the communication between subsystems for achieving the sustainability outcomes which emerging from the flows, interactions and mutual impacts (Caputo et al., 2019). Emergent behaviour is a system-level outcome that arises from these interconnections rather than from a single element (Cavalcante et al., 2016). Phenomena such as air pollution and congestion are the results of numerous interactions in the city system which cannot be analysed, controlled or predicted in isolation (Kandt & Batty, 2021).

Dynamic complexity refers to unintended consequences in system behaviour over time that might result from delays, evolving responses and unexpected situations. Central to this concept are feedback loops, which are circular relationships between the system components shaping

future system behaviour (Meadows, 2008). Within cities, feedback loops between citizens, governance strategies, organisations and infrastructure can generate sustainable or unsustainable patterns of development (Jouzdani, Javidroozi, Garcia, et al., 2025).

Finally, leverage points are the system components where comparatively small change in the system may generate disproportionately large systemic impacts (Meadows, 2008). In city system governance structure, data integration platforms and smart grids might function as leverage points due to their capacity to impact multiple interventions at the same time (Abson et al., 2017).

Therefore, systems thinking suggests that city transformation requires an integrated, adaptive process rather than isolated optimisation of single interventions and sectors (Gallotti et al., 2021).

2.3 Knowledge graphs as system representation and analysis approach

A knowledge graph can support integrating systems thinking in the city context by providing a structural representation of city services, technologies and interventions with their interconnections and relationships. Rather than analysing fragmented information across isolated fields, a knowledge graph organises the knowledge as connected entities such as energy components, policies, citizens' roles, transportation and building services and structures them through a shared representational scheme (Abson et al., 2017). This capacity supports representing a complex city system as a structured, interconnected system where any change, feedback loop and behaviour can be traced back across the city components (Benes & Svitek, 2022).

Knowledge graphs also support city data integration across services and technologies. For example, data from traffic, services and public resources can be integrated using a knowledge graph, contributing to more efficient decision-making. This capacity supports consolidating these data sources into an organised and connected structure that can be utilised as a decision-making system for city planners and governance strategies (Z. Wang et al., 2024). This is particularly important for SNC digital transformation. Achieving net-zero targets through digital transformation approaches requires systemic analysis for proposing coordinated strategies across city sectors and services (Jouzdani, Javidroozi, Garcia, et al., 2025). A knowledge graph provides contextual analysis and reasoning for making cross-sectoral decisions by identifying interdependencies, enabling technologies and leverage points (Androna et al., 2024).

A knowledge graph therefore provides a mechanism for integrating systems principles into a queryable, analytical, traceable form. They can be used to integrate heterogeneous information into an interconnected and structured format for generating insights for resource allocation and intervention design strategies across the city system (Zaidan et al., 2022). Table 1 provides the linkage between systems thinking principles, knowledge graphs, and SNC development.

Table 0.1 : The contribution of using a knowledge graph for applying systems thinking principles for SNC development

Systems-thinking principle	Knowledge graph performance	Relevance to SNC development
Interdependency	Supports structural representation of directed and indirect relationships among interventions and enabling factors	Shows how changes in one intervention impact others
Connectivity	Facilitates modelling physical, digital, governance and environmental relationships	Represents cross-sector connections between interventions
Emergence	Supports identifying the impact of multiple interventions on shared outcomes	Demonstrates and supports tracking the outcomes resulting from combination interactions
Dynamic complexity	Support analysing direct, indirect and mixed relationships	Support identifying and highlighting possible unintended effects
Leverage points	Identifies highly connected nodes	Supports identifying and prioritisation of system-wide enablers
System representation	Integrates heterogeneous entities and evidence into organised and structural representation	Creates a queryable city-system model to support deploying systemic strategies for SNC development

3. Research Methodology

3.1 Overall research design

This study utilised a qualitative multi-method methodology including data collection, identification of main interventions, RAG development, knowledge graph development, systemic strategy and digital transformation framework formulation and validation and evaluation (Figure 1).

The methodology was designed to integrate practical smart city evidence with academic knowledge to support proposing systemic strategies for interventions. Official smart city documents provided applied strategies, programmes, and governance priorities for interventions. Academic literature supported integrating theoretical and technical information related to interventions and enabling factors.

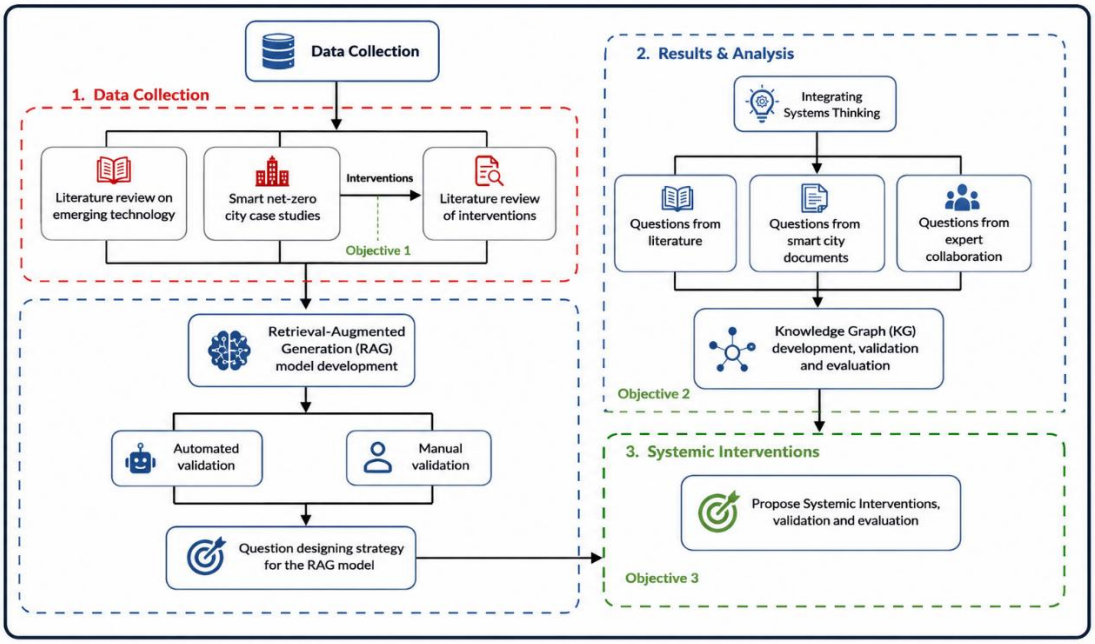


Figure 1: Overview of the research methodology

3.2 Data collection techniques

Two complementary data sources were utilised for constructing the evidence base for this study. The first includes official documents, such as frameworks, roadmaps, reports and policy strategies published by the top ten smart cities according to the 2024 IMD Smart City Index. The operational data sources were integrated because they capture real-world experiments, which are often underrepresented in academic sources (Joss et al., 2019). This supports a comparative analysis across city systems and provides relationships, enabling factors and contextual conditions that are used in subsequent knowledge graph development.

The second data source includes two systematic literature reviews comprising high-impact journals and conferences: one to address the identified interventions and the other to address emerging technologies for supporting interventions integration and deployments. These reviews support capturing recent theoretical progress and evidence on identifying challenges, opportunities and interdependencies in the city system, informing the development of RAG.

The selection of smart cities based on the IMD Smart City Index comprised Zurich, Oslo, Canberra, Geneva, Lausanne, Singapore, Copenhagen, London, Helsinki, and Abu Dhabi. The eligible documents were selected from those published by regional, city or government institutions, official net-zero and sustainability organisations or recognised smart city projects. The data source had to be plans, reports, policies, roadmaps, or official strategies published within the past 15 years and available in English. This process provided 135 official documents.

Two reviews based on Scopus search complemented the official city documents. First, a review of identified interventions from the smart city documents was followed by a screening process by publication year, language, type and abstract relevance, which provided 1078 documents. Second, on emerging technologies for enabling the interventions' deployment, following similar screening, 1045 documents were retained.

Table 2 represents a composition of the data corpus of 2258 documents. The corpus size was

deliberately retained due to the complexity and multidisciplinary nature of SNC. This supports a broad coverage in the subsequent RAG analysis.

Table 2: data sources compositions

Data sources	purpose	Documents
Documents from top ten smart cities	Identifying implemented interventions and conditions in the real-world	135
Literature on SNC interventions	Knowledge on performance, impact and interdependencies and relationships between the interventions	1078
Literature review on emerging technologies	Identifying enabling technologies and factors for interventions	1045
Total resources	Developing knowledge based for RAG-supported analysis	2258

3.3 Interventions identification and RAG deployment

The most deployed interventions across the top ten smart cities were identified through thematic analysis. This process yielded 16 distinct interventions, which formed the analytical framework of the literature review on interventions and emerging technologies.

Manual analysis of the total resources (2258 documents) was impractical and challenging due to the following factors: the volume of the documents, the risk of overlooking details and resource diversity across city sectors, technologies and environmental factors. Each involved field in the documents has distinct terminologies and cross source nature of relationships between the identified interventions. Therefore, RAG was adopted to combine semantic document retrieval with Large Language Model (LLM) generation to support cross-domain synthesis and analysis (Lewis et al., 2020).

For this purpose, all documents were verified as machine-readable PDF or Word files; the duplicates documents were identified and removed, followed by a manual evaluation process. The RAG pipeline was developed using LangChain, OpenAI, PyPDF and Maximal Marginal Relevance. In the final optimisation results of chunking parameters, the 1,000-token chunks and 200-token overlaps were selected to provide sufficient content while minimising redundancy. Out-of-scope questions were also used to test the RAG system to ensure providing supported responses by system.

The RAG system was finally validated using 500 evaluation questions across city sectors. The manual evaluation process assessed the accuracy, scope and completeness, while the automated assessment ensured the precision (85%), recall (86%), and relevance (88%) of the responses. The strong results of automated and manual evaluation confirmed the reliability of the developed RAG system for developing a knowledge graph.

3.4 Knowledge graph development

To structure the heterogeneous evidence into entities and relationships, a knowledge graph was constructed. For extracting the candidate nodes and relationships for knowledge graph development, the RAG model was utilised. Questions from independent literature were designed for each intervention to extract the relevant information. Table 3 shows the extracted themes from the literature and an example of design questions for one intervention (EVs). For each of the 16 identified interventions, the same five theme-based questions were submitted to the RAG system, resulting in a total of 80 responses. The responses generated from RAG were then collected, structured, and analysed to identify relevant nodes and relationships, which subsequently informed the development of the knowledge graph.

For ontology design, the nodes represent interventions, enabling technologies, policy and governance, physical infrastructure, data resources and outcomes, while the arrows present the relationships between the nodes coded as positive, negative, or mixed. This is accompanied with relationship description capturing the underlying mechanism of the connection.

Table 3: Theme-Based Question Designing Framework: EVs used as an Example

Theme	Purpose and evidence base	EV-specific question
Systemic impact	Examining system-wide impacts across interconnected city sectors. Supported by a systems-thinking approach in the literature (Duan & Kim, 2023c; Seto et al., 2021b).	How do EVs impact the wider city system and interconnected city sectors?
Enabling technologies	Identifying digital technologies and data capabilities which enable implementation, monitoring, integration, and optimisation of the interventions (Duan & Kim, 2023a; Łaźniewska et al., 2021).	What technologies enable deployment, integration, and monitoring of EVs and how?
Infrastructure systems	Identifying the required physical infrastructure for effective intervention deployment and integration (Gazzola et al., 2019; Komninos, 2022; Razmjoo et al., 2021c).	What infrastructure is required to support effective EV deployment and integration, and how?
Governance and policies	Examining policies, regulations, governance, and institutional mechanisms to support intervention implementation and adaptation (European Commission, 2020; Kılkış, 2021).	What governance and policy mechanisms support EV adoption and integration into the city system?
Cross-intervention relationships	Examining interdependencies and feedback between interconnected interventions (Diodati et al., 2022; Urrutia-Azcona et al., 2020).	How do EVs interact with intervention X?

Note. The same five questions were applied to each of the 16 interventions, resulting in 80 RAG queries. The responses were collected and analysed to inform knowledge-graph development. X represents each of the remaining 15 interventions considered in the study.

The RAG outputs were extracted, organised, and structured based on the source node, target node, relationship type and description. All extracted knowledge underwent human review for duplicate identification and removal (nodes and relationships), naming consistency, and accuracy to ensure that the knowledge graph produced verified model outputs. The knowledge graph was subsequently constructed and visualised using Neo4j, with the structured data in CSV and Cypher employed for node and relationship creation. Furthermore, in analytical validation, Cypher queries were used to test the knowledge graph's capability to retrieve meaningful patterns. For this purpose, the knowledge graph relationships were cross-checked against independent literature.

3.5 Development and validation of systemic strategies

Through a structural analysis of intervention connections, enabling factors, risks and leverage points in the knowledge graph, the systemic strategies were developed. The proposed systemic strategies were organised into four systemic levels, which were informed by smart city literature. The structure shows an evolution from foundational deployment to real-time monitoring, system integration, predictive optimisation and circularity (El-Agamy et al., 2024). These four levels were therefore used as an analytical framework rather than being employed to structure the systemic strategies (Table 4).

Table 4: Systemic strategies proposing stages

Systemic level	Analytical focus	Organisation of Knowledge-Graph-Derived Systemic Strategies
Level 1 – Deployment	Foundational implementation	Information extracted from the knowledge graph relating to physical infrastructure and foundational deployment factors such as policy, planning, finance, governance, and workforce was categorised under Level 1.
Level 2 – Digital monitoring	Monitoring and data collection	Information related to digital monitoring, sensors, real-time data collection, and performance monitoring was extracted and organised under Level 2.
Level 3 – System integration	Connectivity and integration	Information describing connections and integration between the intervention and wider city systems, such as interoperability, data sharing mechanisms, and coordinated system management, was extracted and organised under Level 3.
Level 4– Predictive optimisation and circularity	Advanced optimisation and sustainability	Information related to prediction, simulation, smart optimisation, automation, and circular economy/lifecycle management was extracted and organised under Level 4.

3.6 Developing digital transformation framework

Following the development of systemic strategies for each intervention, the knowledge graph was utilised to translate these strategies into people, Process, technology, and Data (PPTD). For each intervention and systemic level, the relevant node descriptions were extracted from the knowledge graph according to their functional focus and classified into four dimensions of PPTD. Table 5 summarises the digital transformation development stages. The developed framework structured the proposed systemic strategies and their associated PPTD into an organised progression of levels. This integration enabled the proposed framework to address not only the required technological advancement in cities to move towards SNC but also the human capabilities, data management and the organisational process.

Table 5: Digital transformation framework development stages

Systemic level	Knowledge-graph node extraction focus	PPTD classification
Level 1: Physical deployment	Foundational nodes for enabling the deployment	People: Foundational skills & awareness; Process: feasibility assessment, standards & incentives; Technology: Deploying physical infrastructure; Data: baseline data management
Level 2: Digital monitoring	Nodes related to real-time monitoring	People: Improving digital skills; Process: monitoring & cybersecurity; Technology: Deploying IoT & digital sensors; Data: real-time operational data collection and management
Level 3: City-wide integration	Nodes related to integration, interoperability and shared systems	People: Improving cross-sectoral coordination; Process: Coordinating system and demand; Technology: Deploying integrated platforms & smart systems; Data: Developing shared system data
Level 4: Predictive optimisation	Nodes relevant to advanced analysis and lifecycle optimisation	People: Stakeholders advanced analytical skills; Process: predictive optimisation & circularity process deployment; Technology: Integrating AI & digital twins; Data: predictive maintenance and performance data

Finally, the proposed systemic strategies and framework were validated through a focus group. The focus group included eight experts in smart cities, sustainability, energy systems and digital transformation. They reviewed a summary of the knowledge graph, the proposed systemic strategies, and the framework and discussed the relevancy, feasibility, sustainability impact and applicability of them in SNC planning. The results were utilised to refine stakeholders' roles, dependencies, and relationships among the four systemic levels.

4. Results

This section presents the key findings of this study, including the identified interventions, knowledge graph analysis and visualisation results, proposed systemic strategies, digital transformation framework and validation findings from the focus group session.

4.1 Identified interventions

Framework analysis results of 135 smart city documents identified 16 core interventions across the energy, transportation and building sectors (Table 6). The identified interventions represent the most recurrent deployed or planned actions in the selected smart cities. The sectoral classification of the interventions reflects their primary sector; however, many interventions show significant cross-sectoral relationships beyond their primary classification.

Table 6: 16 identified interventions for SNC development

Sector	Identified interventions
Transportation	Electric vehicles; EV charging points; public transportation; electrification of public transportation; cycling; clean-air zones; mobility as a service
Energy	Renewable energy; solar PV, district energy; energy storage
Buildings	Heat pumps; HVAC electrification; building retrofitting; multipurpose buildings; green roofs and walls

4.2 Knowledge graph results

The developed knowledge graph showed an integrated view of the identified interventions and the wider systemic factors impacting SNC transformation (Figure 2). The final developed graph comprised 319 nodes and 892 relationships. The graph represents the complex interactions in the city system. It supports observation and analysis of direct and indirect relationships between city system components which were connected through shared environmental, technological and governance factors. The intense topology indicated that SNC interventions do not operate in isolation but as components of an interconnected system. The developed knowledge graph provides a structural foundation for visualising and analysing the city system required for proposing systemic strategies.

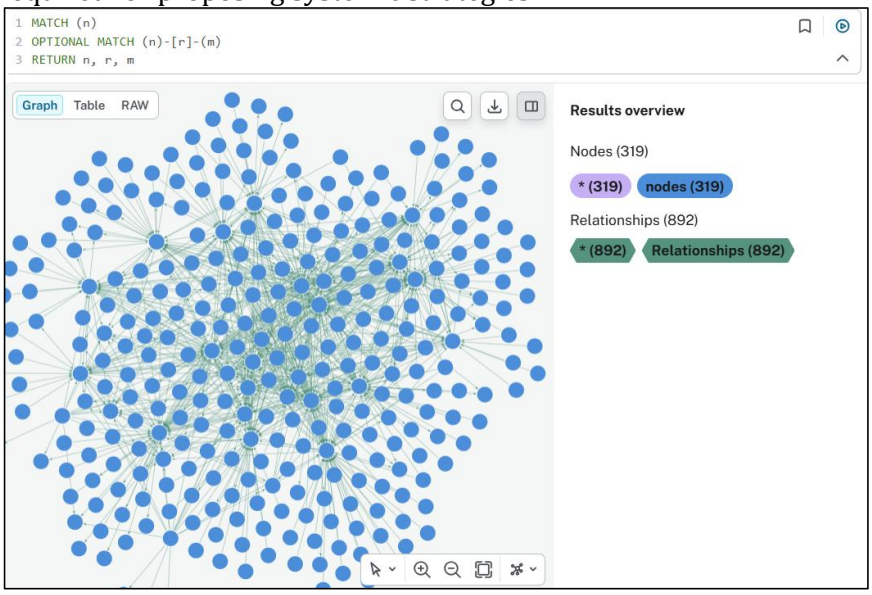


Figure 2: Full visualisation of the developed knowledge graph including 319 nodes and 892 relationships (source: Neo4j output)

The knowledge graph can be used to represent direct and indirect relationships between nodes, contributing to identifying interconnections within a complex city system. Figure 3 shows the direct relationship between two specific nodes, including building retrofitting and public health. The relationship type is positive, and the relationship description illustrates how building retrofitting can improve public health, clarifying the underlying mechanism of this specific relationship.

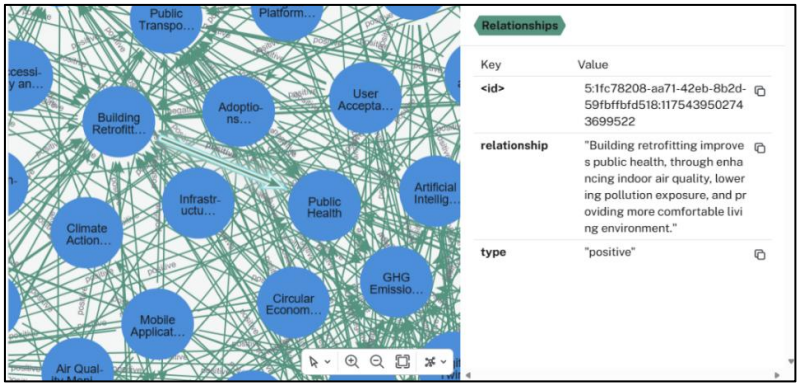


Figure 3: The visualisation of the direct relationship between two specific nodes

The knowledge graph can also be employed to present indirect relationships between interventions that are not directly connected. For example, district energy and public transportation have an indirect relationship through shared enabling factors, particularly the Smart City Data Platform and Energy Management System (Figure 4). These nodes connect the two interventions by supporting data integration, monitoring, and coordinated energy management. Identifying such indirect relationships can support recognising hidden cross-sectoral interdependencies and help practitioners identify opportunities for integrated planning and governance across the city.

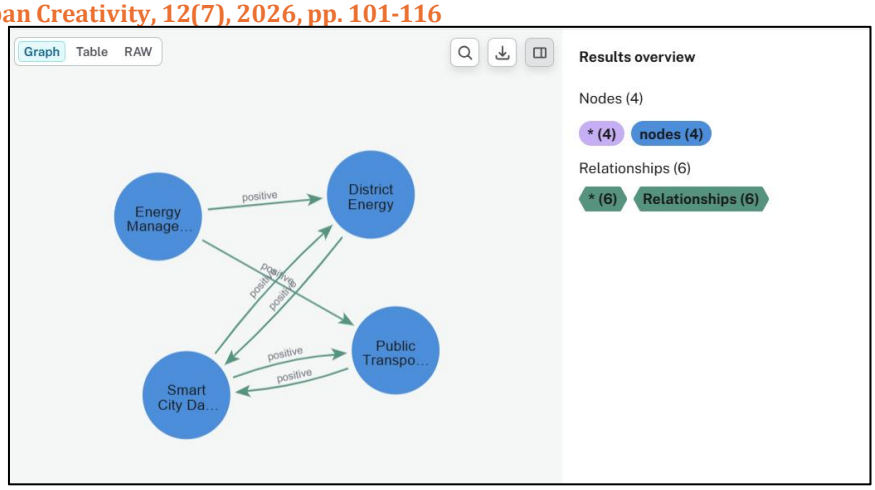


Figure 4: An example of indirect relationship representation in knowledge graph

Through Cypher queries, direct and indirect relationships can be identified, queried and analysed. Identifying the direct and indirect relationships within the city system can support practitioners to develop and implement more coordinated strategies. It can enable revealing cross-sector dependencies, potential synergies and unintended consequences across the city sector. This capability supports systemic and integrated governance approaches for transforming city systems to SNC (Jouzdani, Javidroozi, Shah, et al., 2025)

The knowledge graph can be utilised to reveal cross-sectoral relationships and dependencies across city systems, providing a more systemic understanding of SNC development. For example, electric vehicles were connected to EV charging infrastructure and renewable energy, while also depending on smart grid performance, smart meter integration, energy management systems, and city data platforms, demonstrating the necessity of deploying a coordinated strategy for deployment. Similarly, heat pumps were connected to renewable energy, HVAC electrification and building retrofitting, highlighting the significance of integrating building and energy strategies for effective integration. Identifying cross-sectoral relationships can support practitioners and governance institutions to develop coordinated cross-sectoral strategies.

Centrality analysis suggested another important capability of the knowledge graph by recognising the nodes which are highly connected within the system. This analysis showed that the smart city data platform had the highest connections (74), followed by smart grid (58), energy management system (57), and smart meters (50). These highly connected nodes can operate as leverage points, enabling multiple interventions and connecting otherwise separate sectors. Figure 5 shows the leverage points in the knowledge graph, and table 7 illustrates the number of their connections.

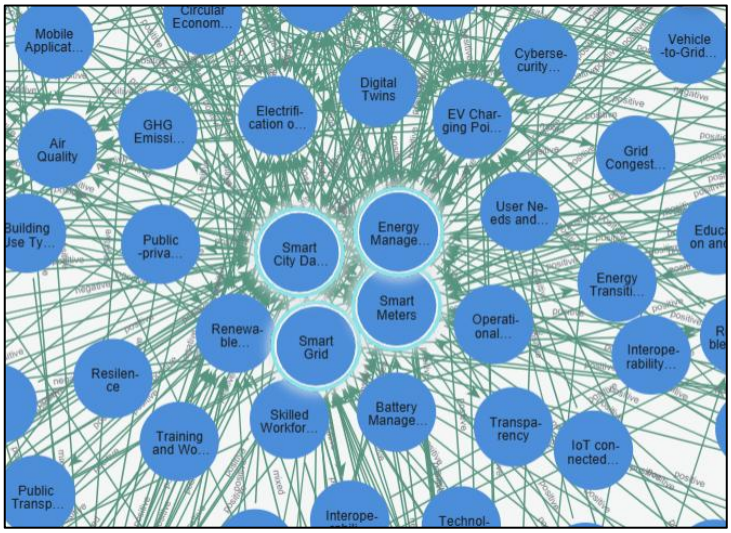


Figure 5: Identifying and illustrating the highly connected nodes as leverage points in the knowledge graph

Table 7: The identified leverage points in the knowledge graph and their systemic roles

Highly connected node	Connections	Systemic role
Smart City Data Platform	74	Integrating cross-sector city data for planning, monitoring and optimisation of city systems
Smart grids	58	Coordinating electricity demand, renewable supply and system flexibility
Energy Management System	57	Optimising energy use and linking operational processes across interventions
Smart meters	50	Providing real-time measurement, pricing and demand-response data

4.4 Proposing systemic strategies for Smart Net-zero City development

Finally, the knowledge graph was employed to propose systemic strategies for all 16 interventions. Each strategy was informed by a direct connection to the intervention, enabling factors, risks and leverage points. Table 8 shows the final proposed systemic strategies for SNC development, demonstrating how each intervention can progress through four systemic levels. These levels include physical and enabling foundations, monitoring, city system integration, predictive maintenance and circular economy. For example, the proposed strategies for electric vehicles, district energy and public transportation indicate how individual interventions are connected with supporting technologies, infrastructure, governance, city systems, and optimisation mechanisms rather than being deployed in isolation. By employing the same approach, strategies were proposed for a total of 16 interventions, providing a consistent framework for understanding how four levels of strategic implementation can support systemic deployment of SNC interventions.

Table 8: The proposed systemic strategies for three nodes as examples (EVs, heat pumps, public transportation)

Intervention	Systemic Level	Strategy
Electric Vehicles	Level 1 – Physical & Enabling Foundations	Integrating EVs with required charging infrastructure which is supplied by renewable energy sources. Supporting implementation through city planning, zoning, permitting, incentives, building requirements for EV integration, investment and workforce capability.
	Level 2 – Monitoring & Data Collection	Employing IoT and smart meters to collect real-time data from cars, chargers and the grid, supporting smart charging, pricing, demand management, fault detection and performance monitoring.
	Level 3 – System Integration & Coordination	Integrating energy management systems to optimise charging demand and energy distribution systems; smart grids to support dynamic charging and renewable energy integration; and the Smart City Data Platform to integrate EV, traffic, parking and grid data.
	Level 4 – Predictive Optimisation & Circularity	Applying AI for energy demand management, routing, pricing and energy load optimisation; digital twins for simulating EV fleets, charging impacts and infrastructure requirements; and circular-economy measures for battery reuse, recycling and recovering the material.
Heat Pumps	Level 1 – Physical & Enabling Foundations	Integrating heat pumps with HVAC electrification and building retrofitting which is supplied by energy from renewable sources, including standards, incentives, workforce skills, feasibility assessment and suitable conditions for buildings.
	Level 2 – Monitoring & Data Collection	Using IoT to collect temperature, humidity, occupancy and energy-consumption data, employing smart meters to provide real-time consumption and pricing information.
	Level 3 – System Integration & Coordination	Employing energy management systems to coordinate energy demand, renewable energy availability and operation; using smart grids to support energy demand response and flexibility; and utilising the Smart City Data Platform to integrate building, energy and grid data.
	Level 4 – Predictive Optimisation & Circularity	Applying AI to predict heating demand and optimise schedules; digital twins for modelling building behaviour and system performance; and circular economy measures to support reusable materials, recycling and efficient manufacturing processes.
Public Transportation	Level 1 – Physical & Enabling Foundations	Integrating public transportation with electrification, renewable energy and Mobility as a Service (MaaS). Supporting deployment through planning, standards, accessibility, finance and stakeholder coordination.
	Level 2 – Monitoring & Data Collection	Using IoT for real-time monitoring, maintenance and scheduling, integrating smart meters to measure and manage energy consumption.
	Level 3 – System Integration & Coordination	Employing smart grids to coordinate energy supply for electrified fleets, using energy management systems for optimising energy consumption, and the Smart City Data Platform to integrate vehicle, traffic and infrastructure data.
	Level 4 – Predictive Optimisation & Circularity	Applying AI for energy demand forecasting, route and schedule optimisation and predictive maintenance; digital twins for simulating network operation; and circular-economy measures for extending asset life, enabling reuse and improving resource efficiency.

4.5 Digital transformation framework development

The developed digital transformation framework for SNC integrates four systemic levels with PPTD dimensions. It progresses from foundational deployment to digital monitoring, city system integration, predictive maintenance and circular economy (Figure 6). It treats digital transformation as a socio-technical process where technological deployment is supported by appropriate capabilities from People, Process and Data.

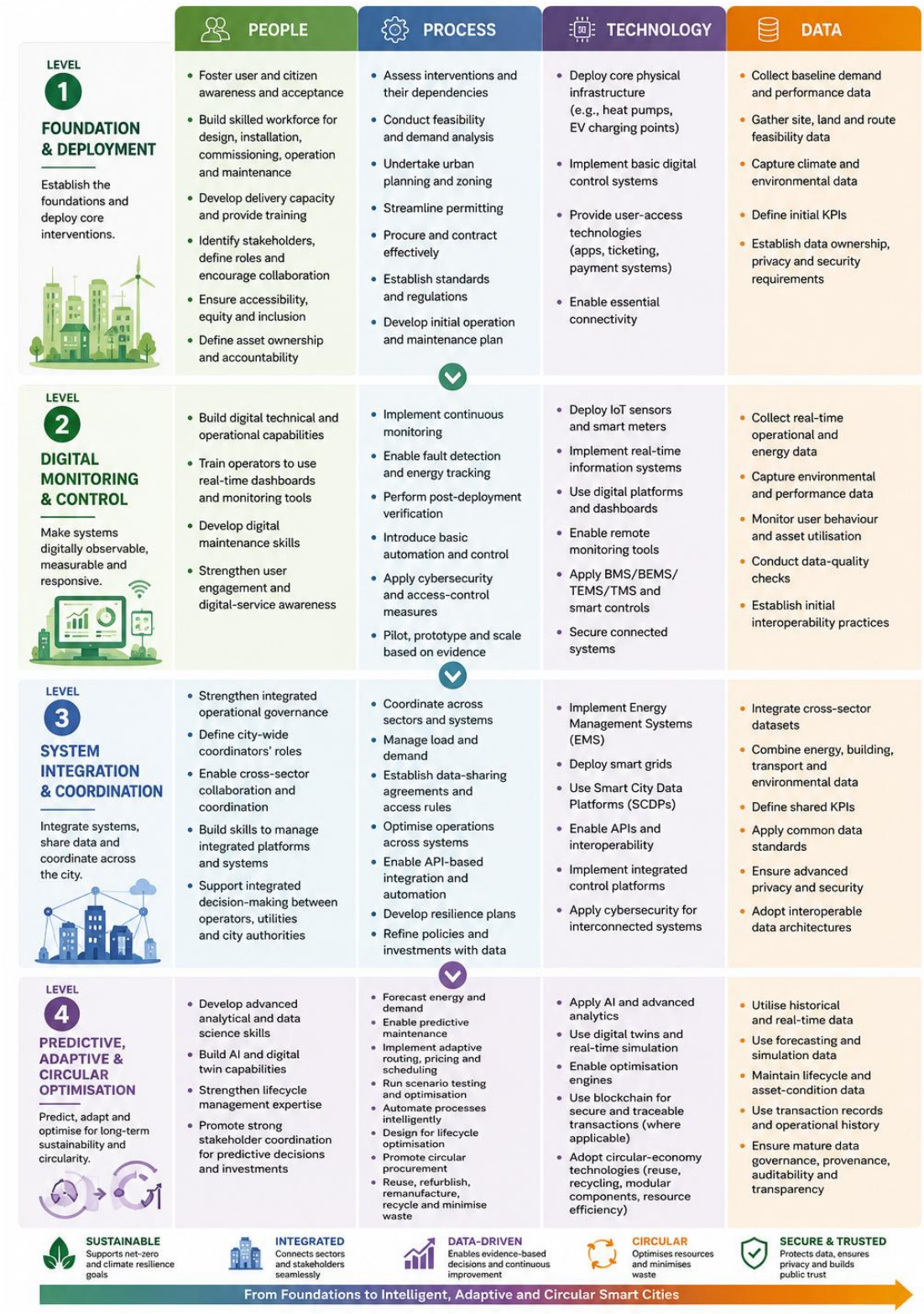


Figure 6: Digital transformation framework for SNC development

4.6 Focus-group findings

The focus group validated the overall structure and systemic logic of the proposed strategies and digital transformation framework. However, some minor implementation considerations were proposed. Table 9 summarises the main validation findings and shows how this feedback

was translated into specific refinements to improve the framework's feasibility, adaptability and practical application.

Table 9: Focus group validation results of systemic strategies and framework

Validation area	Focus group result	Implication
Level 1 – Foundation	Deploying the required infrastructure, governance, skills, and citizens' acceptance were confirmed as essential components.	Supports retaining Level 1 as the basis for SNC implementation. Readiness and enabling conditions were clarified before implementation
Level 2 – Monitoring	Deploying real-time monitoring and performance verification was confirmed as a necessary component.	Confirms that Level 2 enables measuring intervention performance.
Level 3 – Integration	This level is considered to have the most systemic impact through deploying an integrated and shared system.	Supports Level 3 as the main systemic integration layer. KPIs, data quality management and performance verification were clarified within the monitoring stage.
Level 4 – Optimisation	Integrating AI, digital twin and circularity practices were valued but depend on the earlier levels.	Their dependency on the readiness of earlier levels was made clearer.
Implementation & governance	Experts requested to clarify the roles, responsibilities and dependencies.	Stakeholder roles, ownership and dependencies were clarified across the framework levels.
Overall result	Positive overall but affected by differences in city readiness and capacity.	No structural changes were required; only minor clarifications related to implementation were integrated

5. Discussion

The finding indicates that SNC development requires a shift from the deployment of isolated technological interventions towards the coordinated and holistic transformation of an interconnected city system. While existing research in SNC development has extensively assessed individual interventions such as EVs, heat pumps, and renewable energy, the results of this study demonstrate that their effective impact depends on the interconnection with other interventions and shared resources such as infrastructure, governance and data platforms. This study's contribution, therefore, is demonstrating how RAG, knowledge graphs, and systems thinking, accompanied by human validation, can be integrated for synthesising fragmented city knowledge, representing cross-sectoral dependencies, identifying potential leverage points and translating these relationships into systemic strategies and a digital transformation framework. Importantly, the findings position AI not as an independent solution for SNC transformation, but as an enabling capability for enabling a systemic transformation through appropriate deployment of physical infrastructure, monitoring systems, interoperable data, governance arrangements and organisational capabilities. Figure 7 illustrates the study contributions.

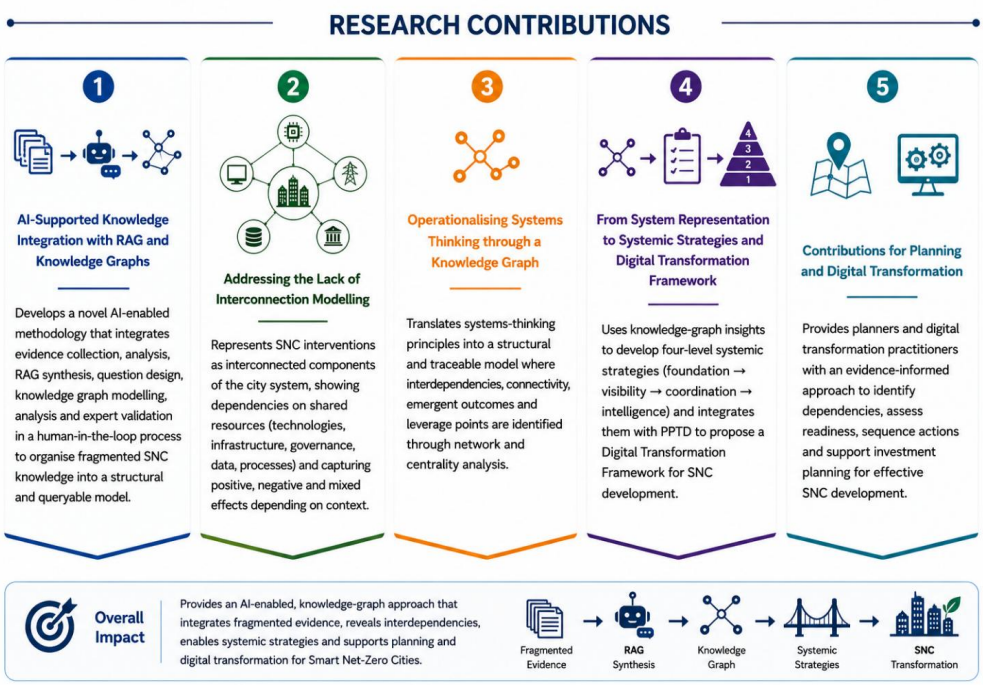


Figure 7: Research contributions

This study contributes to a novel methodological approach by developing an AI-enabled knowledge graph for organising fragmented information of city systems into a structural knowledge graph. The methodology connects evidence collection, framework analysis, RAG development, question designing strategy, knowledge graph modelling, graph results analysis and the expert validation process.

A key contribution is the role of AI in integrating fragmented SNC knowledge that is distributed across various sources such as policies, reports and academic literature. In this study, RAG supported systemic synthesis of evidence while the knowledge graph transformed this knowledge into a structural and queryable model of entities and their interconnections. This provides a transparent foundation for decision support in SNC. However, the process remained human-in-the-loop, requiring entity standardisation, relationship extraction, and validation.

The research finding directly addresses the first identified research gap. Existing efforts commonly recognise and classify SNC interventions but provide limited interconnected representations of interventions. The developed knowledge graph in this study extends beyond this and represents the interventions as components of the city system. The graph indicates that the performance of interventions depends on shared resources such as technologies, governance data and processes. As examples, EVs, heat pumps, and district energy all relied on a combination of infrastructure, policy, monitoring and management. This shows why the interventions should not be planned in isolation or independently.

The relationship representation and description in the knowledge graph were particularly important. It enables the model to capture various effects of interventions depending on context. For example, according to the knowledge graph, EVs can support reducing city emissions but may create challenges related to supplying the required electricity without adequate integration of renewable energy sources, smart charging and grid management.

The study contributes to translating systems thinking into a structural and queryable model. The cities' interdependencies are represented as relationships. Connectivity is shown through the city network structure. Emergent outcomes illustrated through multiple interventions contributing to shared outcomes. Interdependencies are represented as relationships, and connectivity is represented through the network structure. Emergent outcomes are represented through multiple interventions contributing to shared outcomes, and potential leverage points are recognised through centrality and cross-sectoral analysis. This contribution is important because systems thinking is mainly discussed conceptually without a mechanism for effective integration in SNC development. Therefore, the developed knowledge graph creates a bridge between systems thinking theory and practical SNC analysis.

Another key contribution is addressing the lack of systemic strategies for SNC interventions. The developed knowledge graph was utilised as a visualisation and analysing model to identify direct connections, indirect relationships, risks and leverage points. This information was utilised to propose systemic strategies at four systemic levels.

This process demonstrated how knowledge modelling through a knowledge graph can support proposing systemic strategies. Level 1 established the foundation for physical and institutional requirements. Level 2 supported real-time visibility. Level 3 enabled coordination across the city system, and Level 4 supported simulation, prediction and circularity.

The progression from level 1 to 4 explains how isolated interventions can transform into a part of an integrated SNC system. For example, a heat pump deployment can systemically progress when it is implemented alongside building retrofitting measures, while its performance is monitored; smart grids enable systemic integration, the energy supplied by renewable energy sources and predictive control technologies utilised for predictive maintenance.

Integrating systemic levels with PPTD further translates the systemic strategies into a digital transformation framework. This contribution indicates how AI-enabled knowledge modelling can support converting fragmented evidence into systemic understanding of SNC transformation. It can provide a structural approach for cities to identify the interdependencies required to transform isolated interventions towards an integrated city system.

For city planners, the knowledge graph and systemic strategies provide a means to identify dependencies before implementation. For example, for heat pump development, city planners are required to examine the relevant factors such as building condition, grid capacity, availability of renewable energy, and workforce. For planning EV deployment, they need to examine some factors such as travel demand, energy supply, charging locations, parking, and affordability.

For digital transformation practitioners, the research findings confirm that technology

should be integrated with PPTD. Employing AI, digital twins, and city data platforms in SNC development requires integrated information and a reliable monitoring approach, effective governance, interoperability and clear responsibilities. Therefore, the digital transformation framework can support readiness assessment, sequencing and investment planning for SNC development.

6. Conclusion

This study demonstrates how employing an AI-enabled knowledge graph can support a systemic approach for SNC development. By synthesising and organising heterogeneous evidence across city sectors, the study identified 16 key interventions and developed a knowledge graph including 319 nodes and 892 relationships. The developed knowledge graph uncovers cross-sectoral dependencies, shared resources and enablers, potential leverage points and challenges in SNC development. These findings indicate that SNC interventions should be understood as interconnected components of a city system rather than isolated interventions.

This study makes three interconnected contributions. First addressing the lack of knowledge modelling for SNC development by illustrating interventions, their interconnections, enabling technologies, governance, data requirements, and associated relationships with the city sectors. Second, it facilitates operationalizing systems thinking approach by making cities' connectivity, shared resources and outcomes, and interdependencies structured, identifiable, queryable and traceable. Third, this study moves beyond systemic representation by translating the gain in insight from the knowledge graph into systemic strategies for 16 interventions at four levels. Subsequently, these findings were integrated with PPTD to develop a digital transformation framework for SNC. These findings provide a structural basis for planners and digital transformation practitioners to identify dependencies, assess readiness and coordinate the city's capabilities for a systemic SNC transformation.

There are some limitations identified for this study. The main limitation is that the developed knowledge graph provides qualitative relationships between the interventions rather than quantitative effects. Therefore, this outcome should be utilised as a structural decision-support foundation rather than a dynamic model. Future research can concentrate on extending the approach through quantitative relationship modelling based on real-world data across the city system. Overall, this study positions AI as an enabling mechanism for transforming fragmented evidence in SNC into a structured and queryable knowledge graph, integrated systemic strategies and an actionable digital transformation framework.

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